Changes in Australian Rainfall Runoff and Its Implication for Estimating Design Rainfall

Muhammad Muhitur Rahman[1] and Ataur Rahman[1]
[1]School of Computing, Engineering and Mathematics, Western Sydney University, Building XB 2.48,
Kingswood, Penrith NSW 2751, Australia

Corresponding author's E-mail: muhit.rahman@westernsydney.edu.au

Abstract

Recently, Geoscience Australia has released updated national guidelines for the estimation of design floods in Australia, commonly known as Australian Rainfall Runoff (ARR). The methodologies and guidelines proposed in ARR are crucial for an accurate estimation of flood risk and for the design of safe and sustainable infrastructures in Australia. The newly proposed ARR (ARR2016) has adopted new methods and data compared to old ARR (ARR1987), which resulted differences in the estimation of design rainfall across Australia. For example, in ARR2016 additional 30 years' rainfall data and 2300 extra rainfall stations have been included compared to ARR1987. Rainfall frequency analysis has been conducted by Generalised Extreme Value (GEV) distribution compared to Log-person Type III (LPIII), previously adopted in ARR1987. Bayesian Generalised Least Square Regression (BGLSR) is adopted in ARR2016 to predict daily rainfall from sub-daily rainfall statistics, which was previously done by Principal Component Analysis (PCA). In this paper, we review the guidelines for both ARR2016 and ARR1987 for design rainfall estimation and evaluate changes in design rainfall for selected stations in 8 major cities in Australia including Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Sydney and Perth. Results presented in the paper will help Engineers and Managers of local governments to understand and implement new regulations proposed in ARR2016 for the estimation of design rainfall.

Keywords: *ARR1987, ARR2016, rainfall frequency, design flood.*

1. INTRODUCTION

Estimation of design rainfall is crucial to rainfall runoff modelling. Design rainfall, commonly known as intensity-frequency-duration (IFD) curves are frequently used by design engineers and scientists as an input to a wide range of design flood model, environmental studies and to design water infrastructure including bridges, culverts, stormwater drains, flood embankments and constructed wetlands. In Australia, the guidelines and methodologies for accurate estimation of design rainfall is provided by Australian Rainfall Runoff (ARR). The first edition of ARR was published in 1958, the second in 1977; however, the third version of ARR in 1987 (ARR1987) incorporated a complete revision of materials previously covered with a broader range of topics relevant to flood estimation (IEAust 2001). ARR1987 has been accepted and widely used by the relevant practitioners.

In ARR1987, IFD was developed using daily rainfall data from approximately 7500 stations with more than 30 years of record, and short duration (down to 6 minutes) data from approximately 600 rain gauges (pluviographs) with more than 6 years of record. The rainfall data was supplied by Australian Bureau of Meteorology (BOM), which operates and maintains such stations throughout Australia. With time, BOM has extended its network of meteorological stations and has improved the rainfall database significantly. Recently, the new ARR2016 is released, which is an updated version of ARR using daily rainfall data from 8074 stations and continuous (pluviographs) data from 2280 stations (BOM 2017); rainfall records of more than 30 years and 8 years are used, respectively for daily and continuous data. The inclusion of additional continuous rainfall data in ARR2016 has improved the accuracy and representativeness of the newly estimated IFDs, significantly. In addition, new probability distribution is fitted to the annual maximum series of rainfall data for at site and regional frequency analyses, which is regarded more appropriate distribution across Australia (Green et al 2012). In this paper, we review the guidelines for both ARR1987 and ARR2016 for design rainfall estimation and evaluate changes in design rainfall for selected stations in 8 major cities in Australia including Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Sydney and Perth.

2. SALIENT FEATURES OF ARR1987

ARR1987 was developed with the aim of providing spatially and temporally consistent IFD design rainfall information in a comprehensive, yet relatively simple way. Design rainfall can be estimated following one of the three procedures, namely (IEAust 2001):

- algebraic equation procedure;
- graphical procedure and
- computerised technique.

Algebraic equation and graphical procedures are provided in hard copies published by IEAust (1987). These two methods involve 8 steps to obtain complete IFD information for any location using input data from detailed *rainfall intensity maps*. The computerised method, termed as CDIRS (Computerised Design IFD Rainfall System) is available from the BOM website (BOM 2017). CDIRS provides a full set of IFD curves derived automatically for any given latitude and longitude. The system has a large data base covering Australia at a latitude and longitude resolution of 0.025 degrees for high rainfall gradient areas and 0.05 degrees for elsewhere. One of the advantages of using CDIRS is that the user does not need to read data from design rainfall maps; maps were digitised and gridded using a Laplacian smoothing spline technique, where grid point values were calculated iteratively.

In ARR1987, IFD curves consistent to topographical, spatial and temporal scales were obtained using *generalised technique*. The generalised technique is based on charts of rainfall intensity for six combinations of durations and Average Recurrence Interval (ARI). The combinations are 1 hour, 12 hours, 72 hours and ARIs of 2 years and 50 years; the combination commonly known as *master charts*. For any given location, the six specific intensities are obtained from the master charts along with a regionalised skewness, and interpolation and extrapolation methods are used to obtain a full set of IFD curves. There are thirteen standard durations have been selected using interpolation and extrapolation methods, namely, 5, 6, 10, 20, 30 minutes and 1, 2, 3, 6, 12, 24, 48 and 72 hours, and seven standard ARIs, namely, 1, 2, 5, 10, 20, 50 and 100 years.

Different probability distributions can be fitted to annual maximum rainfall series data including normal, log-normal, log-log normal, gamma, Gumbel, Pearson Type III, log-Pearson Type III and different extreme value distributions. However, log-Pearson Type III (LPIII) by method of moments was found to be more appropriate for most of the regions in Australia and availed in ARR1987 (IEAust 1987). Briefly, the random variable x has a log-Pearson Type III distribution if $y = log_a x$ has a Pearson Type III distribution. In general case, LPIII distribution is derived from the Pearson Type III distribution by change of variable on the logarithm of this variable (Bolgov and Korobkina 2013). Normally, the commonly used logarithm is the natural logarithm with base e. The density function of the LPIII can be written as:

$$f(x; a, b, m) = \frac{|a|}{\Gamma(b)x}[a(\ln x - m\,)]^{b-1}\exp[-a(\ln x - m)] \qquad (1)$$

Where, a, b, m are scale, shape and location parameters of the distribution, respectively and $\Gamma(b)$ is the gamma function. Relationships between parameters of distribution and moments of logarithms of the observed series can be written as:

$$a = \frac{2}{C_{S_{ln}}\sigma_{ln}},\ b = \frac{4}{C_{S_{ln}}^2},\ m = M_{ln} - \frac{2\sigma_{ln}}{C_{S_{ln}}} \qquad (2)$$

Where, M_{ln}, σ_{ln}, $C_{S_{ln}}$ are mean, mean square deviation and coefficient of asymmetry of series of natural logarithms of the observed data, respectively.

For the determination of LPIII distribution parameters a, b, m, the methods of moments can be applied to the observed data, as expressed below:

$$b = \frac{\ln\beta_2 - 2\ln\beta_1}{2\ln(1-{}^{1}/_{a}) - \ln(1-{}^{2}/_{a})}, \qquad m = \ln\beta_1 + b\ln(1 - {}^{1}/_{a}),$$

$$\Phi(a) = \frac{2\ln(1-{}^{1}/_{a}) - \ln(1-{}^{2}/_{a})}{3\ln(1-{}^{1}/_{a}) - \ln(1-{}^{3}/_{a})} - \frac{\ln\mu_2 - 2\ln\mu_1}{\ln\mu_3 - 3\ln\mu_1} = 0 \qquad (3)$$

Where, β_1, β_2, β_3 are sample moments about the origin and μ_1, μ_2, μ_3 are moments about the mean.

The LPIII distribution is mainly applicable to the south coast, the south-east high topographic areas, and the north-west and south-west regions of Australia. For determining short duration design values (less than one hour), Principal Component Analysis (PCA) of pluviometers data was found to be the most appropriate method and hence was adopted in ARR1987. Details of PCA method can be found in Haque et al (2013).

3. SALIENT FEATURES OF ARR2016

In ARR2016, the commonly used design rainfall frequency term, ARI is omitted; instead, Annual Exceedance Probability (AEP) has been used. There is a misconception about ARI that ARI of 100 years (for example) means that the event will occur once every 100 years. Rather the reality is, for each and every year there is a 1% chance, more elaborately, a *1 in 100 chance* that the event will be equalled or exceeded once or more than one time. In contrast, the AEP is the probability of a particular rainfall amount for a specified duration being equalled or exceeded in any 1 year period. The use of AEP to describe the chance of a particular rainfall is preferred as it conveys the probability or chance that exists for each year (BOM 2017).

Design rainfalls in ARR2016 are proposed in three sets of frequencies (BOM 2015):

- Very frequent,
- Frequent and infrequent, and
- Rare.

The *very frequent* (or sub-annual) design rainfalls are proposed for the estimation of small flood events, water sensitive urban design and some stormwater design tasks such as gutters. This ranges from 2 Exceedances per Year (EY) to 12 EY. Table 1 shows a comparison between the new EY terminology and its equivalency to the old terminologies.

Table 1. Very frequent design rainfalls proposed in ARR2016 (Green et al 2014)

EY (exceedance per year)	AEP (Annual Exceedance Probability (%)	ARI (Average Recurrence Interval) (Months)
12 EY	99.99	1 month
6 EY	99.75	2 months
4 EY	98.17	3 months
3 EY	95.02	4 months
2 EY	86.47	6 months
1 EY	63.21	12 months

The *frequent and infrequent* design rainfalls cover the probabilities of 1 EY, 50% AEP (2 years ARI), 20% AEP (5 years ARI), 10% AEP (10 years ARI), 5% AEP (20 years ARI), 2% AEP (50 years ARI) and 1% AEP (100 years ARI). This range of design rainfall probabilities commensurate to that proposed as ARI in ARR1987. The *rare* design rainfalls have probabilities less than 1% AEP (between 1 in 100 and 1 in 2000). This category of design rainfalls is used to design large bridges and for the assessment of adequacy of spillway of existing dam and other important infrastructure.

The at-site frequency analysis of annual maximum rainfall data in ARR2016 is conducted by Generalised Extreme Value (GEV) distribution fitted by L-moments instead of LPIII as done in ARR1987. GEV distribution is a continuous probability distribution that combines Gumbel, Frechet and Weibull distributions (Millington et al 2011). Like LPIII distribution, GEV also uses 3 parameters namely, location, scale and shape. While location parameter describes the shift in each direction on the horizontal axis, the scale parameter describes how spread out the distribution is, and the shape parameter determines the shape of the distribution and governs the tail of the distribution. The CDF and PDF of this distribution can be written as below (Hosking and Wallis 1997):

$$F(x)exp\left[-\left(1-\frac{\kappa(x-\xi}{\alpha}\right)^{1/k}\right]$$

$$f(x)\alpha^{-1}exp[-1(1-\kappa)y-\exp(-y)]\text{, where } y-\kappa^{-1}\log\left[1-\frac{\kappa(x-\xi}{\alpha}\right], when\ \kappa \neq 0 \qquad (4)$$

Where ξ is the location parameter, α is the scale parameter and κ is the shape parameter.

As stated in Section 2, for the determination of daily to sub-daily rainfall frequency in ARR1987, PCA followed by regression was used; however, one drawback of this approach is its inability to account for variation in record lengths from site to site and inter-station correlation (Green et al 2012). In ARR2016, sub-daily rainfalls are derived using Bayesian Generalised Least Squares Regression (BGLSR) (Haddad et al 2011; Haddad and Rahman 2014). This approach is found suitable as it accounts for possible cross-validation and can justify sampling uncertainty (by separating the sampling and statistical modelling errors) and inter-site dependence (Green et al 2012).

Another difference between ARR1987 and ARR2016 is that the gridding system in ARR2016 implemented by software package ANUSPLIN (Hutchinson 2007 reported in Green et al 2012) as compared to manual drawing of the isohyets in ARR1987. GEV parameters have been gridded in ANUSPLIN, which provides more flexibility in the choice of extracting design rainfall (Green et al 2012).

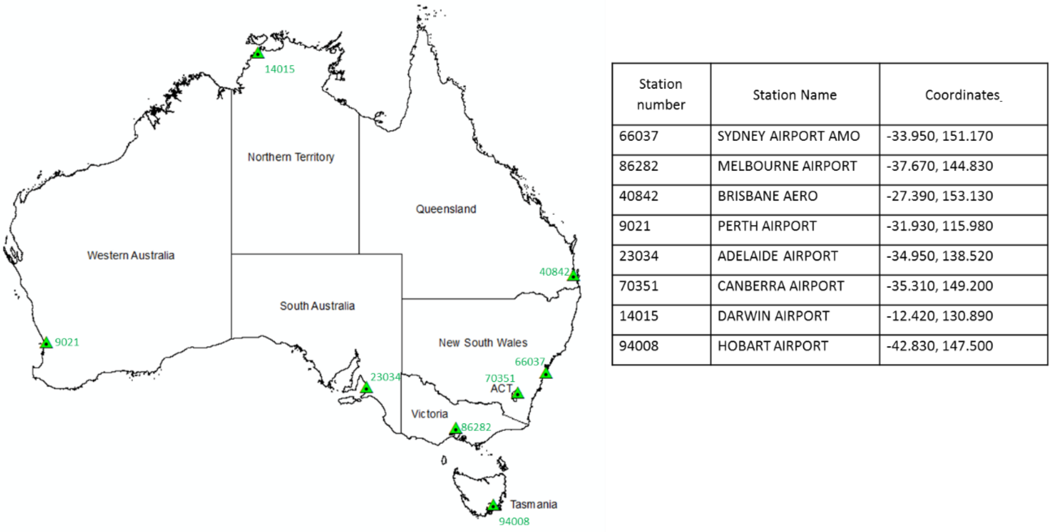
4. COMPARISON OF DESIGN RAINFALL ESTIMATION USING ARR1987 AND ARR2016

To see the impact of changes implemented in ARR2016 discussed above, rainfall gauging stations situated in airports of eight major cities across Australia were selected. Details and geographical locations of the stations are shown in Figure 1. It is assumed that selected stations are representative of geographical variations of a large country like Australia, to some extent. IFD curves were generated by computerised technique of ARR1987 and ARR2016 using online tool provided by BOM (BOM 2017). Three ARIs of 2 years, 50 years and 100 years, and corresponding AEPs of 50%, 2% and 1% were used. Three durations of 1hr, 12hr and 72hr were used for each combination resulting in a total of 9 combinations of IFD for each station. It should be noted that the selected combinations of durations and frequencies represent the six master charts as reported in ARR1987 (except the 100 year ARI or 1% AEP).

The relative differences in design rainfall between the new ARR2016 and the ARR1987 IFDs have been calculated by:

$$\% \, difference = \frac{(ARR2016\ IFD - ARR87\ IFD) * 100}{ARR87\ IFD} \qquad (5)$$

Percent changes in design rainfall using ARR2016 compared to ARR1987 for eight stations are shown in Figure 2 for 1hr, 12hr and 72hr durations.



Station number	Station Name	Coordinates
66037	SYDNEY AIRPORT AMO	-33.950, 151.170
86282	MELBOURNE AIRPORT	-37.670, 144.830
40842	BRISBANE AERO	-27.390, 153.130
9021	PERTH AIRPORT	-31.930, 115.980
23034	ADELAIDE AIRPORT	-34.950, 138.520
70351	CANBERRA AIRPORT	-35.310, 149.200
14015	DARWIN AIRPORT	-12.420, 130.890
94008	HOBART AIRPORT	-42.830, 147.500

Figure 1: Geographical distribution of stations used in the study

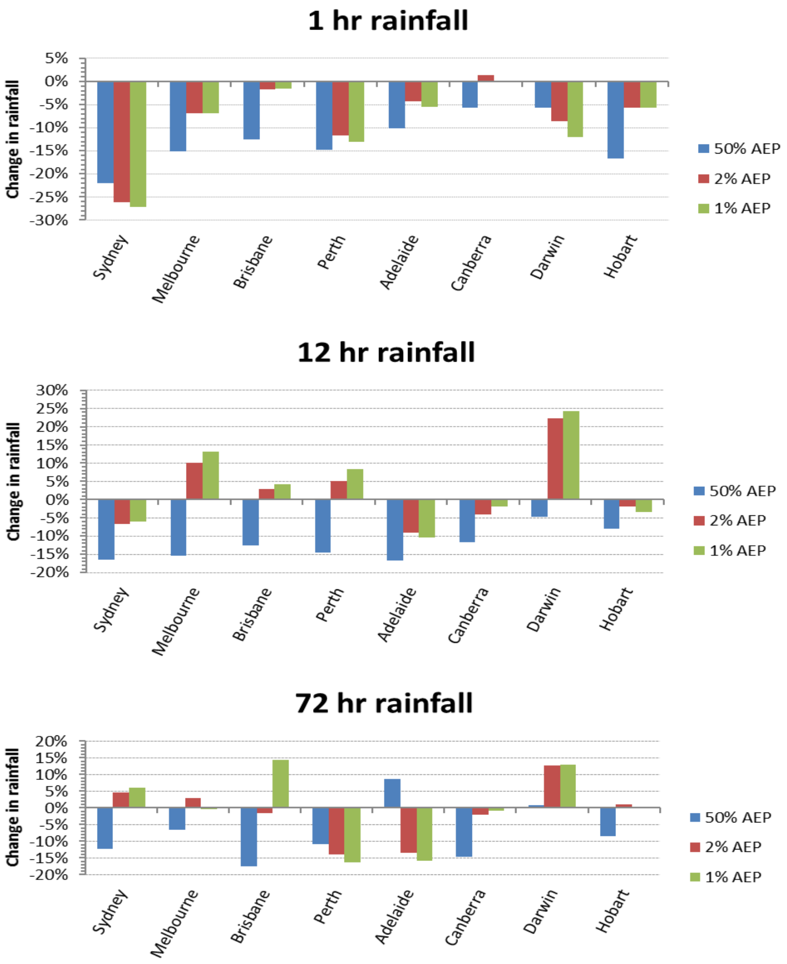


Figure 2: Percent changes in design rainfall using ARR2016 compared to ARR1987

As shown in Figure 2, for 1 hr duration, for most of the stations, percent changes in design rainfall are negative. This means the new method for the estimation of 1hr design rainfall gives smaller values compared to ARR1987. For 12hr duration of rainfall, stations in Melbourne, Brisbane, Perth and Darwin were found to have an increase in design rainfall values in the range of 3% to 22% for 2% AEP, and 4% to 24% for 1% AEP; for both these AEPs, Darwin had the highest increase (about 25%). For 12 hr duration, Sydney was found to have a decrease in design rainfall for 50%, 2% and 1% AEPs. For 72hr duration, Perth was found to have a decrease in design rainfall for 50%, 2% and 1% AEPs, Sydney had a decrease (by about 12%) for 50% AEP, but about 5% increase for AEPs of 2% and 1%, and Brisbane had the highest decrease (by 17%) for 50% AEP.

5. CONCLUSIONS

The paper presents a short review on design rainfall estimation methods in ARR1987 and ARR2016. Eight different locations are selected across Australia and design rainfall values are compared between ARR1987 and ARR2016 methods for three durations (1hr, 12hr and 72hr) and three AEPs (50%, 2% and 1%). It has been found that ARR2016 design rainfalls vary by about -25% to +25% compared with ARR1987 values. For 1hr duration, Sydney shows the highest change (by about by -25%), for 12hr duration, Darwin shows the highest change (by about + 25%), and for 72hr duration, Brisbane shows the highest change (by about -17%).

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