Enhancing the New Intensity-Frequency-Duration (IFD) Design Rainfalls – Sub-Annual IFDs

Janice Green
Supervising Hydrologist, Bureau of Meteorology, Canberra, Australia

Karin Xuereb
Senior Meteorologist, Bureau of Meteorology, Melbourne, Australia

Catherine Jolly
Hydrologist, Bureau of Meteorology, Hobart, Australia

The Intensity-Frequency-Duration (IFD) revision project, part of the Australian Rainfall and Runoff (AR&R) Revision, has made available new IFDs for durations from one minute to seven days and for probabilities from 1 Exceedance per Year (EY) to 1% Annual Exceedance Probability (AEP). The new IFDs meet the design probability requirements of most infrastructure, however, for Water Sensitive Urban Design and some stormwater applications, IFDs for probabilities more frequent than 1 EY are required. In order to address this need, enhancements to the new IFDs to be provided over the next 12 to 18 months include the provision of estimates of sub-annual IFDs for probabilities of 2, 3, 4, 6, and 12 EY. However, as sub-annual IFDs have not been previously derived, it will be necessary to first develop the method to be adopted when deriving the sub-annual IFDs.

To ensure consistency, the overall approach adopted for the sub-annual IFDs will be similar to that used for the new IFDs. However some changes will be necessary because of the increased frequency of occurrence. One difference will be the necessity to extract the Partial Duration Series (PDS) rather than the Annual Maximum Series (AMS). While the new IFDs used stations with at least nine values in the AMS, the number of exceedances per year to be used for IFDs more frequent than 1EY is expected to be at least 12. The PDS approach was explored previously and the Generalised Pareto distribution was found to provide the best fit for an average of three exceedances per year. However, the appropriateness of this distribution for 12 exceedances or more will need to be explored.

Consistent with the new IFDs, the Bayesian Generalised Least Squares Regression (BGLSR) method will be applied to the sub-daily data to generate L-moments for sub-daily durations at the daily read stations. Regionalised L-moments will be derived using a similar approach to the regionalisation that was carried out for the new IFDs. These regionalised L-moments will then be used to estimate the parameters of the appropriate distribution to be fitted to the data. The parameters of the distribution will be gridded using ANUSPLIN and rainfall quantile estimates will be calculated for standard durations from one minute to seven days and probabilities of 2, 3, 4, 6 and 12 EY.

1. INTRODUCTION

The new IFDs released by the Bureau of Meteorology (the Bureau) in July 2013, as part of the Australian Rainfall and Runoff (AR&R) Revision, were for durations of one minute to seven days and probabilities of 1 Exceedance per Year (EY) to 1% AEP. This range of probabilities is consistent with those of the previous IFDs which were provided in *Australian Rainfall and Runoff (AR&R87)* – although the terminology adopted for the two sets of IFDs differs.

The range of IFD probabilities provided as part of the Phase 1 release meet the design requirements/guidelines for the design of most infrastructure assets. However, to date, neither the new IFDs nor the AR&R87 IFDs have been provided for probabilities more frequent than 1 EY (or the corresponding one year Average Recurrence Interval (ARI)) which are used primarily in Water

Sensitive Urban Design (WSUD) and some stormwater applications. In order to address this omission, Phase 2 of the IFD Revision Project will derive IFDs for the sub-annual probabilities of 2, 3, 4, 6, and 12 EY. However, prior to deriving the sub-annual IFDs, it is necessary to first develop the method that will be adopted. The method will need to be appropriate for the derivation of IFDs for probabilities more frequent than 1 EY while being sufficiently consistent with the method used for the new IFDs to ensure a smooth transition between the two sets of IFDs.

2. TERMINOLOGY

Prior to discussing the need for sub-annual IFDs and the method to be adopted for their derivation, it is necessary to first discuss the terminology that will be adopted for these more frequent IFDs. To date, ARI terminology has been widely adopted for IFDs, including the, not strictly correct, usage for sub-annual IFDs; for example six month average recurrence interval.

In keeping with the probability terminology to be adopted in the new edition of AR&R, the terminology to be adopted for the sub-annual IFDs can be summarised as follows. Events more frequent than 50% AEP will be expressed as X EY. For example, 2 EY is equivalent to a design event with a 6 month recurrence interval. Table 1 shows a comparison between the new EY terminology and the terminologies that have been adopted previously.

Table 1. Adopted Terminology

EY	AEP (%)	ARI (years)	ARI (months)
12	99.99	0.08	1 month
6	99.75	0.17	2 month
4	98.17	0.25	3 month
3	95.02	0.33	4 month
2	86.47	0.50	6 month
1	63.21	1.00	12 month

3. CURRENT PRACTICE

3.1. Australia

In Australia hydraulic design guidelines generally specify probabilities of 1 EY to 10% AEP (or 1 – 10 year ARI) for the sizing of infrastructure for minor flood events and probabilities of 2% to 1% AEP (50 – 100 year ARI) for the design of infrastructure for major flood events. In contrast, the aim of WSUD is to effectively integrate the urban water cycle into the natural water cycle. It incorporates aspects of water supply, wastewater and stormwater management strategies to reduce the impact of development on the quantity and quality of urban runoff (BMT WBM 2009). Many stormwater quality or WSUD guidelines recommend a flow threshold of Q_{3month} for the design of stormwater quality treatment devices.

However, as discussed in Section 1, IFDs for a three month average recurrence interval or 4 EY have not previously been provided and many guidelines do not specify how the 4 EY IFD or subsequent Q_{3month} value is to be calculated. 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 sub-annual IFDs.

As the first step in the development of the approach to be used for estimating the sub-annual IFDs, a review of several design guidelines from both local and state governments was undertaken to identify how these values are being estimated. Table 2 shows a summary of the different estimation methods that were found. The results show that there is currently no standard way of determining the 4 EY IFD or Q_{3month} value, or any other design value more frequent than 1EY, even though this has been accepted as the design flow for stormwater quality treatment devices.

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Table 2. Summary of Australian Practice for estimating sub-annual IFDs

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)

3.2. International

In the absence of a consistent approach across Australia for the estimation of sub-annual IFDs, a preliminary search for the estimation of sub-annual IFDs and water quality design guidelines for other countries was undertaken. Table 3 summarises the key findings from this search. In some cases, reference was made to sub-annual IFD values, but again, no calculation method was indicated. This was particularly the case when factors or ratios of other frequencies were defined without specifying how they were derived.

Table 3. Summary of International Practice for estimating sub-annual IFDs

Source	Guideline	Method
Low-Impact Development: An Integrated Environmental Design Approach (US)	Water quality control volume = first 1/2 inch of runoff from impervious areas	Treatment of percentage of annual average runoff.
Rainfall Frequency Atlas of the Midwest. Bulletin 71 Research Report 92-03 (US)	Frequency relations < 12 months calculated using ratios of 24 month rainfall for each of the recurrence intervals	Mean ratio for x-month x 24-month rainfall
Auckland Council Introduction to Stormwater Issues (NZ)	Fraction of 2 year 24 hour ARI	Sd = (2 year 24 hour rainfall depth at site) / 3.
Urban Stormwater Management Manual for Malaysia	Factors of 2 year ARI	$^{0.250}I_t = 0.5^2 I_t$ for 3 month ARI

3.3. Summary

Sub-annual IFDs are used around the world and throughout Australia. However, as can be seen from the previous sections, several different methods are currently used to estimate sub-annual IFDs for the purposes of hydraulic design, particularly for WSUD. The differences in estimation methods within Australia are of particular concern as this affects the consistency of design outcomes. In light of this, the provision of sub-annual IFDs on a national scale was identified as a priority for Phase 2 of the IFD Revision Project.

4. APPROACH

Having identified the need to provide estimates of sub-annual IFDs, the next step is to develop the approach to be adopted. A summary of the method used for the new IFDs is provided in Table 4. While the data base and method adopted for deriving the new IFDs for probabilities from 1EY to 1% AEP will form the basis of the approach to be adopted, variations will be required when deriving the more frequent sub-annual IFDs.

Table 4 Summary of new IFDs method

Variable	Output
Data	Bureau stations plus stations from other data collecting agencies
Record length	Up to 2012; 8074 daily read > 30 years; 2280 continuous stations > 8 years (754 Bureau; 1526 Regs)
Durations	1 minute to 168 hour (7 day)
Frequencies	1 EY to 1% AEP
Frequency analysis	Annual maximum series; L-moments; GEV
Daily to sub-daily	Bayesian Generalised Least Squares Regression (BGLSR)
Gridding	ANUSPLIN
Delivery method	New webpage on Bureau's website

4.1. Data base

The data base that will be adopted is the quality controlled data base collated for the new IFDs. This comprises 8074 daily read rainfall stations and 2280 continuous rainfall stations. Although the daily read rainfall stations are primarily those from the Bureau's network, the continuous rainfall stations comprise both Bureau operated gauges and gauges operated by other organisations, including the urban water utilities. The location of the continuous rain gauges used in estimating the new IFDs are shown in Figure 1. While sub-annual IFDs will be determined for durations ranging from one minute to seven days, it is at the sub-daily durations that the more frequent IFDs are most commonly required due to the shorter time of concentration for urban catchments. Thus, the inclusion of the continuous stations operated by other organisations will be important.

4.2. Minimum number of years of record

For the new IFDs a minimum record length of 30 years was set for the daily read stations and more than eight years for the continuous stations. In data spare areas daily sites with 20 years or more were also included to increase the spatial coverage. This was in order to ensure that there was sufficient data to accurately estimate rainfall quantiles for the range of probabilities from 1 EY to 1% AEP.

As sub-annual IFDs estimates are required for the more frequent probabilities of 12, 6, 4, 3, and 2 EY, additional stations with shorter record lengths could also be included. The advantage of this would be that the inclusion of rainfall stations with shorter periods of records may improve the spatial coverage of the data. The disadvantage would be that the data from the additional stations would require quality controlling to the same degree as the existing data base, which would be a time consuming process (Green et al 2011; 2012).

4.3. Extreme value series

For the new IFDs the AMS was extracted for each station and a Generalised Extreme Value (GEV) distribution fitted using L-moments. The rationale for the adoption of the AMS was that it is unambiguous and easy to apply, and produces an estimate almost identical to the PDS for events rarer than the 10% AEP.

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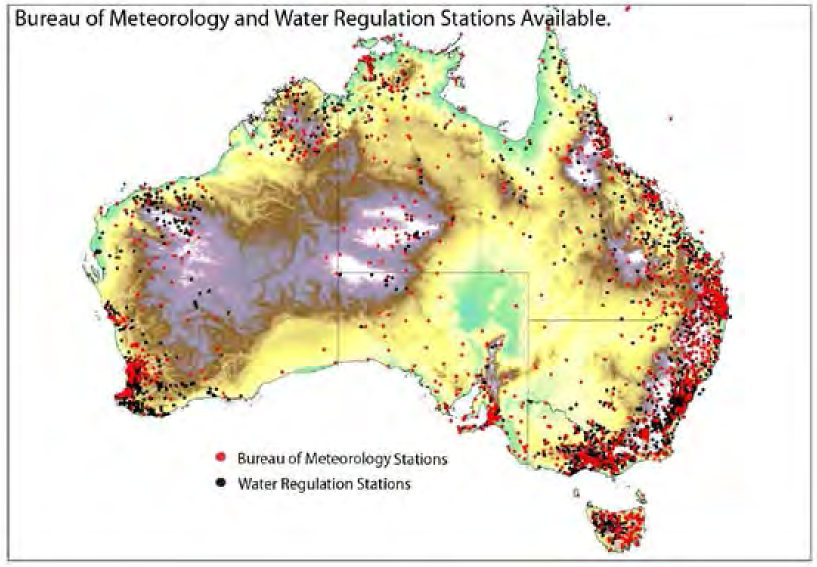

Figure 1 Location of continuous rain gauges adopted for new IFDs

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 sub-annual IFDs it will be necessary to adopt a PDS approach to estimate probabilities for events occurring more frequently than once a year. The advantages of the PDS are that it “mines” as much information as possible about large events and produces direct estimates for probabilities more frequent than the 10% AEP. The disadvantages of the PDS are that ensuring independence of events can be a major issues and it requires the definition of a threshold.

4.3.1. Independence

Prior to the IFD Revision Project, very little work had been undertaken into testing for independence between events in a PDS of rainfall. As part of the IFD Revision Project, a consistent and meteorologically rigorous approach to defining independence of rainfall events across Australia was developed. Details of the approach can be found in Xuereb and Green (2012); however in summary Minimum Inter-event Times (MIT) were found using the following approach:

- A window was identified based on typical meteorological conditions beyond which events could be assumed to be independent – for Melbourne this was 10 days
- Events falling within the window from a period for which there was satellite imagery available (~30 years) were selected from the PDS
- The meteorological influences were assessed and classified in terms of the causative meteorological conditions using satellite imagery and mean sea level pressure charts.
- The point when a different meteorological influence occurred was identified.
- The duration of each event was graphed and the MIT determined from the plot.

The analyses suggested that a MIT that varied from two to six days with latitude across Australia was appropriate. The variation in MIT for the one day rainfall duration is shown in Figure 2. Table 5 summarises the MIT adopted for durations from one day to seven days. From subdaily data, it was found that the MIT was greater than 24 hours, therefore for durations of less than one day, the MIT for the one day duration was adopted.

Table 5 – MIT for durations from 1 day to 7 days

Duration (days)	1	2	3	4	5	6	7
2 day zone	2	0	0	0	0	0	0
4 day zone	4	2	0	0	0	0	0
6 day zone	6	4	2	0	0	0	0

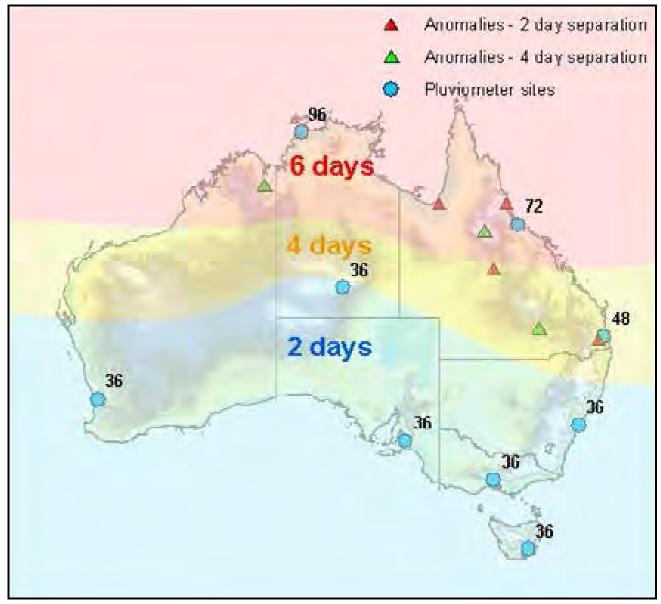

Figure 2 MIT for one-day rainfall across Australia

4.3.2. Definition of threshold

When adopting the PDS it is necessary to define the threshold above which all events will be included. Two approaches are commonly to define the threshold:

- Specifying a magnitude (rainfall depth in mm or intensity in mm/hr)
- Using the average number of events per year.

For the sub-annual IFDs it will be necessary to identify the number of values per month that are required to accurately estimate the more frequent IFDs. Given that the most frequent probability is 12 EY, at a minimum there should be, on average, one value per month or 12 times the length of record. This will vary with duration. For the duration of seven days the maximum number of values possible is four per month, although realistically three is more likely to be achievable. In contrast for the shorter durations, a much wider range of values will be possible. As part of the estimation of the new IFDs the appropriate number of values per month to be adopted for each of the standard probabilities will be investigated.

4.4. Distribution to be fitted

As part of the IFD Revision Project, 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. 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 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 for each distribution was assessed using the approach recommended by Hosking and Wallis (1997) and the distributions were found to produce the best fit on an at-site analysis were the GEV distribution for the AMS and the GPA distribution for the PDS.

The same results were reached using regional estimates. On the basis of the results from the above comparison, the GEV distribution was fitted to the AMS using L-moments to estimate the new IFDs for the probabilities of 1 EY to 1% AEP. For the sub-annual IFDs, it is proposed that the GPA distribution be fitted to the PDS for all stations which meet the required record length. However, as the adoption of the GPA for the PDS was based on an average of three exceedances per year, it will be necessary to determine whether this distribution is the most appropriate for an average of 12 or more exceedances.

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4.5. Regional frequency analysis

For the new IFDs, regional frequency analysis was undertaken using L-moments extracted from each of the at-site frequency distributions. While for durations of one day and longer this process was straightforward, 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 new IFDs, a Bayesian Generalised Least Squares Regression (BGLSR) approach was adopted. The BGLSR approach used various predictors, including latitude, longitude, elevation, slope, aspect and Mean Annual Rainfall to provide predictions of the mean, L-coefficient of variation and L-skewness. More details on the BGLSR approach can be found in Johnson et al. (2012a).

In order to be consistent with the new IFDs, the BGLSR approach will be applied to the sub-annual IFD estimates in order to optimise the spatial coverage of the sub-daily data. However, because the BGLSR for the new IFDs was based on the AMS, it will be necessary to modify the approach for use with the PDS. These modifications will build on the work of Madsen et al (2009) who applied the BGLSR to the PDS when deriving design rainfalls for Denmark. The resultant L-moments will then be regionalised using the Region of Influence approach adopted for the new IFDs (Johnson et al, 2012 b) to provide L-moments at all daily read rainfall stations. The regionalised L-moments will then be used to estimate the parameters of the selected distribution.

4.6. Gridding

In order to enable sub-annual IFDs to be derived at any point in Australia, the parameters of the selected distribution will be gridded using ANUSPLIN in the same manner as was undertaken for the new IFDs (The et al, 2012). This will enable sub-annual IFDs to be calculated for probabilities of 2, 3, 4, 6 and 12 EY and for the standard durations.

5. CONCLUSIONS

The provision of new IFDs for probabilities more frequent than 1 EY has been identified as the first priority for enhancements to the new IFDs to be undertaken during Phase 2 of the IFD Revision Project. These values will help to increase the consistency of design flow estimation for WSUD in urban development by supplying nationally consistent, scientifically based sub-annual IFDs to meet these design guidelines. The sub-annual IFDs will be estimated using an approach that is consistent with the method adopted for the less frequent IFDs but will require some modifications to make use of the increased number of rainfall stations that can be used and to take into account the use of the PDS instead of the AMS.

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