Improved Rare Design Rainfalls for Australia

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Rare design rainfalls for probabilities less frequent than 1% Annual Exceedance Probability (AEP) are an essential part of spillway adequacy assessment as they enable more accurate definition of the design rainfall and flood frequency curves between the 1% AEP and Probable Maximum events.

Estimates for rare design rainfalls were previously derived using the CRC-FORGE method which was developed in the 1990s. However, as the method was applied on a state-by-state basis, there are variations in the approach adopted for each region. Differences in the cut-off period for data, the amount of quality controlling of the data undertaken, the base used for the 2% AEP estimates, gridding settings and smoothing processes have created inconsistencies which are particularly apparent in overlapping state border areas.

The Bureau of Meteorology has derived new rare design rainfalls for the whole of Australia using the extensive, quality-controlled rainfall database established for the new Intensity-Frequency-Duration (IFD) design rainfalls. These data have been analysed using a regional LH-moments approach which is more consistent with the method used to derive the new IFDs and which overcomes the limitations of the spatial dependence model in the CRC-FORGE method. In particular, the selection and verification of homogenous regions and the identification of the most appropriate regional probability distribution to adopt relied heavily on the outcomes of the testing of methods undertaken for the new IFDs. However, to focus the analysis on the rarer rainfall events, only the largest events have been used to define the LH-moments.

Keywords: *Rare design rainfalls; Intensity-Frequency-Duration (IFD); Annual Exceedance Probability*

Introduction

Rare design rainfalls are those design rainfalls which have probabilities in the range from 1% Annual Exceedance Probability (AEP) to 0.05% or 1 in 2000 AEP as shown in Figure 1;

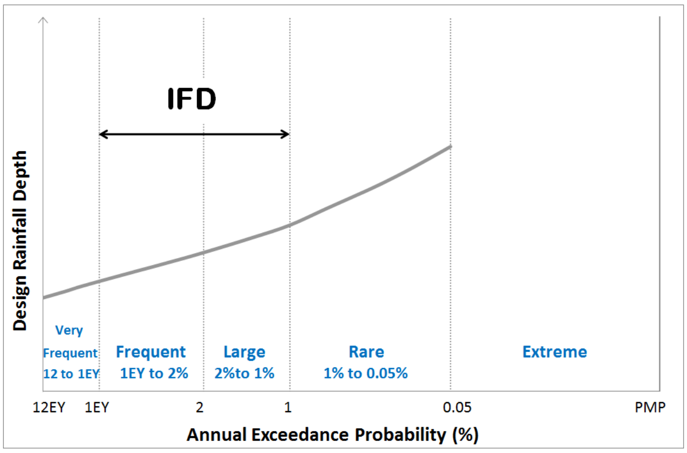

Figure 1 – Types of design rainfall

Rare design rainfalls are used in the undertaking of spillway adequacy assessments of existing dams as the Dam Crest Flood (DCF) of many of these dams lies between 1% AEP (as defined by Intensity-Frequency-Duration, IFD, design rainfalls) and the Probable Maximum Flood (as defined by the Probable Maximum Precipitation, PMP). Rare design rainfalls enable more accurate definition of the design rainfall and flood frequency curves between the 1% AEP and Probable Maximum events. Rare design rainfalls are also used in the design of dams that fall into the Significant and Low Flood Capacity Category (FCC) where the Acceptable Flood Capacity (AFC) is the 0.1% or 1 in 1000 AEP design flood.

Other uses of rare design rainfalls are in the design of bridges, where the ultimate limit state adopted in the Australian bridge design code is defined as 'the capability of a bridge to withstand, without collapse, the design flood associated with a 2000 year return interval'(AUSTROADS, 1992). More recently, the Interim Climate Change Guideline for

Australian Rainfall and Runoff (ARR) recommends that if the design probability for a structure is 1% AEP, then the possible impacts of climate change should be assessed using 0.5% and 0.2% AEP (Bates et al, 2015).

In light of the importance of the infrastructure that is designed using rare design rainfalls, it is essential that a reliable method for deriving design rainfall estimates in the rare range of probabilities is provided.

Background

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, 1 to 5 day rainfall estimates in the large 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) is based on the UK Institute of Hydrology FORGE concept (Reed and Stewart, 1989) 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 parts of the Northern Territory. The references for each of the state CRC-FORGE estimates are listed in Table 1.

Table 1 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

The CRC-FORGE estimates were provided for durations of 1, 2, 3, 4 and 5 days and for probabilities of 1 in 50; 100; 200; 500; 1000; and 2000 AEP.

Although all the CRC-FORGE design rainfalls estimates were derived using essentially the same method, there were variations in the way in 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.

For all states except Western Australia and Queensland, the CRC-FORGE growth curves were anchored to the 2% AEP ARR87 IFD estimates. With the revision of the IFDs, the CRC-FORGE estimates for these states would need to be revised to incorporate the new IFDs. For the states of Western Australia and Queensland, where the CRC-FORGE estimates of the 2% AEP were considered more accurate than the ARR87 IFD estimates, the revision of the IFDs means that better estimates of the 2% AEP IFDs are now available.

A final, pragmatic issue with the CRC-FORGE estimates is that there is no central point of dissemination for each of the state CRC-FORGE estimates, instead, it is necessary to contact the individual or organisation responsible for preparing each of the state estimates. As the organisations may have changed or the individuals moved to other positions, this can make obtaining the CRC-FORGE estimates difficult.

Options for new rare design rainfalls

In view of the issues with the existing CRC-FORGE estimates discussed above, the Bureau of Meteorology considered it important that new rare design rainfalls be provided as part of the continuum of new design rainfalls produced as part of the IFD Revision Project (Green et al, 2015).

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

- Using the existing gridded CRC-FORGE data but 'anchoring' the estimates to new IFDs 2% or 1% AEP design rainfalls

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

Option 1

This option would have been the easiest to apply as the data are already available. However, the disadvantages of this approach include:

- Many of the issues listed in the section above including differences in the length of record used and inconsistencies in the application of the method would still be inherent in the re-anchored CRC-FORGE estimates
- The state grids may not align with each other or the new IFDs and there will be two sets of depths close to state borders
- The longer periods of record and contemporary statistical techniques that are now available would not be utilised.
- National estimates of rare design rainfalls would still not be available as part of the Northern Territory would still not be included.

Option 2

The application of the CRC-FORGE method to the new IFD rainfall database but with enhancement to the method to take into account developments in gridding techniques would have the advantage have the advantage of providing rare design rainfalls that were derived using an approach that had previously been applied. However, the disadvantages of this approach include:

- Not addressing the limitations of the method that have been identified during the application to each of the states.
- Adopting an approach that was developed nearly 20 years ago and which does not incorporate advances in the method and philosophy of the statistical analysis of rainfall data.
- Not being consistent with the approach adopted for the new IFDs, in particular, the 2% and 1% AEP new IFDs.

Option 3

The application of a new / updated approach applied to the new IFD database has the disadvantage of not being able to leverage off the work undertaken previously on rare design rainfalls in Australia, including the CRC-FORGE method. However, it has the following advantages:

- Consistency with not only the data but also the method adopted for the new IFDs.
- Ability to leverage off work undertaken for the new IFDs
- Incorporation of new statistical and gridding techniques that have been developed in recent years.
- Building on work undertaken recently overseas into the estimation of rare design rainfalls.

For these reasons, Option 3 was selected as the approach to be adopted for the estimation of new rare design rainfalls for Australia.

Adopted approach – regional LH-moments

The adopted approach is a regional L-moments approach developed by Hosking and Wallis (1990, 1997); adapted by Schaefer (1990); and further adapted and applied in the United States by Wallis et al (2007). However, in order to take into consideration the rarer observed rainfall events, LH-moments (Wang 1997) have been adopted instead of L-moments. The approach is a parametric method – that is, a method that assumes that a certain probability distribution describes the data and that a statistical method can be used to estimate the distribution parameters.

The steps involved in the application of the regional L-moments approach include:

- Establishment of a rainfall data base consisting of long-term, high quality rainfall records and extraction of Annual Maximum Series
- Assessment of stationarity of rainfall record
- Identification of climatic / geographic regions
- Calculation of LH-moment statistics for all rainfall gauges within each regions
- Identification of hydro-climatic predictors of regional LH-moments
- Identification of a suitable probability distribution for each regional growth curve
- Gridding of mean annual maxima and regional statistical parameters
- Preparation of grids of rainfall quantiles

Establishment of a rainfall data base

The quality controlled rainfall data base established for the derivation of the new IFDs was used as the basis for the data base used for the rare design rainfalls. This data base consisted of data from over 8000 daily read rainfall stations with more than 30 years of record. All the data had been quality controlled using both automated and manual procedures (Green et al, 2012a). The quality controlling procedures included

- Infilling of missing data
- Disaggregation of accumulate daily rainfall totals
- Detection of suspect data and identification of unflagged accumulated totals and of time shifts in data
- Correction of time shift errors and disaggregation of unflagged accumulated totals
- Identification of gross errors
- Manual checking and correcting of gross errors.

As the estimation of rare design rainfalls relies on long term records, only those stations with more than 60 years of record were selected. A second subset of those stations with more than 100 years of record was also selected. The location of the stations in these two subsets is shown in Figure 2.

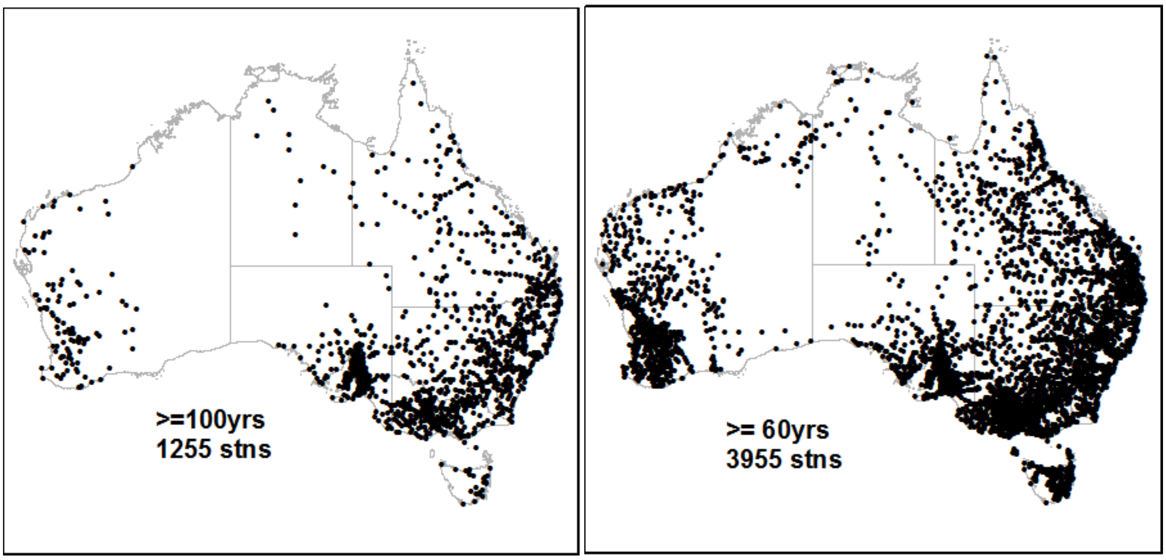

Figure 2 – Coverage of daily rainfall gauges with more than (a) 100 years and (b) 60 years of record

In light of the much greater spatial coverage, the daily rainfall gauges with more than 60 years of record were adopted for the analyses.

The restricted 9am to 9am totals from the daily read rainfall stations were converted to unrestricted totals using the factors 1.15, 1.11, 1.07, 1.05, 1.04, 1.03, 1.02 for 1, 2, 3, 4, 5, 6 and 7 day durations respectively and the Annual Maximum Series (AMS) extracted for durations of 1, 2, 3, 4, 5, 6 and 7 day durations.

Assessment of stationarity

A requirement of a regional frequency analysis is that the data must be homogeneous with respect to space and time. Longer and shorter term climate variability and climate change can mean that data samples, particularly short records, may not be representative of the longer term conditions.

Stationarity testing was carried out on the AMS as part of the IFD revision project (Green and Johnson, 2011). This involved assessing the AMS and fitted distributions for individual sites as well as regional averages for rainfall trends over time for 6 minute to 72 hour duration events. The point based tests included the Wilcoxon (or Mann-Whitney) rank-sum test and the two-sample Kolmogorov-Smirnov test which involve splitting the record into two equal periods and comparing for statistical differences. A t-test and non-parametric Spearman’s rank correlation test were also used on the entire record to detect significant linear trends. These found that while a number of sites failed one or more of the test, there was no clear spatial pattern associated with these sites. The regional average methodology is described by Green and Johnson (2011). The assessment revealed that trends in rainfall district areas were affected by the period of analysis and it was suggested that multi-decadal variability could be a reason for this. The recommendation from the results of this study was to use the entire length of record for generating the new IFD estimates.

Since the data set used for the rare design rainfall analysis is a subset of the data assessed by Green and Johnson (2011), the assumption of stationarity based on that work was adopted.

Identification of climatic / geographic regions

The identification of homogenous climatic / geographic regions leverage the extensive work undertaken for the Bayesian Generalised Least Squares Regression (BGLSR) analyses undertaken for the new IFDs (Johnson et al, 2012a). As part of this work rainfall stations were grouped into areas where the causative mechanisms for large rainfall events are similar. The rainfall stations were grouped primarily according to climatic zones by considering the seasonality of rainfall events and mean annual rainfalls. Australian drainage divisions were also used to guide the division of larger climatic zones into smaller areas, such as in the northern tropics where three analysis areas have been adopted. The final BGLSR regions are shown in Figure 3; these regions were adopted for the current analyses.

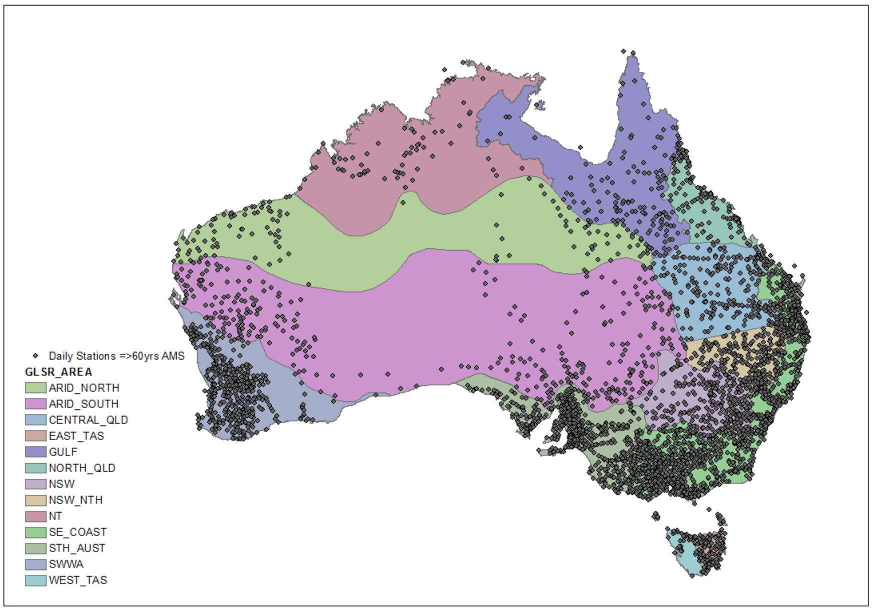

Figure 3 – Climatic / geographic regions adopted

Calculation of LH-moment statistics

LH-moment statistics were calculated from the AMS of the rainfall gauges with more than 60 years of record using software developed for the estimating of the new IFDs. Figure 4 shows the 24 hour L-CV and L-skew for these sites.

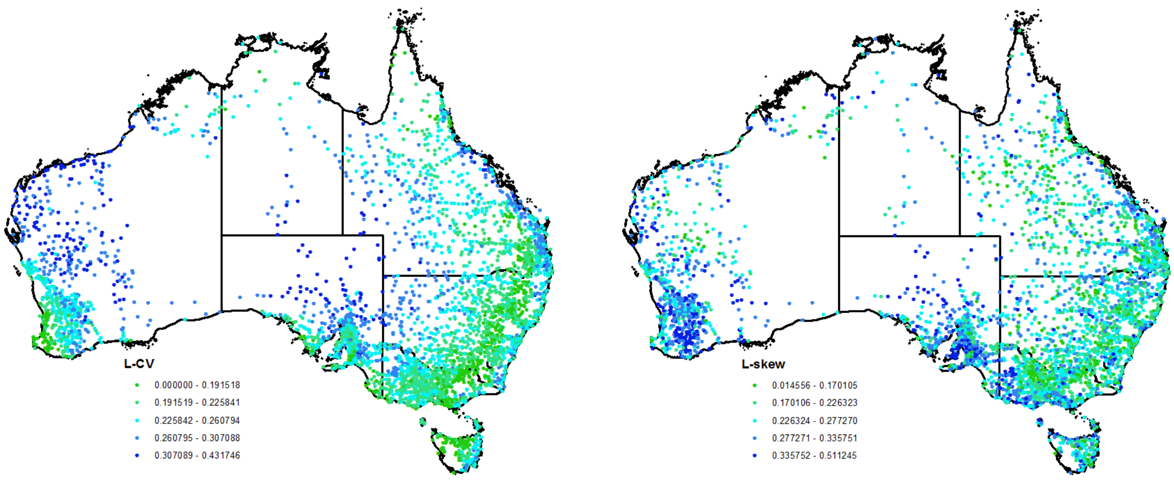

Figure 4 – 24-hour L-moment statistics (a) L-CV and (b) L-skew

Identification of hydro-climatic predictors

As part of the BGLSR application for the new IFDs, extensive work was undertaken identifying and assessing appropriate hydro-climatic predictors of regional L-moments. The selected predictors were also adopted for the rare design rainfall analyses and include:

- Latitude and longitude
- Elevation
- Slope
- Aspect
- Distance from the coast
- Mean annual rainfall (MAR)

Numerous trials were undertaken using of each of these predictors and both L-moments and LH-moments (Wang, 1998). The results of three of these trials for the 24 hour duration are shown in Figure 4

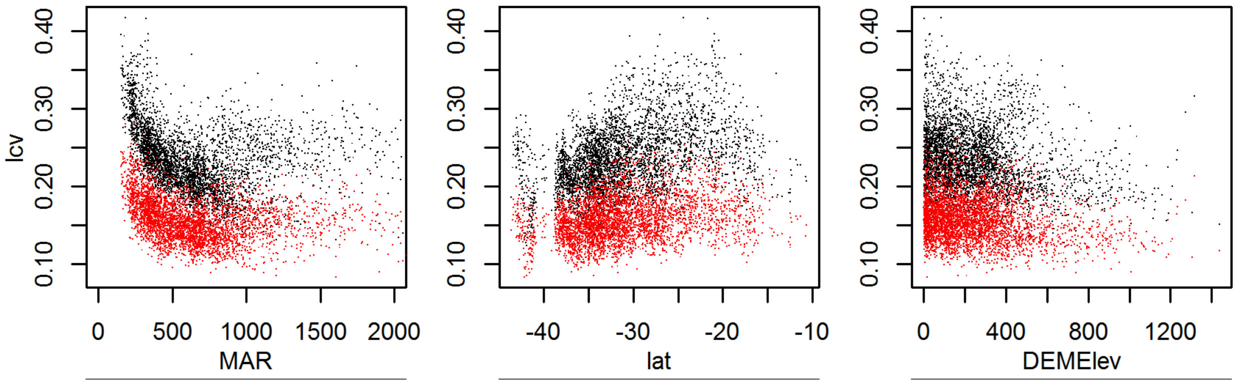

Figure 4 – L-moments (black points) and LH-moments (red points) plotted against (a) 24-hour MAR (b) Latitude (c) Elevation

Identification of suitable distribution

Considerable trialling was undertaking as part of deriving the new IFDs to test the most appropriate distribution to adopt with Australian rainfall (Green et al 2012b). Five distributions – GEV, Generalised Logistic (GLO), Generalised Normal (GNO), Pearson Type III (PE3) and Generalised Pareto (GPA) – were fitted to the AMS extracted from the available long-term rainfall stations across Australia. 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 GEV distribution was found to produce the best fit on an at-site analysis. The comparison of distributions was subsequently repeated for regional estimates with the same results.

On the basis of these trials and similar results found by Nandakumar (1997) and Schaefer (1990), the GEV distribution was adopted for the rare design rainfall analyses.

Gridding of mean annual maxima and regional statistical parameters

The mean annual maxima (which was adopted as the index variable) and the GEV parameters that were derived using the hydro-climatic predictors were gridded using ANUSPLIN (Hutchinson 2013). 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 (The et al, 2014).

Preparation of grids of rainfall quantiles

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 using Equation 1.

$$Q_y = \xi + \frac{\alpha\left(1-\left(-\log(1-\frac{1}{y})\right)^k\right)}{k} \qquad \textbf{\textit{Equation 1}}$$

Dissemination

The rare design rainfall depths have been incorporated into the Bureau of Meteorology's IFD website (http://www.bom.gov.au/water/designRainfalls/ifd/) as can be seen in Figure 5.

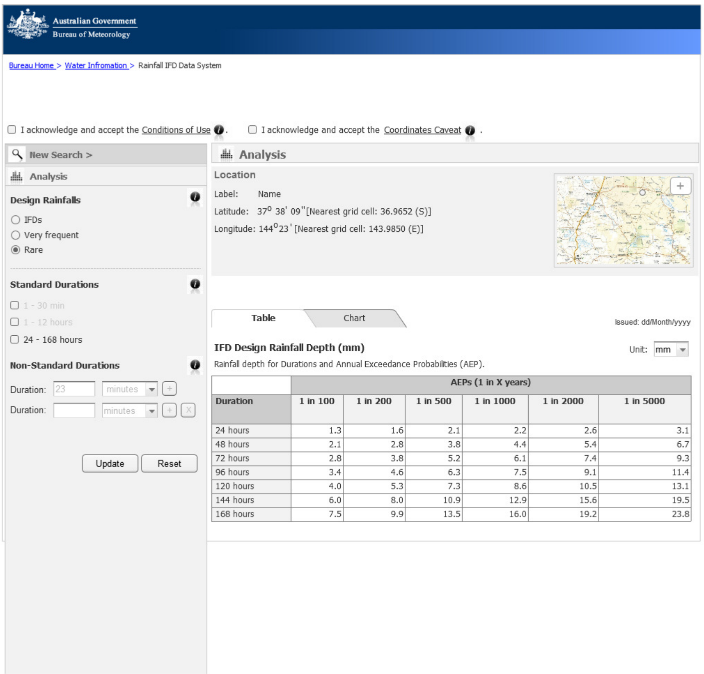

Figure 5 – Rare design rainfall webpage

By entering a location of interest, users can now obtain design rainfall estimates from 12 Exceedances per Year (EY) to 0.05% AEP for 24 hr to 168 hr durations in a single query.

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 large; 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. In particular, the new rare design rainfalls provide improved estimates for any point in Australia which can be accessed from Bureau's website.

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