Very Frequent Design Rainfalls – An Enhancement to the New IFDs

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Abstract

The Bureau of Meteorology (BoM) has released new Intensity-Frequency-Duration (IFD) design rainfalls for Australia for probabilities from 1 Exceedance per Year (EY) to 1% Annual Exceedance Probability (AEP). This is suitable for most hydraulic infrastructure design; however Water Sensitive Urban Design (WSUD) requires IFD's for events more frequent than 1 EY. Many stormwater quality or WSUD guidelines recommend a flow threshold of Q3month for the design of stormwater quality treatment devices. Design rainfalls for the 3 month average recurrence interval (4 EY) have not been previously available, with agencies giving their own advice on the approach for estimating very frequent design rainfalls. To address this need, estimates for probabilities more frequent than 1 EY will be provided as part of Phase 2 of the IFD Revision Project.

A ratio approach has been adopted, using the at-site Partial Duration Series (PDS) to determine the ratio of the various very frequent design rainfall values with the 50% AEP IFDs. L-moments were used to characterise the distributional properties of the PDS data with the Generalised Pareto Distribution (GPA) found to best represent the at-site PDS. Quantile depths calculated at each site are used to derive the ratios relative to the 50% AEP value. They are then gridded in the smoothing spline software ANUSPLIN. The splines are fitted using three independent variables; latitude, longitude and elevation, with the appropriate degree of smoothing for the fitted functions determined through generalised cross validation. Depths have been calculated from the gridded ratios and the 50% AEP IFD depths for durations from one minute to seven days and probabilities of 2, 3, 4, 6 and 12 EY. The very frequent design rainfall estimates will improve consistency of design flow estimation for WSUD and urban development by providing nationally consistent values for use with the design guidelines.

1. INTRODUCTION

The Bureau of Meteorology (BoM) released new Intensity-Frequency-Duration (IFD) design rainfalls in July 2013 (Bureau of Meteorology 2015). As part of this Phase 1 release IFD values have been calculated for durations of one minute to seven days and probabilities of 1 Exceedance per Year (EY) to 1% AEP. This range of IFD probabilities meets the design requirements/guidelines for the design of most infrastructure assets. In Australia hydraulic design guidelines generally specify probabilities of between 1 Exceedance/s per Year (EY) to 10% Annual Exceedance Probability (AEP) for the sizing of infrastructure for minor flood events and probabilities of 2% to 1% AEP for the design of infrastructure for major flood events. However Water Sensitive Urban Design (WSUD) and some storm-water management applications (e.g. bio-retention systems, small detention basins and infiltration systems) require probabilities more frequent than 1 EY, which have not been provided to date.

Many stormwater quality or WSUD guidelines recommend a flow threshold of Q_{3month} for the design of stormwater quality treatment devices. Design rainfalls for this 3 month Average Recurrence Interval (ARI) (4 EY) have not previously been available and many guidelines do not specify how the 4 EY IFDs or subsequent Q_{3month} flow 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 for estimating very frequent design rainfalls. An investigation of the available guidelines show that there is currently no standard way of determining any design value more frequent than 1 EY in Australia, even though these have been accepted as design flows for stormwater quality treatment devices (Table 1).

Table 1. 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 ARR87
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)

To address the need for nationally consistent very frequent design rainfall estimates, estimates for probabilities of 2, 3, 4, 6, and 12 EY have been derived as part of Phase 2 of the IFD Revision Project which will provide enhancements to the new IFDs. Producing these values will improve the consistency of design flow estimation for WSUD. This paper describes the method adopted to produce the very frequent design rainfall depth estimates.

2. METHOD

A summary of the adopted method is presented in Table 2 followed by a discussion in later sections

Table 2. Summary of adopted approach for the very frequent design rainfalls

Variable	Output
Data	Daily and Sub-daily from BoM and other data collecting agencies
No. Sites & record length	15364 daily read & 2722 continuous stations > 5 years; up to 31/12/2012
Durations	1 minute to 168 hour (7 day)

Frequencies	12, 6, 4, 3, 2 EY
Frequency analysis	Partial Duration Series; L-moments; GPA
Ratios	Ratio XEY to 50% AEP
Gridding	ANUSPLIN – thin plate smoothing spline
Delivery method	Incorporated into new IFD webpage on Bureau's website

2.1. Data and minimum effective years

The data adopted comprise both BoM stations and gauges operated by other organisations. It includes the stations used for the new IFD's (Bureau of Meteorology 2015; Green *et al* 2011) and an additional 7290 stations with shorter periods of record, which have undergone rigorous quality controlling (Green *et al* 2011; 2012a). These additional stations were required as the minimum number of years has been reduced from 30 (new IFDs) to five years for the very frequent design rainfalls. A threshold of five effective years was selected for daily and sub-daily sites as this was deemed to be statistically acceptable given the sub-annual frequency of estimated exceedances compared to the 1 EY previously. The shorter record length ensures greater use of available sites but also ensures that there is sufficient information available to derive the more frequent probabilities (12-2 EY).

A partial duration series (PDS) approach has been adopted to estimate probabilities for events occurring more frequently than once a year. The advantage of using the PDS is that it extracts as much information as possible about large events and produces direct estimates for probabilities more frequent than the 10% AEP. As a PDS is being used for the at-site series the selection of independent events is based on rank rather than temporal periods, thus completeness of record is not a consideration.

2.2. Minimum inter-event time and definition of a threshold

The event independence testing criteria used were based on the minimum inter-event time (MIT), as was applied in the new IFD method (Xuereb and Green, 2012). The analyses suggested that a MIT that varied from two to six days with latitude across Australia was appropriate. For durations of less than one day the MIT for the 1 day duration was adopted (Green *et al* 2014).
As a PDS is being adopted it was necessary to define the threshold above which all events will be included. It was important to identify the number of values per year that are required to accurately estimate the more frequent IFD's. Given that the most frequent probability is 12 EY, a minimum of 12 events per year was used to adequately represent the at-site distribution for these higher frequency events.

2.3. Rainfall event series

The very frequent design rainfalls were derived from a PDS, with the optimum number of events per year (nE) determined by calculating the effective number of years of record (EfY) for the site (i.e. count of days with valid data / 365) and extracting nE x EfY independent events from the rainfall record, based on descending rank, for each standard duration once quality control (QC) criteria were met. The PDS values for several geographically distributed locations were extracted for testing purposes. L-moments (linear combinations of the data of mean, variation (L-CV) and skewness (L-skewness)) and quantile depths (rainfall depths at each probability) were then calculated using the same method that was applied during the AMS and PDS comparison phase of the IFD revision project for events with AEPs less than 1 EY. For the PDS with greater than 1 EY probabilities, the Generalised Pareto Distribution (GPA) as defined in Hosking and Wallis (1997) (shown in equation 1) was found to best represent the at-site PDS distribution:

$$x(F) = \xi + \alpha\{1 - (1 - F)^k\}/k \quad \textbf{(1)}$$

where $x(F)$ is the quantile function and ξ, α and k are the location, scale and shape parameters. Here F is the cumulative frequency and is given as the annual non-exceedance probability (ANEP) divided by nE. Initially when calculating F using a nE of 12, the probability definitions in Table 3 were used. The results for the test locations indicated that this definition was not suitable for derivation of sub-annual return periods. For events more frequent than 1 EY, *F* becomes very small and the depths ‘flatten out’, tending towards the 1EY at-site value (Table 3, Figure 1). This may be due to an error in the way that *F* has been derived, based on the ANEP values.

Table 3. Annual exceedance probabilities for site 33119 (nE=12)

	12 EY	6 EY	4 EY	3 EY	2 EY	1 EY	50%	20%	10%	5%
AEP	0.9990	0.9975	0.982	0.950	0.865	0.632	0.500	0.200	0.100	0.050
ANEP	0.0001	0.0025	0.018	0.050	0.135	0.368	0.500	0.800	0.900	0.950
F (ANEP/nE)	0.0000	0.0002	0.002	0.004	0.011	0.031	0.042	0.067	0.075	0.079
Depths	139.8	139.9	140.9	143.0	148.9	169.7	186.1	258.1	321.9	395.2

To resolve this, an alternative approach was adopted. This approach effectively treats the PDS as a Monthly Partial Duration Series or - more correctly for the current dataset - a Monthly Exceedance Series (MES) (PDS where number of values = number of effective months: 12 nE). While the extracted PDS is the same, the averaging duration is changed, representing the time in months rather than years. It is important to note that this is not equivalent to a Monthly Maximum Series where the maximum value for each month would be selected. The MES is extracted using the PDS methodology, based on a ranking method, rather than the AMS temporal approach. Consequently the scale of the sub-annual GPA would be relative to months rather than years and frequencies are expressed as monthly non-exceedance probabilities (MNEP) instead of ANEP. The number of values then becomes 1 event per effective month (nEm = 1) instead of 12 nE. Table 4 shows the results for the monthly exceedance series. The selection of a MES rather than an annual series allowed significantly more records to be included from each site to establish the at-site rainfall distribution, capturing the more frequent rainfall patterns.

Table 4. Monthly exceedance probabilities for site 33119 (nEm=1)

	12 EY	6 EY	4 EY	3 EY	2 EY	1 EY	50%	20%	10%	5%
MEP	0.632	0.500	0.333	0.250	0.167	0.083	0.042	0.017	0.008	0.004
MNEP	0.368	0.500	0.667	0.750	0.833	0.917	0.958	0.983	0.992	0.996
F (MNEP/nEm)	0.368	0.500	0.667	0.750	0.833	0.917	0.958	0.983	0.992	0.996
Depths	35.7	45.7	64.2	78.2	99.2	140	185.5	256.4	325.9	484.7

Figure 1 shows the calculated depths for the one day duration across the range of probabilities for both the annual and monthly series, compared to the at-site PDS for Bureau Site Number 033119. The at-site values were plotted using the Gringorten plotting position. It can be seen that the depths for > 1 EY frequencies are similar for the two approaches; however the more frequent event depths are quite different, with the MES approach producing results that more closely follow the at-site data. This approach requires that the average number of events extracted for each site per effective year is 12. The MES is considered analogous to generating the IFD depths from 1 EY to 1% AEP using an annual series and is therefore appropriate for the very frequent design rainfall estimates.

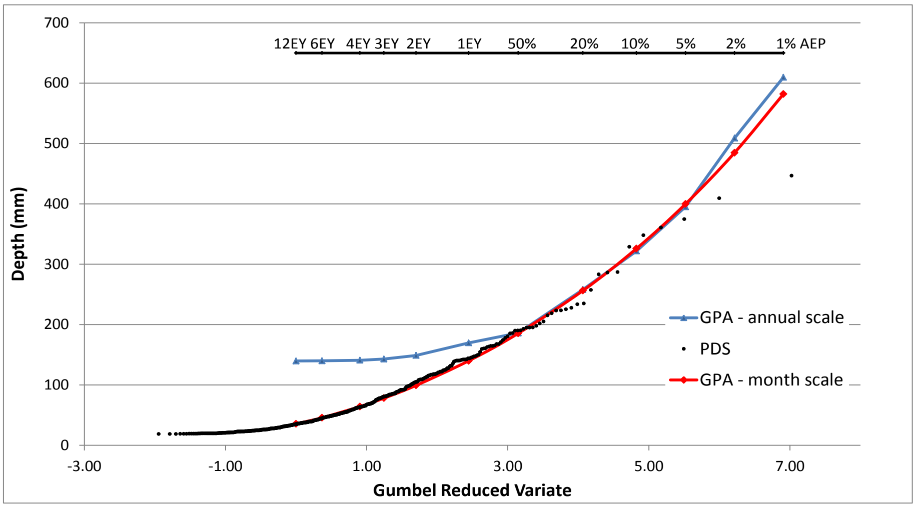

Figure 1 An example of the 1 day quantile estimates for site 033119 using a GPA distribution treating the data as a PDS (annual scale) and a MES (monthly scale).

2.4. Distribution to be fitted

As part of Phase 1 of the IFD Revision Project, the goodness of fit for five different distributions (GEV, Generalised Logistic (GLO), Generalised Normal (GNO), Pearson Type III (PE3) and Generalised Pareto (GPA)), was assessed using the approach recommended by Hosking and Wallis (1997). The best fit on an at-site analysis was achieved using the GEV distribution for the AMS and the GPA distribution for the PDS. By adopting a monthly exceedance data series there is some added uncertainty; to address this, a comparison was conducted of the GEV and GPA distributions. Twenty-four geographically distributed test sites with medium to long record lengths were selected for assessing the relative fit of the distributions to the at-site data. The test sites indicate that the GPA provides a closer fit to the site data in the majority of cases. In the very frequent range, the errors are much lower due to the magnitude of data in that area of the curve. Both distributions are reasonable for the higher frequency estimates, but the GPA is consistently closer to the site data. On the basis of this, the very frequent design rainfalls use the GPA distribution fitted to the PDS for all stations which meet the required record length.

2.5. Estimation of L-moments and quantiles

Regional frequency analysis was undertaken using L-moments extracted from each of the at-site frequency distributions for sub-daily and daily data. The L-moments were used to estimate the parameters of the selected GPA distribution.

Extracting 12 independent events per year of record for the MES introduced the issue of zero values included in the PDS at some sites. This particularly occurred through the arid areas of central Australia to the west coast, where annual rainfall is highly variable and strong seasonality can occur. These areas have short wet seasons and can fail to have 12 rain events on average that are independent of one another for every year. However, given the previously defined minimum number of events being 12, these zero values events are considered as part of the distribution. To manage the occurrence of the zero values in the extreme value series, Hosking and Wallis (1997) suggest using a 'mixed distribution' or more correctly a conditional probability adjustment that gives a probability of a zero value, and cumulative distribution for the non-zero values as seen in equation 2 (Guttman *et al*, 1993).

$$F(x) = p + (1 - p)G(x) \quad (2)$$

Where p is the probability of a zero rainfall value which is estimated by dividing the numbers of zeros by the total number of events and $G(x)$ is the cumulative distribution function of the non-zero rainfall events. Using this approach, if the non-exceedance probability (NEP) of interest is less than p, then the quantile estimate is zero and if the NEP is greater than p, the quantile is estimated from $G(x)$ using the adjusted NEP shown in equation 3. This method was used by Guttman *et al*. (1993), with the proportion of zero values as the total for the whole region and $G(x)$ estimated from regional average L-moments of the non-zero site data.

$$NEP_{adj} = (NEP - p)/(1 - p) \quad (3)$$

For series with small proportions of zeros, the impact on the distribution and resulting quantiles was negligible. For records with less than 10% zeros, there is very little difference and up to nearly 20% zeros there is less than 10% average difference in the quantile depths. However the differences become much more significant when the proportion of zeros increases.

2.6. Ratio method

The quantiles derived from parameters of the GPA distribution need to be integrated with the New IFD's >1EY. A ratio based approach has been adopted to derive the very frequent design rainfall estimates. A general ratio approach is currently applied by various councils and authorities in Australia and internationally (Huff and Angel, 1992). It involves using the at-site data to determine the ratio of the various sub-annual IFD values to either the 1 EY or 50% AEP IFD value for that location. In Australia the ratios are usually defined in terms of the 1 year ARI (63% AEP) and are yet to be updated to the new IFD terminology. Internationally the 50% AEP depths are often used with the view that they are more reliable estimates. In ARR87 (Pilgrim, 1987) the 2 year ARI (39% AEP) is a key benchmark for the basic charts and is the probability for which there was the most data upon which to base the estimates. For the new IFDs, the 50% AEP is considered the most reliable probability, and so has been used as the benchmark for the ratios.

The ratio method adopted involves estimating at-site quantiles, using the site 50% AEP as the reference values for the ratios, and gridding the calculated ratios. The advantage of this approach and using the at-site 50% AEP, is that it allows for the spatial variability in the ratios. In addition, the ratio is generally a more accurate representation of the *X* EY to 50% AEP ratio since it is calculated from the same dataset and results in a smooth spatial pattern. Consistency is also inherent since the ratios will always decrease with increasing probability. Since the ratios are spatially consistent, the final very frequent design rainfall depths follow the new IFD 50% AEP depths closely. These depth estimates are calculated using the gridded ratios, and multiplying by the new IFD 50% AEP.

2.7. Gridding ratios

The ratios for all durations and EYs are gridded in the splining software ANUSPLIN (Hutchinson 2013). Thin plate splines have been chosen as the analysis method for the IFD Revision Project (Phases 1 and 2) due to their ability to model the spatially coherent signal in the data and noise inherent in point data (Hutchinson and Gessler 1994). The optimisation of the thin plate spline fits and the evaluation of the different modelling strategies have been achieved by monitoring several summary statistics described in detail in The *et al* (2012; 2014) and referred to in Table 5. The spline surfaces for all durations were fitted independently and the ANUSPLIN log file reports separate results for each surface. Summary statistics for each duration and EY were calculated across Australia.

Table 5. Summary statistics for the daily dataset, 1-7 day duration, 4 EY case. Lowest errors for the generalized cross validation (GCV), fitted values and cross validation statistics are highlighted in blue for the mean absolute error (MAE) and root mean square error (RMSE).

Knots and Spline Case	All Stations	Fitted Variable		Cross Validation Variable	
	GCV	MAE	RMSE	MAE	RMSE
4000 - Bivariate	0.0277	0.0179	0.0249	0.0200	0.0277
4000 - Elevation	0.0275	0.0178	0.0247	0.0199	0.0275
4000 - Covariate	0.0276	0.0179	0.0249	0.0199	0.0276
4000 - Elevation & Covariate	0.0275	0.0178	0.0247	0.0198	0.0275
3000 - Bivariate	0.0278	0.0183	0.0253	0.0201	0.0278
3000 - Elevation	0.0277	0.0181	0.0251	0.0200	0.0277
3000 - Covariate	0.0278	0.0182	0.0253	0.0201	0.0278

To determine the most appropriate method to grid the ratios, four different analyses were tested. This included a bivariate case using longitude and latitude; an elevation case using longitude, latitude and elevation; a covariate case using longitude, latitude and the 50% AEP values as a covariate; and an elevation and covariate case using longitude, latitude, elevation and the 50% AEP values as a covariate. Different knot sets were also trialled, which are used to limit the complexity of the fitted surface. The 0.025 degree Digital Elevation Model (DEM) of Australia was used to provide the elevation data for the rainfall stations which was also used in calculation of the new IFD grids (The *et al* 2014).

The summary statistics for all EYs showed similar results to the 4 EY case presented in Table 5, namely the difference in error statistics between all cases was not significant. The cases that produced the lowest error statistics are cases that use elevation and elevation with a covariate. Closer inspection of the daily and sub-daily dataset showed that in a majority of the cases the results are the same and using a covariate gave no significant improvement that could justify including it in the analysis. The final case adopted was a spline that incorporated latitude, longitude and elevation using 4000 knots for the daily dataset and 1000 knots for the sub-daily dataset. The sub-daily data was optimised in the same manner as the daily data, by monitoring the summary statistics for the respective dataset. Figure 3 (left) shows the gridded ratios for the 1 day 4 EY case.

2.8. Depth estimates

Very frequent design rainfall depth estimates for each duration and EY were calculated by multiplying the ratio grids with the corresponding new IFD 50% AEP grids (
Figure 2). As the new IFD grids were based on AMS estimates, an AMS/PDS conversion factor was applied to account for the lower estimates than those obtained if the PDS had been used (Green *et al*, 2012b).

The grids are then smoothed across duration to reduce any inconsistencies across durations and to smooth over discontinuities in the gridded data. A 6th order polynomial was applied to each grid point for all the standard durations from 1 minute up to 10080 minutes (7 days). Grids were also checked for inconsistencies across EY.

Figure 2 Process to create very frequent design rainfall depth grids from ratios

Figure 3 shows the ratio grid and corresponding final very frequent design rainfall depth grid for the 1 day 4 EY case, based on the model parameters recommended from this investigation. There is a consistent pattern in the rainfall depths across the continent, which demonstrates the reliability of using the gridded ratios (Figure 3). The patterns in the final rainfall depths reflect those similar to the Mean Annual Rainfall (MAR) map and the new IFD mean index rainfall maps (The *et al* 2014). The wettest area in Australia on average is along the tropical north Queensland coast. In this region the moisture-laden southeast trade winds meet the Great Dividing Range. Rainfall is also relatively high along the New South Wales coast, the adjacent ranges and Western Tasmania as a result of close proximity to moisture source and reliable rain producing weather systems. High rainfall in the Top End of the Northern Territory is associated with the monsoon. These rainfall mechanisms, support the larger depths observed along the coast which decrease towards central Australia and to the west which is generally very dry.

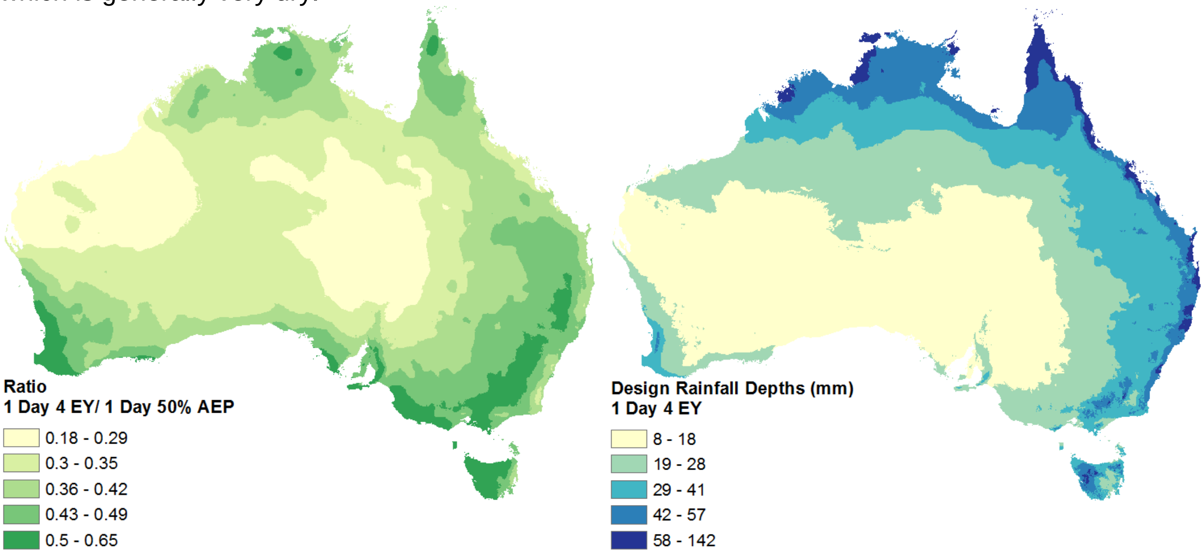

Figure 3 ANUSPLIN gridded data. Left: 1 day 4 EY ratio grid. Right: 1 day 4 EY very frequent design rainfall depth grid

3. CONCLUSION

The Bureau of Meteorology has created new very frequent design rainfalls which are available on the BoM webpage. The provision of estimates for probabilities more frequent than 1 EY will help increase the consistency of design flow estimation for WSUD in urban development by providing nationally consistent, scientifically based very frequent design rainfalls to meet these design guidelines. They are provided for durations from 1 minute to 7 days, and are consistent with the new IFDs currently available for 1 EY and AEPs from 50% to 1%. They are provided for probabilities from 12 EY to 2 EY which will complement the new IFDs currently available on the website and enable a smooth curve to be derived from 12 EY to 1%. This analysis has adopted an innovative and robust method which incorporates statistically rigorous techniques including the Generalised Pareto distribution and regional average L-moments for rainfall frequency analysis, a ratio approach based on the 50% AEP quantile values and thin plate smoothing spline methods for gridding. This technique has resulted in a sensible gradient across the Australian continent consistent with the new IFDs and reflects the known rainfall pattern of distribution and variability across the continent.

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