# Testing of Monte Carlo and Design Event Models for Flood Estimation

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*Abstract*

*This study, as part of the Australian Rainfall and Runoff revision, investigated and compared the performance of the Monte Carlo (MC) and Design Event (DE) methods to estimate design flood events on ten test catchments located in Australia. The catchments were selected to cover a range of climatic conditions, catchment sizes and characteristics. The methods were tested on their ability to reproduce the design flood quantiles over a range of AEPs from 50% to 1%. The effects of record length on their performance, ability to be applied to ungauged catchments and performance in internal gauges were also investigated.*
*In general, both methods performed well over the range of catchments tested. Tests on the effect of record length showed that the performances can vary significantly based on the period of record used, thus highlighting the need to investigate how representative the available flow data is in the context of any available long-term rainfall records. The tests on the applicability of MC and DE methods in ungauged catchments, generally produced poor model performances, thus suggesting that careful consideration should be given in transposing parameters to an ungauged catchments even when there is data available at a neighbouring gauged catchment. The performance of the models in internal gauges was tested in three internal gauge sites within Mary River catchment. In two of the three sites tested both methods performed reasonably well, despite these sites being relatively high in the catchment.*
*From this testing it was concluded that whilst both the MC and DE approaches generally performed similarly, the advantage of the MC method was in the information on uncertainty provided by the spread of results from individual model runs.*

*Keywords: Monte Carlo model, Design Event model, design flood estimation, Australian Rainfall and Runoff.*

## 1. INTRODUCTION

Estimation of flood flow in the absence of at-site recorded data generally requires either a regional method or a rainfall based approach. Rainfall based approaches are based on using a catchment modelling system to predict the response of a catchment to a storm burst (or event) or to a sequence of storm events.

At the time of the publication of the current edition of Australian Rainfall and Runoff (1987), the recommended approach implicitly assumed that the frequency of the rainfall was translated into the desired frequency of flood flow through use of median values of other inputs to the catchment modelling system. This implicit assumption has been tested in the period since publication of the current edition of Australian Rainfall and Runoff and a number of alternative approaches have been proposed as a means of circumventing the need for this implicit assumption. These methods include the ‘Monte Carlo’ (MC) approaches and ‘continuous simulation’ approaches. The reliability of these approaches and their associated uncertainty in prediction need to be defined for different types of problems so that suitable guidance can be presented in the revision to Australian Rainfall and Runoff. The purpose of this project was to investigate and compare the performance of the MC and Design Event (DE) methods under a range of conditions including:

- different climatic conditions

- different size catchments
- rural and urban catchments
- gauged and ungauged catchments
- a range of Annual Exceedance Probabilities (AEP)
- predictions at multiple points within catchments.

This paper reports on testing DE and MC approaches to design flood estimation. An accompanying paper (Pokhrel et.al., 2015) describes testing of continuous simulation methods.

## 1.1. Design Event Approach

The DE approach assumes a “probability-neutral” transformation from rainfall to runoff. This essentially means that a rainfall of a given AEP should always result in the flood of the same AEP. This is achieved by using representative values of model inputs and parameters. The DE approach is the most comprehensively used approach to estimate design floods in Australia. It is simple to implement and is not computationally intensive. It has been tailored to Australian conditions, and makes use of data that are readily available in Australia. The inputs used by the method are reasonably well defined, leading to good consistency between studies conducted using this approach. It has also been thoroughly tested in Australian catchments and the limitations of the method are well understood (Engineers Australia, 1998; Hill & Mein, 1996; Rigby & Bannigan, 1996; Walsh, Pilgrim, & Cordery, 1991).

Kuczera et al. (2006a) analyzed the conditions under which the selection of average values for initial catchment conditions (specifically initial loss) and a given storm temporal pattern could preserve the probability neutrality assumption. Using the joint probability description of the rainfall-runoff process they showed that the use of fixed average values can only be justified (to preserve ‘probability neutrality’) if the flood response of a catchment was linear.

There are a number of limitations of the DE approach. There are many possible interactions between rainfall and catchment characteristics that cannot be properly characterised by the use of fixed representative values of the flood producing variables, especially when they are sensitive and show large variability. This possibly jeopardizes applicability of the probability neutral assumption in many catchments. The probability neutrality assumption in the DE approach is maintained by selecting representative (usually average) temporal, spatial patterns and fixed values (median/average) of parameters. The success of the DE approach lies in how strongly the fixed values of the flood producing variable are able to preserve the ‘probability neutrality’ assumption.

It is well understood that there are many possible interactions between rainfall and catchment characteristics, which cannot be properly characterised by the use of fixed representative values of the flood producing variables, especially when they are sensitive and show large variability. This possibly jeopardizes applicability of the probability neutral assumption in many catchments.

There is a strong consensus in the literature that the processes involved in generating the design flood are probabilistic in nature and are best represented under a joint probability framework (Engineers Australia 1998, Kuczera et al. 2006a; Mirfenderesk et al. 2005; Nathan et al. 2003; Rahman et al. 2002b). This essentially means that the model output (design flood), inputs (rainfall duration, losses, intensity, spatial and temporal patterns), parameters and the model states should exist in the form of jointly distributed random variables. From this perspective, conditioning the model output on fixed (mean or median) values does not preserve the probability neutral transformation of rainfall to runoff and introduces biases (Nathan et al. 2003; Weinmann et al. 2002; Hill & Mein 1996) in the estimate of design flood.

## 1.2. Monte Carlo Approach

Considerable attention has been given to applying MC methods, also referred to as joint probability methods, to flood models over the last two decades in Australia (e.g. Rahman et al. 2002a; Mirfenderesk et al. 2005; Charalambous et al. 2013). The MC method for flood analysis outlined by

Engineers Australia (2013) offers a different approach to determining flood magnitudes and probabilities than the DE approach. This method is also event based, and can be regarded as an extension of the DE approach, with more rigorous treatment of parameter variability (Weinmann et al., 2002). The advantages of the MC method are best exploited when the catchment being modeled is thought to have a non-linear response to rainfall input (Nathan & Weinmann 2013).

A common argument in favor of this approach, over the DE approach, is that sampling from a distribution of values for model inputs is more representative of the physical system being modeled (Weinmann et al. 2002; Kuczera, et al. 2006a). Sampling from probability distribution of inputs rather than adopting a fixed (mean or median) 'representative' values allows for the joint probability interactions between various (climatic and catchment characteristics) flood producing components in the system and relaxes the AEP-neutral assumption (Kuczera et al. 2006a).

An advantage of the MC method is in modelling infrastructure as it is possible to represent the probability of system failure (such as spillway blockages or machine outages in a power station) through a distribution, just as any other model input. The MC method also inherently provides estimation of the uncertainty through its stochastic modelling approach (Nathan and Weinmann 2013).

Engineers Australia (2013) summarises the advantages of the MC approach as follows:

- The ability to concurrently determine flood characteristics at multiple points within a system/catchment
- The ability to sample the range of storm durations, as opposed to using fixed durations
- The stochastic sampling of variable values overcomes the limitation of fixing values. For example, antecedent catchment conditions can be captured through a distribution of loss values rather than relying on fixed values.
- The probability of a given peak discharge (or other measure of runoff intensity) is not linked to the probability of a given rainfall input (i.e. the method relaxes probability neutrality)

The determination of distributions for input parameters can present difficulties when adopting the MC method for flood estimation (Kuczera et al. 2006a). Determining parameter sensitivity, and therefore which parameters to use as variable inputs and which parameters to assign constant values, can also be a complex task. A related area of complexity is identifying relationships between parameters and the nature of these relationships (e.g. linear or otherwise) (Nathan & Weinmann, 2013). Another difficulty associated with this approach is the separation of uncertainty from natural variability (Nathan & Weinmann, 2013). Input observations and parameters, such as rainfall and streamflow records, initial loss values, the AEP of the PMP, are subject to varying degrees of uncertainty. This uncertainty is not always quantifiable, and therefore may be inadvertently captured as natural variability.

# 2. METHODOLOGY

## 2.1. Approach

In order to achieve the objectives of this project, data was collated from ten gauged catchments across Australian states and territories, representing a range of climatic conditions and catchment characteristics.

An overview of the method used for the testing is as follows:

i. Data acquisition
   - Collate continuous streamflow, rainfall, gauging and rating data for all catchments
   - Check all data for suitability for use in the project, including investigating inconsistencies and errors

ii. Model development
   - Develop semi-distributed initial loss-continuing loss rainfall-runoff models for each catchment, with channel routing between sub-catchments
   - The loss model used was initial loss with a constant continuing loss with the exception of Yeates Creek catchment where SWMod (Water and Rivers Commission, 2003) was also trialed

iii. Derive and collate all model inputs
- Rainfall temporal patterns. For MC method, 30 patterns were extracted from the nearest pluviograph site. For DE method, and ensemble approach was used, with 10 design temporal patterns for use with revised IFDs.
- Distributions of losses for MC tests
- Design rainfalls for a range of durations and AEPs up to 1 in 100, using revised IFDs (Bureau of Meteorology, 2015).

iv. Performance of DE and MC methods over range of AEPs
- Calibration of routing parameters through calibration to selected large flow events for MC and DE models
- Calibration of model losses by fitting the modelled flood frequency curve to flood frequency curve fitted to observed flow data for MC and DE models

v. Performance of the DE and MC methods at gauged and un-gauged locations
- For gauged locations, the models were calibrated to recorded large flow events and the at-site frequency curve
- To test the ability of the methods to perform on un-gauged basins the calibrated model parameters from one catchment were transposed to two other catchments; one with similar characteristics, and one with different characteristics

vi. Performance of the methods as a function of AEP
- The results from the models calibrated using all available data were compared with at-site frequency curve
- For selected sites, the models were re-calibrated using sub-sets of data and the results were then compared with the at-site frequency curve derived from the full data set

vii. Ability to predict flood characteristics at multiple points within catchments.
- A large catchment with observed rainfall and streamflow data available at the outlet as well as at interior sites was used for this test. The DE and MC models were calibrated to the data available at the outlet of the catchment and the performance of the model was evaluated against the observed flood frequency curve at the interior site.

## 2.2. Test Catchments

The test catchments were selected to cover a range of catchment sizes and catchment conditions (Table 1).

**Table 1. Test catchments, showing start and end date of flow record at catchment outlet**

| State | Station ID | River Name | Station Name | Catchment Area (km2) | Start | End |
|---|---|---|---|---|---|---|
| QLD | 138111A | Mary River | Moy Pocket | 820 | 1964 | 2004 |
| WA | 802213 | Hann River | Phillips Range | 5070 | 1967 | 2008 |
| WA | 603190 | Yates Flat Creek | Woonanup | 56 | 1963 | 2008 |
| NT | G8170075 | Manton River | upstream Manton Dam | 28 | 1965 | 2007 |
| SA | A5040523 | Sixth Creek | Castambul | 44 | 1979 | 2008 |
| VIC | 231213 | Lerderderg River | Sardine Ck-O'Brien | 153 | 1959 | 2005 |
| TAS | 304040 | Florentine River | upstream Derwent Junction | 436 | 1951 | 2008 |
| TAS | 499 | Tyenna River | at Newbury | 198 | 1965 | 1997 |
| TAS | 353 | Hobart Rivulet | at Gore St | 16 | 1985 | 2014 |
| NSW | 204025 | Orara River | Orara River at Kurangai | 134 | 1969 | 2012 |

# 3. RESULTS

## 3.1. Full Data Set

The MC and DE models were calibrated using the full data set available, and were run using design inputs. The results of the runs for all catchments at 20% and 1% AEP are shown in Table 2. Full results for each catchment are presented in Engineers Australia (2015).

**Table 2. Percent difference between modelled flood quantiles (MC/DE) and quantile estimates from frequency analysis of observed annual maximums.**

| | 20% AEP | | 1% AEP | |
|---|---|---|---|---|
| **River Name** | **DE** | **MC** | **DE** | **MC** |
| Mary River | 7 | 15 | -9 | 10 |
| Hann River | -10 | -1 | 13 | 14 |
| Yates Flat Creek | -24 | -63 | 45 | 22 |
| Manton River | 3 | 1 | 6 | 6 |
| Sixth Creek | -4 | -2 | 3 | -1 |
| Lerderderg River | -3 | -30 | 15 | 10 |
| Florentine River | -6 | -24 | 11 | 3 |
| Tyenna River | -2 | -5 | -8 | 0 |
| Hobart Rivulet | -10 | -9 | 12 | 23 |
| Orara River | 3 | 1 | -5 | -3 |

The results for Yates Flat Creek showed that an initial loss-continuing loss model did not give a good representation of the runoff response of the catchment. Results using SWMod were greatly improved. The percentage difference between modelled and observed flood quantiles was 8% at 20% AEP and 12% at 1% AEP.

## 3.2. Subset of Data

The MC and DE approaches were tested using a subset of data for two catchments: the Mary River and Manton River catchments. In each case, the flow record was halved, and the calibration process was repeated using each half of the record only.

For Manton River, Period 1 was significantly drier than Period 2. All the flood events used for the original Manton River model calibration were contained within Period 2. The routing parameters remained the same for all periods, but the calibrated losses were higher for Period 1. A poor agreement with the flood frequency curve fitted to the full record was found when the parameters calibrated to Period 1 were used in the modelling. At 20% AEP, the difference between the observed and modelled flows was 40% for the DE model and 49% for the MC model. When the parameters calibrated using data from Period 2 were used in the model, the results of both methods showed reasonable agreement with the flood frequency curve.

For Mary River, there were large flood events in both periods of record, with the two largest events being in Period 2. For this catchment, it was found that it was necessary to vary the routing parameter alpha to obtain a good fit to the events and frequency curves derived from the shorter data sets. For all periods, the continuing and initial losses were zero. The results from the model runs using the parameters calibrated to the shorter data sets showed that the Period 2 parameters gave a higher estimate of the flood frequency curve and the Period 1 parameters gave a lower estimate (Figure 1 and Figure 2). This is consistent with the higher flood events being contained in Period 2.

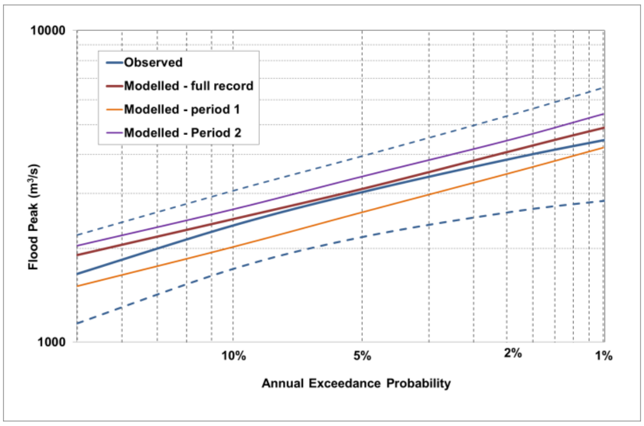


**Figure 1 DE model results for sub-sets of data for Mary River**

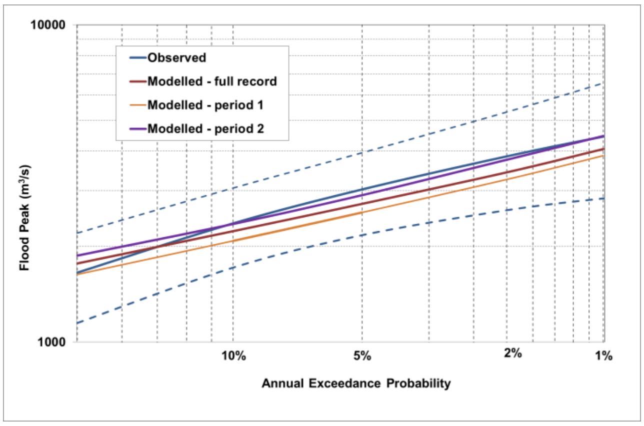


**Figure 2 MC model results for sub-sets of data for Mary River**

## 3.3. Ungauged Catchments

The neighbouring catchments of the Tyenna and Florentine Rivers were used to test transposing model parameters between catchment models, as a test of modelling in ungauged catchments. These two catchments are very similar in terms of characteristics, flow response to rainfall, event hydrograph shapes, and climatic zone. The catchment area of the Florentine River model is 2.2 times that of the Tyenna River. It would be expected that the calibrated model parameters would be similar for these models; however this was not the case. The routing and loss parameters varied between the catchment models for both the MC and DE calibrations. There are likely to be a number of combinations of routing and loss parameters that will produce acceptable model outputs. When the Tyenna River models were run using the Florentine River model parameters, the results of both the MC and DE models were within 20% of the observed values over the full range of AEPs. However, when the Florentine River models were run using the Tyenna River model parameters, the MC method performed slightly better than the DE model which showed up to 43% higher flow compared to up to 36% for the MC. The results illustrate that even when there is a neighbouring gauged catchment, care must be taken in estimating floods for ungauged catchments.

## 3.4. Internal Gauge Sites

The performance of the models in replicating the flood frequency curve at internal gauge sites within the Mary River catchment was investigated. Both the MC and DE models performed reasonably well at the Obi-Obi Creek at Kidaman and Bellbird Creek sites, despite these sites being relatively high in the catchment. Overall MC model resulted in higher flow values than DE for all the internal gauges; this is however due to the fact that the modelled flood frequency curve at the outlet of catchment is higher when using the MC method compared to the DE. The results at Bellbird Creek gauge site (catchment area of 486 $km^2$) are shown in Figure 1.

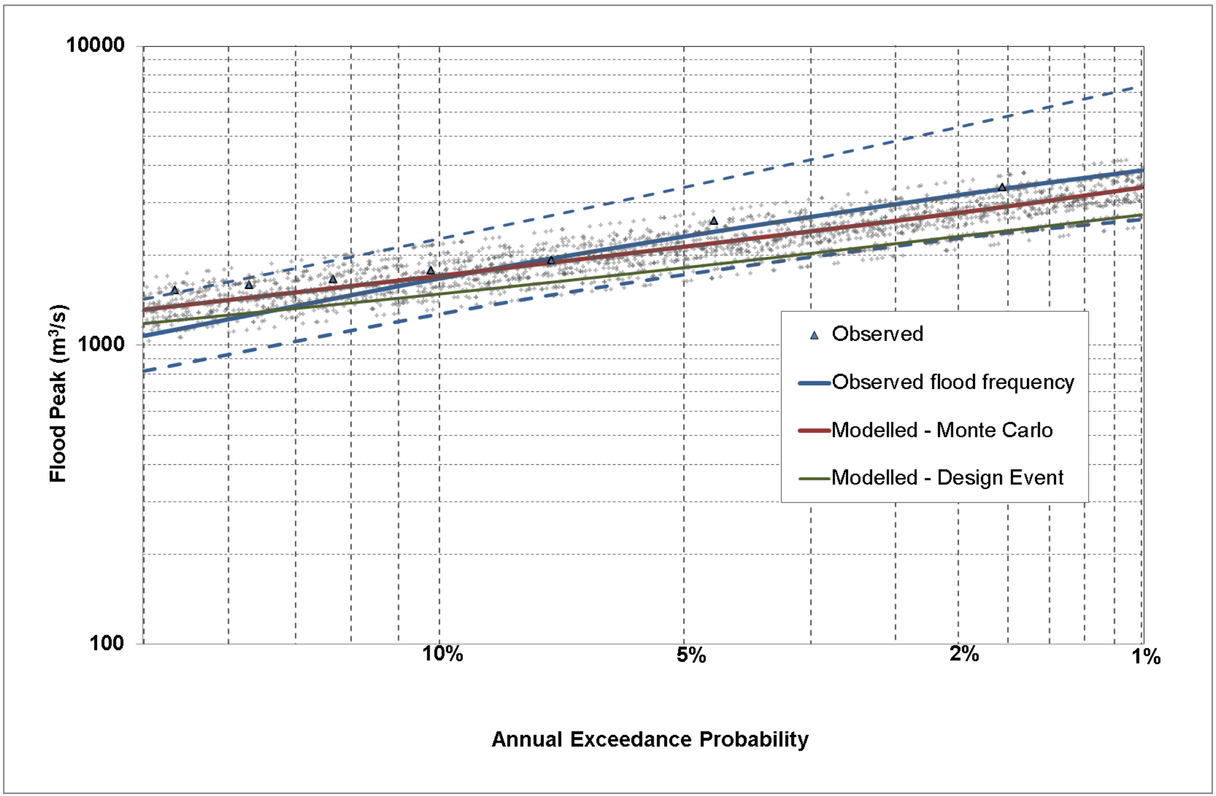


**Figure 1 Bellbird Creek gauge site results. Grey dots represent spread of Monte Carlo results.**

## 4. CONCLUSIONS

From the testing it was concluded that whilst both the Monte Carlo and Design Event approaches generally performed well in producing a flood frequency curve for AEPs in the range of 50% to 1%, the advantage of the Monte Carlo method was in the quantification of uncertainty provided by the spread of results from individual model runs.

Tests on the effect of record length showed that the performance of the models can vary significantly based on the period of record used, thus highlighting the need to investigate how representative the available flow data is in the context of any available long-term rainfall records.

The tests on the applicability of MC and DE methods in ungauged catchments generally produced poor model performances, thus suggesting that careful consideration should be given in transposing parameters to an ungauged catchments even when there is data available at a neighbouring gauged catchment.

The performance of the models in internal gauges was tested in three internal gauge sites within Mary River catchment. In two of the three sites tested both methods performed reasonably well, despite these sites being relatively high in the catchment.

## 5. ACKNOWLEDGMENTS

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