Variability in Rainfall Temporal Patterns: A Case Study for New South Wales, Australia[1]

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Abstract: In Australian Rainfall and Runoff (ARR) 1987, the recommended rainfall-based Design Event Approach (DEA) of design flood estimation has a number of limitations that are likely to introduce a probability bias in the final design flood estimates. Recently, considerable research has been undertaken on the development and application of the Joint Probability Approach (JPA)/Monte Carlo Simulation Technique (MCST) to design flood estimation to overcome the limitations associated with DEA. The applications of this method with Victoria and Queensland data have shown that MCST can overcome some of the limitations associated with the DEA and MCST can produce more accurate design flood estimates. However, the wider application of the MCST needs regionalisation of various input variables to the runoff routing model which include rainfall characteristics such as duration, intensity and temporal pattern. This paper focuses on the regionalisation of the rainfall temporal patterns in New South Wales (NSW), Australia using data from 86 pluviograph stations. The regionalised temporal patterns are then applied with the MCST to obtain design flood estimates for both gauged and ungauged catchments in NSW. Using the MCST, it has been found that the application of at-site and regional temporal patterns can give up to 10% differences in flood quantile estimates. In this study, rainfall inter-event duration (a new random variable) has been tested along with other random variables (i.e. rainfall duration, rainfall intensity, initial loss, continuing loss and runoff routing model storage delay parameter) with their probability distributions in the MCST, which has been shown to provide more accurate flood quantile estimates than the DEA. The findings of this research will assist to apply the MCST in practice in NSW. The method can be adapted to other parts of Australia and similar other countries.

Keywords: Design Event Approach, Australian Rainfall and Runoff, Design rainfall, Complete storm, Joint Probability Approach, Monte Carlo simulation

1. Introduction

Design of hydraulic structures and other water resources planning and management tasks often requires design flood estimation which is commonly carried out by at-site flood frequency analysis provided the availability of recorded streamflow data of adequate quantity and acceptable quality. Though regional flood estimation methods (e.g. index flood, rational and regression-based approaches) are usually adopted for ungauged catchments, these are limited to peak flow estimation. When the estimation of complete streamflow hydrograph is needed (e.g., design of volume sensitive hydrologic systems such as reservoir) rainfall-based methods such as unit hydrograph or runoff routing model are adopted in practice. Australian Rainfall and Runoff (ARR 1987), the national guide for flood estimation, currently recommends the Design Event Approach (DEA) as the preferred method in rainfall runoff modelling in Australia (I. E. Aust., 1987). However, this method has limitations as it only accounts for the probabilistic nature of rainfall depth, but ignores the probabilistic nature of other inputs, such as rainfall temporal patterns and initial loss, in the rainfall runoff modelling (Hill and Mein, 1996).

To overcome the limitations associated with the DEA, a Joint Probability Approach (JPA) has been proposed in the design flood estimation (e.g. Eagleson, 1972; Beran, 1973; Russell et al, 1979; Diaz-Granados et al, 1984; Sivapalan et al, 1990). However, as reported by Rahman et al. (1998) the majority of these applications were limited to theoretical studies, and mathematical complexity, difficulties in parameter estimation and limited flexibility in application prevented the wider application of these methods to practical situations. Rahman et al. (2002) developed and applied successfully a simplified Monte Carlo Simulation Technique (MCST) for flood estimation based on the principles of joint probability. This method uses a non-linear runoff routing model to simulate streamflow hydrographs from probability-distributed input variables and can make use of most of the commonly adopted flood estimation models and design data in Australia.

Carroll and Rahman (2004) tested the MCST to catchments in Victoria and Queensland with URBS model and found that MCST can overcome some of the limitations associated with the DEA, and this can produce more accurate design flood estimates than the DEA. More recently, considerable research has been made on JPA/MCST (e.g. Aronica and Candela, 2007; Muncaster and Bishop, 2009; Kjeldsen et al, 2010; Aronica et al, 2012; Caballero and Rahman, 2013; Charalambous et al, 2013; Mirfenderesk et al, 2013; Svensson et al, 2013). Example includes the MCST method by Aronica and Candela (2007) which reproduced the observed flood frequency curves with reasonable accuracy over a wide range of return periods using a semi-distributed stochastic rainfall runoff model. The method is suitable for ungauged or partially gauged catchments. Though MCST have been applied in many studies in Australia, the method has not been investigated under different hydrologic conditions. Furthermore, the wider application of this method needs

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regionalisation of various input variables so that the MCST can be applied easily in practice. These various input variables include rainfall duration, intensity, temporal pattern and losses. This paper focuses on the regionalisation of the temporal patterns data for the State of New South Wales (NSW) in Australia so that this can be used with the MCST to obtain design flood estimates for both gauged and ungauged catchments in NSW. This paper also investigates the variability of rainfall temporal patterns in NSW and its impacts on design flood estimates using a MCST.

Recently, the temporal patterns of design rainfall have been investigated by many studies (e.g. Rahman et al, 2006; Varga et al, 2009; Ball and Aboura, 2010; Akbari et al, 2011). The design rainfall temporal patterns in the ARR 1987 Volume 2 are commonly adopted in the rainfall runoff modelling using the DEA in Australia. These were derived using the Method of Average Variability (Pilgrim et al., 1969; Pilgrim and Cordery, 1975; Kennedy, 1991). The principal aim of the Method of Average Variability is to derive representative temporal pattern from a set of selected observed temporal patterns (Rahman et al, 2006). For the MCST, the temporal pattern database can be derived using a 'multiplicative cascade model' (Hoang, 2001) or dimensionless pooled historical temporal patterns (Rahman et al, 2002). This study has adopted the historic temporal pattern similar to Rahman et al (2002) to develop regional temporal pattern database for the State of NSW.

2. Adopted Methods

2.1 Selection of rainfall events

In the DEA, rainfall duration is 'fixed' and it does not need stochastic rainfall duration. However, JPA/MCST needs rainfall duration to be a random variable. In previous application of JPA/MCST by Rahman et al. (2002), the three rainfall characteristics (rainfall duration, intensity and temporal patterns) were treated as random variables unlike the DEA. Thus, storm events which can produce rainfall events with rainfall characteristics as random variables need to be defined in the MCST. Hoang et al (1999) defined a rainfall event of random durations as a 'complete storm' (CS) in which it is described as the period of significant rain preceded and followed by an arbitrarily defined period of dry hours (e.g. 6 hours, as adopted in this study). While Rahman et al. (1998) defined the storm burst that produces randomly distributed storm burst durations, called 'storm-core', which is defined as the most intense part of a complete storm. In this study, the inter-event duration has been considered as a new random variable in the application of MCST following the approach of Kjeldsen et al. (2010). Here, the inter-event duration is defined as the time (in hours) elapsed between two successive complete storm events.

Based on an arbitrary threshold value of rainfall intensity, the complete storm events from the selected 86 pluviograph stations are selected in such a way that 2 to 8 rainfall events on average are selected per year from a given pluviograph station. This selection is made by comparing the corresponding complete storm that has the highest rainfall intensity ratio to the 2-year average recurrence interval (ARI) design rainfall value obtained from ARR1987 (I. E. Aust., 1987). These rainfall events are analysed to develop a database of observed temporal patterns, which can then be used in the MCST. Some previous applications of the MCST focused on storm-cores (e.g. Rahman et al, 2002). This study focuses on the analysis of complete storms as it is believed that complete storms are easy to identify and also the rainfall temporal patterns and losses can easily be analysed for a complete storm as compared to a storm-core. A complete storm-based MCST is therefore likely to provide a more comprehensive design flood estimation method, and hence adopted in this study.

2.2 Development of rainfall temporal pattern database for NSW

The temporal pattern (TP) of rainfall is a dimensionless representation of rainfall intensity over the sub-durations of the rainfall event. In this study, hourly pluviograph data is used to derive TP. Here, the TP is characterised by a dimensionless mass curve, i.e., a plot of dimensionless cumulative rainfall depth versus dimensionless storm time with 10 equal time increments (see example in Figure 2). The development and application of the TP database in the MCST can be achieved by following 'multiplicative cascade model' (Hoang, 2001) or historic TP (Rahman et al, 2002). This study uses the historic TP similar to Rahman et al (2002) to develop TP database using 86 pluviograph stations from NSW. To form the regional TP database, the dimensionless temporal patterns from individual stations are pooled irrespective of the season and total rainfall depth as it was found by Rahman et al (2002) that the TP does not depend strongly on season and total rainfall depth. It was also found that TP depends on storm durations (e.g. Hoang, 2001; Rahman et al, 2002), and hence the pooled TPs in this study are divided into two groups: up to 12 hours durations and more than 12 hours durations.

2.3 Adopted MCST

Two catchments (Oxley River and Belar Creek) are selected to test the applicability of the developed TP database in the rainfall runoff modelling using the MCST. Each catchment has a pluviograph station (as shown in Table 2) within or near the catchment centre. For these study catchments, the significant rainfall and runoff events were selected to calibrate the runoff routing model, which is based on the following equation:

$$S = kQ^m \tag{1}$$

where S is the storage (m^3), k is the storage delay parameter (h), Q is the discharge (m^3/s) and m is the non-linearity parameter, which is taken as 0.8 in this application. In the adopted runoff routing model, a single storage concentrated at the catchment outlet was considered, which should provide reasonably accurate results given the two selected study catchments, which are 213 km^2 and 133 km^2 in size. More accurate results would have been obtained with a semi-distributed runoff routing model like RORB; however, this has not been adopted in this study as RORB currently supports only partial MCST i.e. it does not allow to randomly vary all the model inputs simultaneously.

In obtaining the direct runoff from the observed streamflow hydrograph, the baseflow needs to be separated, which was achieved by using Boughton (1988) equation. In this study, the initial loss (IL) and continuing loss (CL) model was used to generate rainfall excess hyetograph as recommended by ARR1987 (I. E. Aust., 1987). The IL is defined as the amount of rainfall that occurs before the start of the surface runoff while CL is calculated as the average rate of loss throughout the remainder of the rainfall event. From the selected rainfall and streamflow events, the rainfall runoff model was calibrated and value of k was obtained for each of the selected events.

For the two study catchments, the distributions of rainfall inter-event duration, rainfall duration, rainfall intensity, IL, CL and k were identified as shown in Table 3. In selecting the appropriate distribution for a given input variable, a number of candidate distributions were tested using a number of goodness-of-fit tests including Chi-Squared (C-S) test, Kolmogorov-Smirnov (K-S) test and Anderson-Darling (A-D) test. The selected distributions and their parameter values are presented in Table 1. The selected best-fit distributions are Gamma for rainfall inter-event duration, rainfall duration, IL and k and Exponential for CL. The stochastic values of rainfall inter-event duration, rainfall duration, rainfall intensity, IL, CL and k were generated (considering their correlations) from the identified probability distributions and the developed TP database was sampled randomly (based on the generated duration) in the adopted MCST. Both at-site TP and regional TP were used in the simulation. In deriving the regional TP, the TP set based on nearby pluviograph stations with distances of 30, 50, 100, and up to 200 km from centre of the catchment of interest or up to maximum of 20 nearby pluviograph stations were considered. The resulting number of pluviograph stations for different distances in deriving the TP database for the two selected catchments are presented in Table 2.

Table 1 Model inputs and probability distributions for MCST application

Model inputs	Probability distributions	Oxley River			Belar Creek		
		Mean	Standard deviation	Median	Mean	Standard deviation	Median
Rainfall inter-event duration (IED)	Gamma	92.23	112.21	38.96	41.95	48.70	24.92
Rainfall duration (D)	Gamma	37.54	32.93	30.00	21.48	19.51	16.00
Initial loss (IL)	Gamma	28.77	27.57	17.04	38.97	20.21	36.30
Continuing loss (CL)	Exponential	3.10	2.43	2.31	6.35	4.15	6.07
Storage delay parameter (k)	Gamma	19.04	6.09	20.46	21.15	7.57	19.42

Table 2 Number of pluviograph stations to derive TP database

Catchments	Distances from catchment centre and number of stations			
	30 km	50 km	100 km	200 km
Oxley River	5	7	10	13
Belar Creek	1	1	1	13

Model inputs were generated 50,000 times to establish 50,000 possible set of input values to the runoff routing model. With these generated model inputs, 50,000 different streamflow hydrographs were simulated. The peaks of these simulated hydrographs were stored for further analysis to determine a derived flood frequency curve following the approach by Caballero and Rahman (2013). The FORTRAN program developed by Rahman (1999) was modified to implement this MCST analysis.

2.4 Validation of the model

The estimated flood quantiles from the MCST (based on the at-site and regional TP data) are compared against the DEA (using the mean and median k values of the observed data set of the respective model input).

The resulting estimated flood quantiles from the MCST based on at-site ($Q_{at\text{-}site}$) and regional TP ($Q_{regional}$) were compared to assess the sensitivity of TP data on the design flood estimates. In this regard, a relative error (RE) is defined as below:

$$RE\ (\%) = [(Q_{regional} - Q_{at\text{-}site})/Q_{at\text{-}site}] \times 100 \quad (2)$$

3. Data Preparation

In this study, the continuous rainfall data from 86 pluviograph stations in NSW were obtained from Australian Bureau of Meteorology. The rainfall record lengths of the selected stations range from 30 years to 101 years with an average record length of 45 years. As displayed in Figure 1, the selected stations present a good spatial distribution over the eastern part of the State; however, no station is selected from far western NSW due to insufficient data lengths. Two catchments were also selected (Figure1 and Table 3) to test the applicability of regionalised TP with the MCST. Each catchment has a pluviograph station (within or near the catchment) with a minimum of 30 years of concurrent rainfall and streamflow data as shown in Table 4.

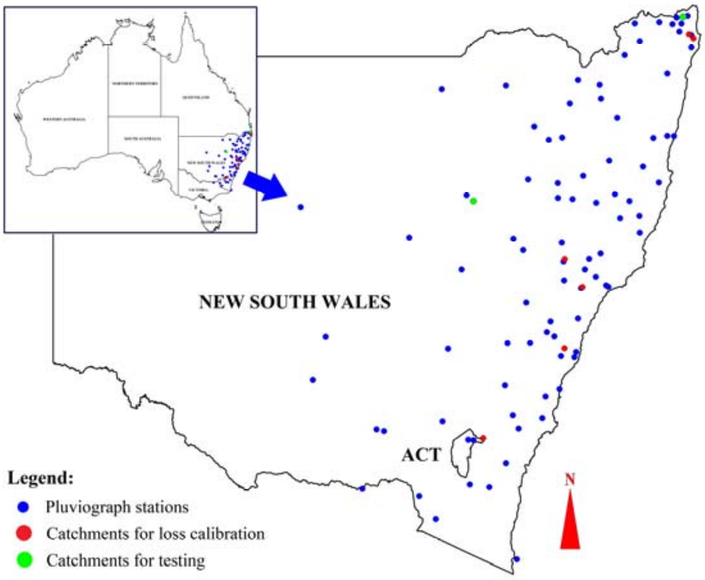

Figure 1 Selected 86 pluviograph stations and 2 catchments in New South Wales, Australia

Table 3 Selected catchments in NSW for rainfall runoff modelling using MCST

Station ID	Station name	Catchment area (km^2)	Period of record	Record length (years)
201001	Oxley River @ Eungella	213	1957 - 2011	55
420003	Belar Creek @ Warkton	133	1976 - 2005	30

Table 4 Nearest pluviograph station for each selected catchment

Catchment station ID	Pluviograph station ID	Pluviograph station name	Distance from catchment's centre (km)	Period of record	Record length (years)
201001	58109	Tyalgum (Kerrs Lane)	2.36	1965 - 1996	32
420003	64046	Coonabarabran (Westmount)	7.24	1970 - 2010	41

4. Results

A total of 19,718 complete storm events from the 86 pluviograph stations are selected from NSW. On average, 229 complete storm events are selected from a pluviograph station (5 events per year on average). The TP are derived for each of the 86 pluviograph stations (50 samples are shown in Figure 2 to show the expected variability in TP of NSW). As can be seen in Figure 2, the plots of both the at-site and regional TP show a wide variability, which raises the question how to select a representative TP from these to apply with the DEA so that TP is probability neutral.

A total of 47 rainfall and runoff events were selected (17 and 30 from Oxley River and Belar Creek catchments, respectively) for estimating IL, CL and storage delay parameter *k*. Model inputs and the obtained distributions are presented in Table 1. These model inputs and parameters are then applied in estimating flood quantiles for the selected catchments using DEA and MCST.

Using the DEA, a number of trial rainfall durations are adopted for each ARI of interest. The corresponding IFD data is obtained from ARR 1987 (I. E. Aust., 1987). The design temporal pattern data from ARR Volume 2 is used. The ARR 1987 IL-CL design values for NSW (IL = 35 mm and CL = 2.5 mm/h) are adopted. The mean and median *k* values, obtained from the model calibration (Table 3) are adopted. For a given ARI, the duration giving the highest flood discharge is taken as the critical duration and the corresponding peak discharge is taken as the design flood for the ARI. The derived flood frequency curves from MCST were obtained for the two study catchments. Figure 3 shows the results for the Belar Creek catchment. Here, the MCST and DEA provide similar results and both overestimate the observed floods at smaller ARIs.

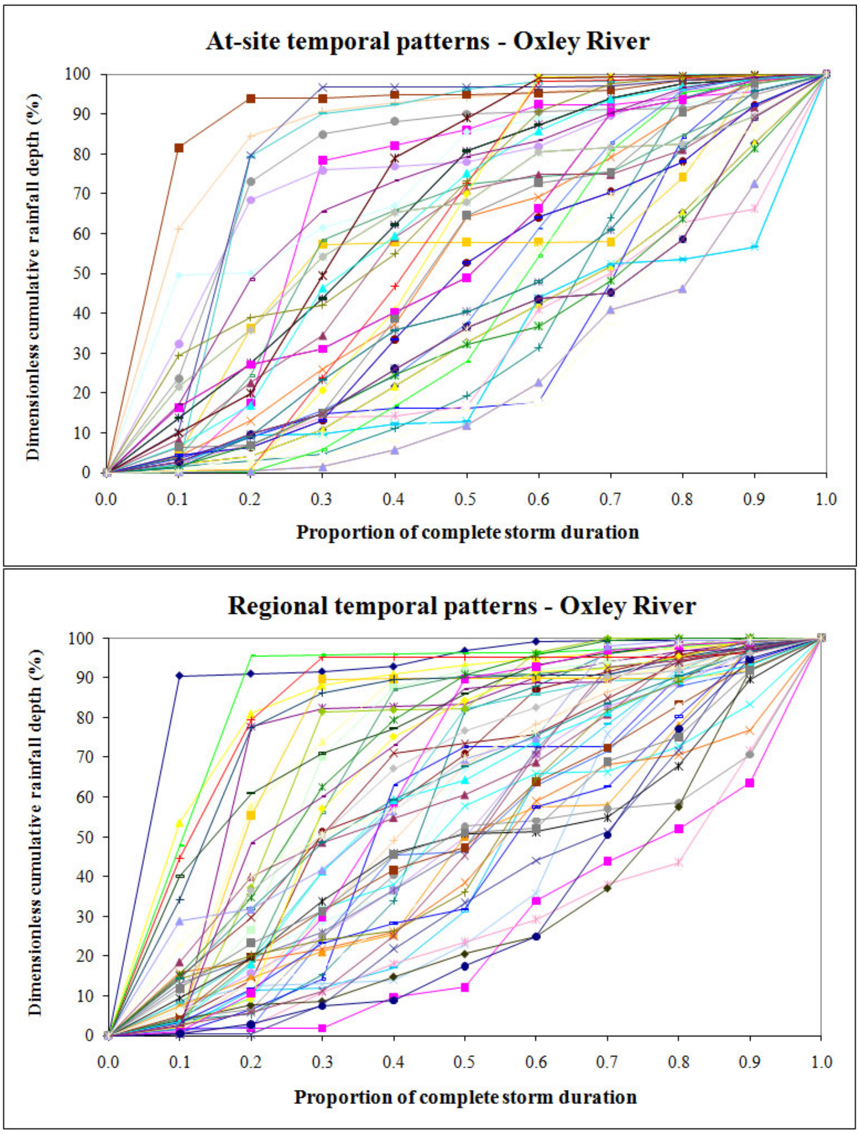

Figure 2 Samples of at-site and regional temporal patterns for Oxley River

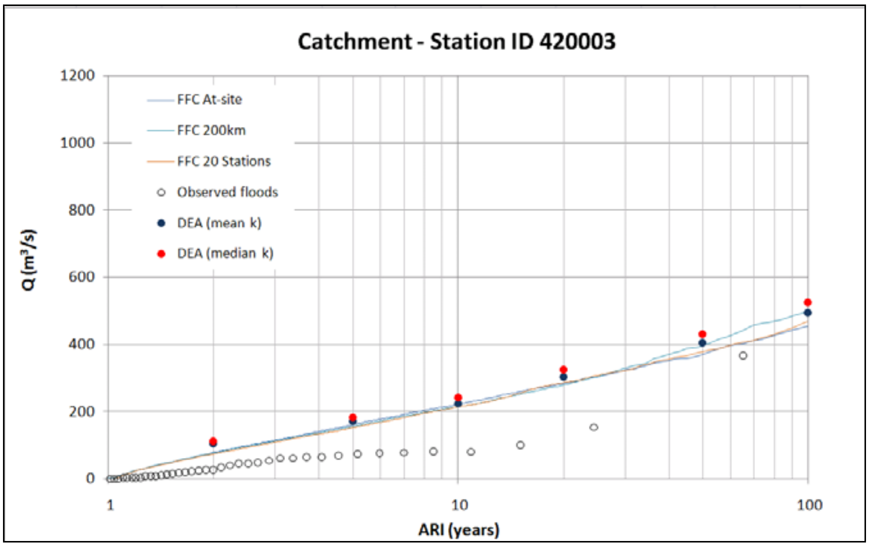

Figure 3 Design flood estimates for Belar Creek catchment

In the MCST, the use of regional TP shows under-estimation in flood quantiles (in relation to the use of at-site TP) for most of the cases of up to 4.5% for the Oxley River catchment as illustrated in Table 5. The maximum over-estimation for this catchment is 3.5%. The regional TP for the Belar Creek catchment was only applied to distances less than 200 km and for 20 stations as no nearby pluviograph station was available for distances less than 100 km. The regional TP for distances under 200 km and for 20 stations show under-estimation of up to 7.1% and over-estimation of up to 10.1% (Table 6). The high degree of variability in the regionalised TP (as shown in Figure 2) show remarkably small differences of up to about 10% in the design flood estimates using MCST for the two catchments.

Table 5 Design flood estimates using regional temporal patterns for Oxley River catchment

ARI (years)	Flood quantiles using at-site TP (m^3/s)	Flood quantiles (m^3/s) for pooled TP and percentage difference from at-site TP									
		Distances (km) for pooled TP								20 stations	
		30		50		100		200			
2	188	191	1.2%	187	-0.5%	183	-2.9%	183	-3.0%	186	-1.3%
5	380	379	-0.4%	375	-1.4%	364	-4.4%	363	-4.5%	366	-3.7%
10	532	533	0.3%	524	-1.5%	510	-4.1%	514	-3.4%	509	-4.2%
20	701	713	1.7%	682	-2.7%	686	-2.2%	687	-2.0%	676	-3.6%
50	938	955	1.8%	941	0.3%	931	-0.8%	925	-1.5%	924	-1.6%
100	1161	1202	3.5%	1169	0.6%	1113	-4.2%	1146	-1.3%	1159	-0.2%

Table 6 Design flood estimates using regional temporal patterns for Belar Creek catchment

ARI (years)	Flood quantiles using at-site TP (m^3/s)	Flood quantiles (m^3/s) for pooled TP and percentage difference from at-site TP			
		Within 200 km distance for pooled TP		20 stations	
2	79	76	-3.5%	73	-7.3%
5	160	156	-3.0%	153	-4.9%
10	222	215	-3.1%	214	-3.3%
20	284	280	-1.6%	287	1.0%
50	372	398	6.9%	380	2.1%
100	452	498	10.1%	467	3.2%

5. Conclusion

This paper investigates the regionalisation of design rainfall temporal patterns for NSW for application with the MCST. Based on complete storm events, temporal patterns data at 86 pluviograph stations in NSW are derived. Pluviograph stations with distances up to 200 km can be used to obtain regional temporal patterns at any arbitrary location in NSW provided there is a sufficient number (e.g. 20 stations) of nearby pluviograph stations. The at-site and the regionalised temporal patterns data are applied with the MCST to two NSW catchments for estimating design floods. It has been found that the use of at-site and regional temporal patterns can give up to about 10% differences in flood quantile estimates using the MCST. In this study, a new random variable, rainfall inter-event duration has been tested along with other randomly distributed random variables (i.e. rainfall duration, rainfall intensity, initial loss, continuing loss and runoff routing model parameter) in the MCST, which has provided reasonable results. The findings of this study will be useful towards the application of MCST in NSW, Australia. The method can be adapted to other countries.

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