Australian Rainfall & Runoff

Revision Projects

PROJECT 4

Continuous Rainfall Sequences at a Point

Supplementary: Constrained Continuous Rainfall Simulation for Derived Design Flood Estimation

STAGE 3 REPORT

P4/S3/027

DECEMBER 2015

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AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 4 CONTINUOUS RAINFALL SEQUENCES AT A POINT

SUPPLEMENTARY: CONSTRAINED CONTINUOUS RAINFALL SIMULATION FOR DERIVED DESIGN FLOOD ESTIMATION

STAGE 3 REPORT

DECEMBER, 2015

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FOREWORD

ARR Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (ARR) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- prediction of extreme flood levels.

However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. A recent and significant development has been that the revision of ARR has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining two projects will commence in Stage 3. The outcomes of the projects will assist the ARR Editorial Team with the compiling and writing of chapters in the revised ARR.

Steering and Technical Committees have been established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-Duration information across Australia) has been provided by the Bureau of Meteorology.

The aim of Project 4 is to validate the use of continuous rainfall sequences for estimation of flood flows with a desired frequency. The supplementary report to project 4 provides an approach to constrain stochastically generated rainfall with an aim of preserving the intensity-duration-frequency (IFD) relationships of the observed data.

M K Babister

James Ball

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

ARR REVISION PROJECTS

The 21 ARR revision projects are listed below:

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	**Continuous rainfall sequences at a point**	**1**
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	3
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

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	Dr Rory Nathan, Jacobs
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EXECUTIVE SUMMARY

Continuous simulation of rainfall sequences is becoming an increasingly important tool in design flood estimation, as it represents arguably the most rigorous technique available to represent the joint behaviour of flood-producing extreme rainfall events and the preceding antecedent rainfall conditions. To inform the forthcoming revision of Australian Rainfall and Runoff (ARR), the aims of this project are to develop, test and validate the procedures for continuous rainfall simulation.

Continuous rainfall sequences can be simulated using a number of models; however, preserving relevant attributes of the observed rainfall — including rainfall occurrence, variability and the magnitude of extremes — continues to be difficult. This report presents an approach to constrain stochastically generated rainfall with an aim of preserving the intensity-duration-frequency (IFD) relationships of the observed data. Two main steps are involved. First, the annual maximum rainfall is corrected recursively by matching the generated intensity-frequency relationships to the observed relationships. Second, the remaining (non-annual maximum) rainfall data is adjusted such that the mass balance of the generated data before and after adjustment is maintained. Storm durations are selected to minimise the dependence between annual maximum values of higher and lower durations. The method is tested on simulated 6 min rainfall series across five Australian stations with different climatic characteristics. The results suggest that the annual maximum and the IFD relationships are well reproduced after constraining the simulated rainfall. The proposed approach can also be easily extended to constrain any other attributes of the generated rainfall, providing an effective platform for post-processing of stochastic model outputs.

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1. Introduction

Continuous rainfall time series at a subdaily resolution are important in the estimation of short-duration floods and pollutant load, and are commonly used for planning, design and management of urban water systems [Sivakumar and Sharma, 2008; Westra et al., 2012]. Continuous subdaily rainfall time series are particularly important for flood estimation, providing one of the primary means to estimate the catchment's moisture conditions prior to the extreme (flood-producing) rainfall event [Berthet et al., 2009; Michele and Salvadori, 2002; Pathiraja et al., 2012; Pui, 2011]. Despite its importance, subdaily rainfall is generally available at only a small number of locations and often contains a large percentage of missing data, mainly due to the cost and time required to collect such data. For this reason, stochastic generation models and rainfall disaggregation procedures are commonly used as an alternative way to obtain suitable subdaily rainfall data.

A number of stochastic rainfall generation approaches have been investigated in the literature, with the most suitable approaches for a particular application depending on the required spatial and temporal scale of the rainfall data. A comprehensive review of annual, monthly and daily rainfall generation methods can be found in Srikanthan and McMahon [2001] and Sharma and Mehrotra [2010]. A number of methods for generating subdaily rainfall through disaggregation procedures are also available, which include canonical and microcanoical models, Poisson cluster models as well as nonparametric based models (See Westra et al. [2012] for a brief review of these approaches). In a recent study, Mehrotra et al. [2012] and Westra et al. [2012] developed a regionalized stochastic model to generate daily and subdaily continuous rainfall sequences throughout Australia. This method involved generating daily rainfall sequences based on data from nearby stations, followed by daily to sub-daily disaggregation to generate 6 min rainfall sequences — again borrowing information from the nearby stations.

Prior to using stochastically generated rainfall data for hydrological applications, it is important to test the data against important characteristics of the observed data at various scales of aggregation [Srikanthan and McMahon, 2001]. In general, the following important characteristics need to be preserved: the mean, variance, coefficient of skewness, extremes, and dry and wet spell length. Mehrotra et al. [2012] and Westra et al. [2012] tested the aforementioned daily and subdaily rainfall generation models at five locations across Australia. Although the models successfully reproduced a range of statistics, biases were found in the intensity-frequency relationships for short (subdaily) durations.

The intended application of the stochastically generated rainfall sequences will inform the selection of the most important characteristics that should be preserved. For planning and designing of infrastructure, accurate representation of extreme rainfall statistics — commonly represented using intensity-frequency-duration (IFD) relationships — is crucial. We present a method to constrain stochastically generated rainfall data to preserve the IFD relationships of the observed rainfall. Two steps are involved: (i) the annual maximum rainfall is rescaled so that the difference between the generated and observed IFDs is below a pre-defined tolerance; and (ii) the remaining rainfall data (i.e., all the rainfall data other than the annual maximum) are rescaled so that the average rainfall of the initial stochastic sequences are maintained. The annual maximum rainfall is adjusted at multiple durations. In refining the algorithm used to constrain the IFD statistics, we also explore the following questions: Do we need to adjust rainfall across all durations or selected target durations? To what extent does adjustment at short duration (say 6 min) affect adjustment at larger duration (say 30 min) or vice versa? Whether the number realisations significantly affect the estimated rainfall adjustment factors or not or not? Note that annual maximum and annual extreme rainfall is synonymously used throughout the report.

2. Methodology

Rainfall adjustment factors for annual maximum and the remaining rainfall data are estimated recursively at multiple durations. A flow chart describing the application of the rainfall adjustments is illustrated in Figure 1 with more detailed explanation given below.

Step-1: Calculate annual maximum and identify the remaining rainfall data. For a selected recursion (e.g. r = 1) and target duration (e.g. D = 6 min), calculate annual maximum and identify the remaining rainfall data of raw continuous rainfall sequences for all the realizations considered (N).

Step-2: Calculate ensemble mean. Estimate the ensemble mean of the annual maximum and the remaining rainfall data across all the realisations.

Step-3: Estimate adjustment factors. Factors to adjust rainfall are estimated in steps 3a and 3b. More details about this is provided in sections 2.1 and 2.2, respectively.

Step-4: Adjust rainfall data: rescaling of the generated rainfall is carried out by multiplying the adjustment factors estimated in step-3.

Step-5: Evaluate adjusted rainfall data: The rescaled rainfall sequences are evaluated by applying an objective function to the IFD relationships before and after adjustment. The analysis ends if the objective function is reduced below a tolerance; otherwise, step-1 to 5 is repeated based on the next recursion and/or target duration. The objective function is described in more detail in section 2.3.

2.1. Annual maximum rainfall adjustment factor (***f_{ex}***)

To estimate adjustment factors for annual maximum rainfall, a ratio (r_{AEP}) between the target (IFD_{AEP}^{T}) and generated (IFD_{AEP}^{G}) IFD is estimated at each of the exceedance probabilities (Equation 1). Twenty one annual exceedance probability values (1, 5, 10, 15, 20… 90, 95, and 99 years) are considered. The target IFD is based on the observed data while the generated IFD is estimated empirically based on an ensemble mean of the generated rainfall sequences. Then, a polynomial regression function is developed between the target IFD (IFD_{AEP}^{T}) and the ratio (r_{AEP}) (Equation 2). Finally, adjustment factors at each of the extreme rainfall ranks (f_{ex}^{n}) (here '*n*' and '*ex*' represent 'rank' and 'extreme', respectively) is estimated using the function g [Equation 3].

$$r_{AEP} = \frac{IFD_{AEP}^{T}}{IFD_{AEP}^{G}} \qquad [1]$$

$$r_{AEP} = g(IFD_{AEP}^{T}) \qquad [2]$$

$$f_{ex}^{n} = g(R_{ex}^{n}) \qquad [3]$$

Finally, the adjusted annual extreme rainfall at each of the ranks is estimated by multiplying the raw annual maximum rainfall by the correction factors (f_{ex}^{n}) for all the realisations. Figure 2 presents the sequence of processes involved in the estimation of the adjustment factors. Figure 2a illustrates an example of the ratio (r_{AEP}) and the function g fitted between the annual maximum rainfall and r_{AEP} at Alice Spring station. The annual maximum 6 minute rainfall before and after adjustment is shown in Figure 2b. As the adjustment factors are less than one, the overall mean annual maximum 6 minute rainfall reduces from 7.1 mm to 5.5 mm after adjustment. The non-annual maximum rainfall thus needs to be rescaled to preserve the overall mean of the rainfall, as described in section 2.2.

2.2. Non-extreme rainfall adjustment factor (f_{no-ex}^{n})

The ensemble mean of the non-extreme (‘*no-ex’*) rainfall across all realisations for each rank (‘*n’*, sorted from smallest to largest) is denoted by R_{no-ex}^{n} , and the corresponding non-extreme rainfall adjustment factor is denoted by f_{no-ex}^{n}. Equation 4 shows the rainfall mass balance before (left-hand side) and after (right-hand side) adjustment.

$$\sum_{n=1}^{N1} R_{no-ex}^{n} + \sum_{n=N1}^{N2} R_{ex}^{n} = \sum_{n=1}^{N1} (f_{no-ex}^{n} \times R_{no-ex}^{n}) + \sum_{n=N1}^{N2} (f_{ex}^{n} \times R_{ex}^{n}) \qquad [4]$$

where *N1* and *N2* represent the total number of data points of the non-extreme and the total rainfall sequence. In Equation 4, all the variables are known except the non-annual maximum rainfall adjustment factor (f_{no-ex}^{n}), which we need for rescaling the non-annual maximum rainfall.

Estimating f_{no-ex}^{n} analytically is complicated as *N1* is commonly very large. Therefore, we make an assumption that f_{no-ex}^{n} decreases from its maximum (f_{no-ex}^{N1}) to minimum (f_{no-ex}^{1}), linearly. Note that the maximum (f_{no-ex}^{N1}) is the same as the minimum value of the annual maximum rainfall adjustment factor ($i.e., f_{no-ex}^{N1} = f_{ex}^{N1}$). With the linearity assumption, the slope of the non-annual maximum adjustment factor (Δ) can be written as shown in Equation 5. The non-annual maximum adjustment factor at any given rank (n) can thus be expressed according to Equation 6.

$$\Delta = \frac{f_{ex}^{N1} - f_{no-ex}^{1}}{N1} \qquad [5]$$

$$f_{no-ex}^{n} = f_{no-ex}^{1} + (n-1) \times \Delta \qquad [6]$$

In Equation 5, since the largest non-annual maximum adjustment factor (f_{ex}^{N1}) is already known based on the annual maximum rainfall adjustment factor discussed in section 2.1, we only need to estimate the lowest adjustment factor (f_{no-ex}^{1}) in order to determine the slope, Δ. The minimum adjustment factor (f_{no-ex}^{1}) is estimated according to Equations 7 and 8. Equation 7 is obtained by substituting Equation 5 into 6 and some re-organisation. Equation 7 is then substituted into Equation 4 and re-organised to develop an expression for f_{no-ex}^{1} in Equation 8.

$$f_{no-ex}^{n} = f_{no-ex}^{1} \times \left(\frac{N1+1-n}{N1}\right) + f_{ex}^{N1} \times \left(\frac{n-1}{N1}\right) \qquad [7]$$

$$f_{no-ex}^{1} = \frac{\left(\sum_{n=1}^{N1} R_{no-ex}^{n} + \sum_{n=N1}^{N2} R_{ex}^{n}\right) - f_{ex}^{N1} \sum_{n=1}^{N1}\left[\left(\frac{n-1}{N1}\right) \times R_{no-ex}^{n}\right] - \sum_{n=N1}^{N2}\left[f_{ex}^{n} \times R_{ex}^{n}\right]}{\sum_{n=1}^{N1}\left[\left(\frac{N1+1-n}{N1}\right) \times R_{no-ex}^{n}\right]} \qquad [8]$$

Once the minimum adjustment factor (f_{no-ex}^{1}) is estimated from Equation 8, Equations 5 and 6 are used to determine the adjustment factor for non-annual maximum rainfall at each of the ranks (f_{no-ex}^{n}), which is used to adjust the non-annual maximum rainfall (R_{no-ex}^{n}) for all the realisations.

Since there is no restriction on the value of the minimum non-annual maximum adjustment factor (f_{no-ex}^{1}), it could potentially become negative, which leads to negative rainfall. For such cases, the minimum adjustment factor is set to zero and the linearity assumption is modified to the parabolic relationship according to Equation 9.

$$f_{no-ex}^{n} = an^{b} \qquad [9]$$

where *a* and *b* are parameters to be estimated according to the following two conditions (Equations 10 and 11).

$$f_{no-ex}^{n} = f_{ex}^{N1} = aN1^{b} \qquad at\ n = N1 \qquad [10]$$

$$\sum_{n=1}^{N1} R_{no-ex}^{n} + \sum_{n=N1}^{N2} R_{ex}^{n} = \sum_{n=1}^{N1}\left(an^{b} \times R_{no-ex}^{n}\right) + \sum_{n=N1}^{N2}\left(f_{ex}^{n} \times R_{ex}^{n}\right) \qquad [11]$$

The first condition (Equation 10) considers the fact that the maximum adjustment factor of the non-annual maximum rainfall, i.e., when *n* = *N1*, is the same as the minimum value of the annual maximum adjustment factor (f_{ex}^{N1}). Since $f_{ex}^{N1}$is known from section 2.1, parameters *a* and *b* are the two unknowns in the equation. The second condition (Equation 11) is similar to the rainfall mass balance expression (Equation 4) with the non-annual maximum rainfall adjustment factor being replaced by a parabolic relationship. Equation 10 can also be written as shown in Equation 12, which is substituted into 11 resulting in a single unknown parameter *b* that can be estimated through optimisation. After the parameters *a* and *b* are estimated, Equation 9 is used to determine the non-annual maximum rainfall adjustment factors at each of the ranks.

$$a = \frac{f_{ex}^{N1}}{N1^{b}}$$

2.3. Objective function

An objective function is used to evaluate the adjusted rainfall sequences through estimation of bias in the IFD before and after adjustment. We use the relative mean absolute error (RMAE) – a dimensionless standardised error measure – for comparison across durations and exceedance probabilities. The RMAE at each annual exceedance probability (AEP) is estimated as the mean of the absolute difference between the target IFD (IFD_{ARI}^{T}) and generated IFD (IFD_{ARI}^{G}) scaled by the target IFD according to Equation 13.

$$RMAE_{ARI} = \frac{\left|IFD_{ARI}^{T} - IFD_{ARI}^{G}\right|}{IFD_{ARI}^{T}} \qquad [13]$$

2.4. Recursion (*R*) and target duration (*D*)

The rainfall adjustment for preserving the IFD relationship is carried out recursively for a number of selected target durations until the relative mean absolute error (RMAE) is below the required threshold. Figure 2c illustrates the need for correcting biases recursively at different target durations. The figure shows that the RMAE estimates before and after adjustment at 6 minute duration at the Alice Springs station. As expected, the RMAE at 6 minute duration has significantly reduced after the adjustment, although, has increased at other durations. This is mainly because of the dependence of higher duration annual maximum rainfall on the lower ones, i.e., whenever lower duration annual maximum rainfall is altered, the higher duration ones — which are highly dependent on the lower duration — will also be altered. The extent of dependence between higher duration rainfall and lower ones is shown in Figure 2d, which provides the percentage of dependence between higher and lower duration extremes for a number of IFD durations. As shown, the dependence is large when two durations that are close to each other are considered. For example, the dependence of 30 min rainfall on 6 minute is 13 % while the dependence of 3 hrs rainfall on 6 min being 0 %.

Two important observations can be made from the above discussion: (i) It is necessary to adjust rainfall recursively at a number of durations to make sure that the IFD relationships are improved in all the durations; and (ii) The issue of dependence of higher duration rainfall on lower ones can be minimised if target durations are selected carefully. We use a recursion (R) of two in this study. This duration was selected because a preliminary analysis showed that $R = 2$ gives plausible results with a reasonable computational time. With regards to target durations, the following scheme is considered, which minimises the dependence between the different duration. For the first recursion, three target durations, i.e., D = 6 min, 1 hr and 3 hrs are considered, which keeps the timing between the durations far enough to minimise the dependence between them. For the second recursion, two alternative approaches are evaluated. The first approach (alterative-a) uses the same set of target durations (i.e., 6 min, 1 hr and 3 hrs). However, in the second approach (alterative-b), target durations are selected from the six durations (i.e., 6 min, 30 min, 1 hr, 3 hrs, 6 hrs and 12 hrs) based on whether the RMAE is reduced or not during the first recursion while keeping a distance of at least one duration between consecutive durations. These two alternative approaches are evaluated and compared.

3. Data

The analysis involves rainfall data at a 6 min interval based on *Westra et al.* [2012] and *Mehrotra et al.* [2012] as well as observed intensity-frequency relationships at six durations (i.e., 6 min, 30 min, 1 hr, 3 hrs, 6 hrs and 12 hrs). Analysis is carried out at five stations across Australia, i.e., Alice Springs, Sydney, Cairns, Perth and Hobart, which are in different climate conditions. For each of these stations, 10 sample realisations are considered to reduce the computation time. However, the effect of using 10 sample realisations on the results is evaluated using 50 and 100 realisations at Hobart and Alice Springs, respectively.

4. Results and discussion

For the sake of brevity, we discuss detailed results of only one station, Alice Springs. Results from the remaining stations are provided in the supplementary material.

4.1. Rainfall adjustment factors

The estimated adjustment factors for annual maximum rainfall for two recursions and three target durations (based on alternative-a) are presented in Supplementary material (Figure S1). The results suggest that there is no noticeable difference in the estimated adjustment factors between the 10 and 50 realisations in Alice Springs and 10 and 100 realisations in Hobart stations, indicating that the results are not influenced by the number of realisations considered for the analysis.

The adjustment factors generally range between 0.5 and 2.0. The adjustment factors for the non-extreme rainfall are presented in the supplementary material (Figure S2). As the non-extreme rainfall data points are large, the distribution of the adjustment factors are presented rather than the actual values. Similar to the extreme rainfall adjustment factors, no significant difference is observed between 10 and 50 realisations in Alice Springs and 10 and 100 realisations in Hobart, however, considerable difference is found between the two recursions. The main difference is positively skewed distribution of the factors obtained at Alice Springs, Cairns and Hobart stations (Figures S2 (ii), (iv), (vii), (xii)) in the second recursion. This is because the minimum adjustment factor, estimated assuming linearity between the factors (Equation 8), is found to be negative at 6 min in the second recursion. Therefore, it is forced to zero and a parabolic relationship is assumed as described in equations 9-11. This explains the non-uniform distribution of the correction factors at 6 min duration.

4.2. Objective function

The RMAE estimates averaged across all the IFD durations (i.e., 6 min, 30 min, 1 hr, 3 hrs, 6 hrs and 12 hrs) for corrections based on two alternative target durations (alternative-a and -b) and two recursions are summarised in table 1. The minimum RMAE, which indicates the best target duration and recursion, is underlined for each case. The ‘NA’ values in alternative-b indicate that correction is not carried out at that particular duration and recursion as the RMAE is already less than the raw RMAE. The result suggests that the RMAE reduced significantly for the best target duration and recursion compared with the raw estimate with large reduction being observed in Alice Springs and Hobart stations. It was also found that the best duration and recursion is not consistent across the different locations. Comparison of the two alternative approaches for selecting target durations indicate that alternative-b does not improve the bias correction as none of the best durations are found in this approach. Therefore, the rest of the results are discussed focusing on alternative-a of the target durations. With regards to sample size of realisations, the RMAE estimates using 50 and 100 realisations at Alice Springs and Hobart stations, respectively, is found to be consistent with the corresponding RMAE estimates using 10 realisations suggesting that the sample size does not have significant influence on the results.

Detailed results of the RMAE at each of the durations are shown in Figure 3 at Alice Springs with results for the other stations presented in the Supplementary material (Figure S3). The figure demonstrates the evolution of the RMAE for correction at different target durations and recursions. For example, for the first recursion (Figure 3a), correction at 6 min reduces the RMAE from about 0.3 to 0.03. However, the RMAE increases at the other durations (e.g. from 0.18 to 0.37 at 30 min). Continuing corrections at the next durations (i.e., 1 hr and 3 hrs) reduces the RMAE at durations close to 1 hr and 3 hrs while increasing the RMAE at durations far from these. During the second recursion (Figure 3b), correction at 6 min significantly increases the RMAE, even greater than the raw estimate. This is mainly because the correction at the last duration in the previous recursion (i.e., first recursion and 3 hrs duration) has significantly magnified the annual extreme rainfall. Therefore, during the second recursion, the correction factor for the annual maximum rainfall is found to be very small while the correction factor for the non-annual maximum rainfall is large. Hence, the non-annual maximum rainfall values that were close in magnitude to the annual maximum rainfall have now become the new annual maximum rainfall. This led to a much larger bias during the second recursion at 6 min correction. However, with further corrections at 1 hr and 3 hrs, the RMAE drops below the raw RMAE in almost all the durations with the best recursion and duration being observed at the second recursion and 1 hr duration. Finally, the RMAE estimates of the 10 and 50 realizations are found to be consistent for both recursions (Figure 3, first and second row), further confirming that the analysis is not significantly influenced by the selection of the number of realisations.

4.3. Intensity frequency duration (IFD) relationships

The IFD estimates before and after rainfall adjustment for the best (second) recursion and target (1 hr) duration at Alice Springs station is presented in Figure 4. IFD estimates for the best recursion and duration for the other stations are presented in the supplementary material (Figure S4). For Alice Springs, the adjusted IFD reproduces the target IFD reasonably well in all the durations with the exception of some bias at lower exceedance probabilities for the 6 min duration (Figure 4a).

Significant improvement in reproducing the target IFD is also observed in the other four stations. In Sydney, significant improvement is observed in the 30 min and 1 hr durations; however, there some worsening is apparent for longer durations (i.e., 6 and 12 hrs), particularly at lower exceedance probabilities. In Cairns, significant improvement is obtained in almost all the cases, except for a slight worsening at the 6 min duration. In Perth, improvement is observed in almost all the durations with few exceptions in the 6 minute and 6 hrs durations. In Hobart, significant improvement is observed in all the durations and the large biases that exist at the lower exceedance probabilities are also completely removed.

Overall, the continuous rainfall sequences adjustment approach developed in this report is found to significantly reduce the biases in the IFD estimates at multiple durations and locations, with the exception of a few durations. This could be due to the dependence of higher duration extreme rainfall on the lower duration extreme (Figure 2d). Although target durations are carefully selected to minimise this dependence, it is impossible to completely eliminate the dependence.

5. Conclusion

Stochastically generated continuous rainfall can be used for a range of hydrological and water resources applications, such as planning, design and management of urban water systems and estimation of floods. However, reproducing important attributes of the observed rainfall for hydrological applications, such as rainfall variability, extreme rainfall amount and antecedent conditions prior to the extremes, remains to be a challenge. This report presents an approach to constrain stochastically generated rainfall with an objective of preserving the observed intensity-frequency-distribution (IFD) relationships. Adjustment factors for annual maximum and non-annual maximum rainfall are recursively estimated until bias in the IFD relationships is reduced below a pre-defined objective. The proposed approach is tested at five stations across Australia (i.e., Alice Springs, Sydney, Cairns, Perth and Hobart).

It is found that the method significantly reduces biases in IFD relationships in all the stations with better results obtained for Alice Springs and Hobart. A sensitivity analysis using 10 and 50 realisations at Alice Springs as well as 10 and 100 realisations at Hobart stations suggests that the results are not significantly affected by the number of realisations.

The main challenge in the development of the bias correction approach is the dependence of higher duration annual maximum rainfall on the lower ones as correction at higher duration disturbs the already corrected annual maxima at lower durations. Although target durations are carefully selected to minimise the dependence, it cannot be eliminated. Finally, the proposed method effectively adjusts the IFD relationships of stochastically generated rainfall and can also be easily extended to adjust any other attributes of the generated rainfall allowing its application for post-processing of stochastic model outputs.

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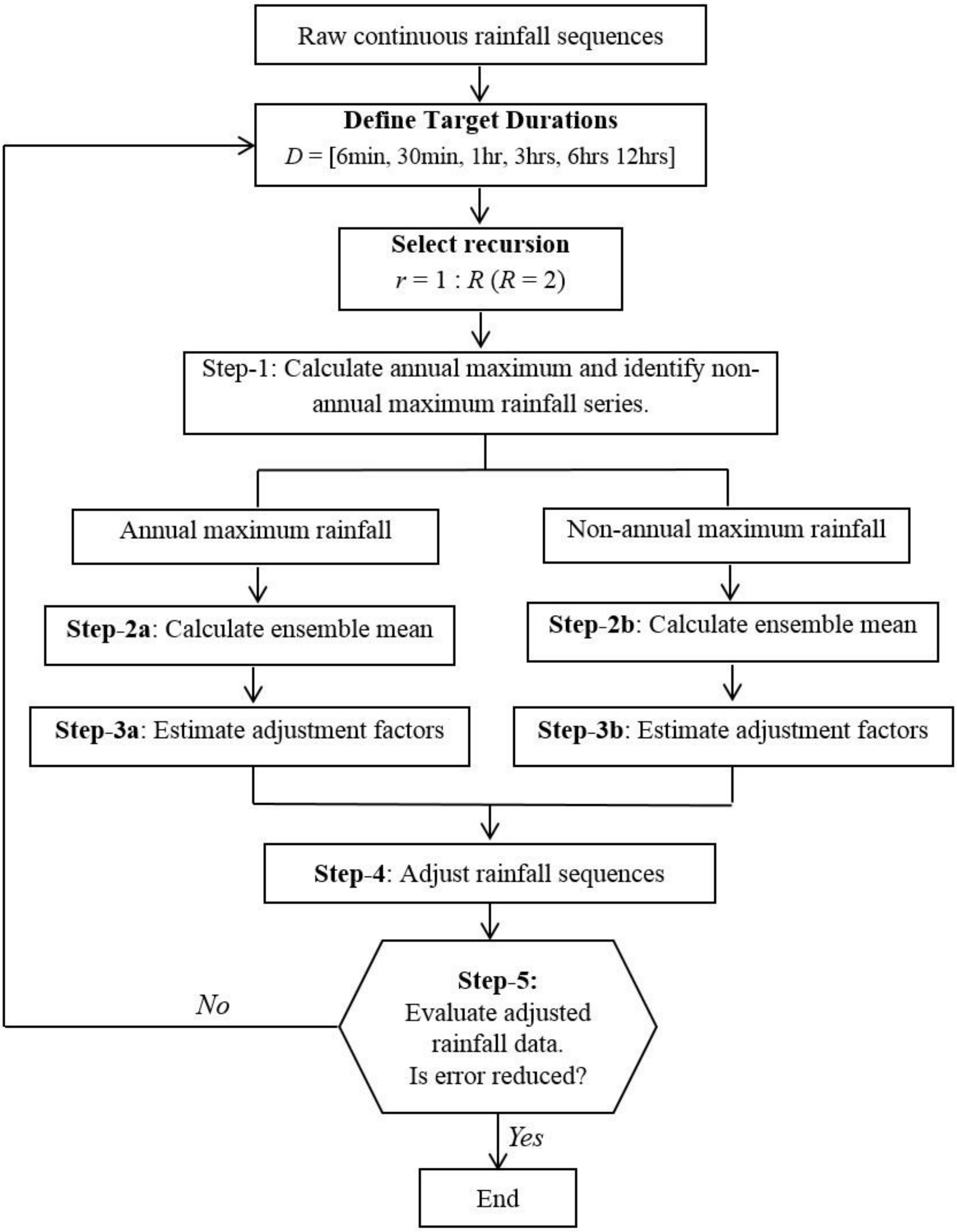
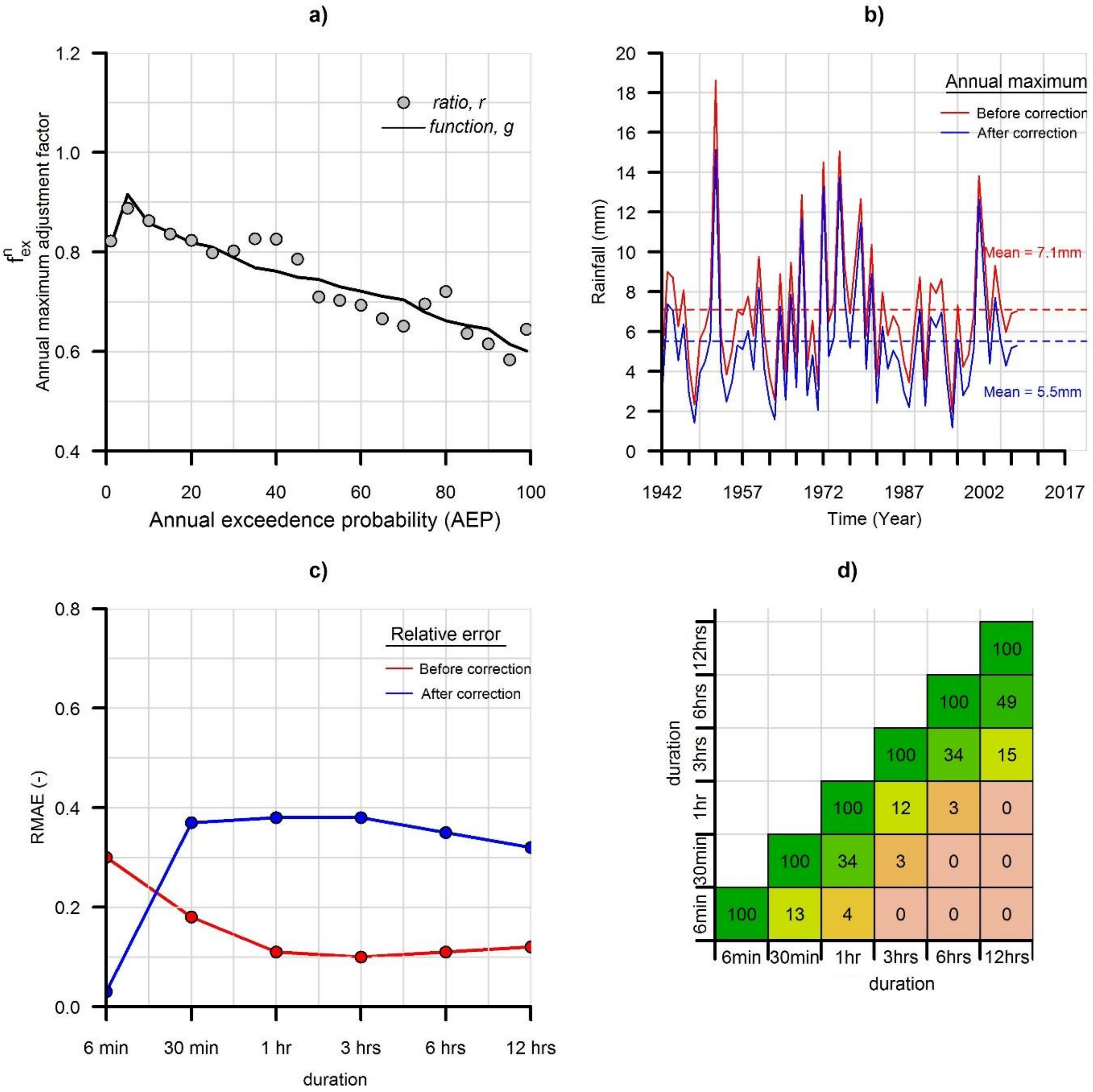


Figure 1: Overview of our workflow illustrating the main steps involved in the adjustment of raw continuous rainfall sequences to preserve the intensity-frequency-duration (IFD) relationships.



duration	6min	30min	1hr	3hrs	6hrs	12hrs
12hrs						100
6hrs					100	49
3hrs				100	34	15
1hr			100	12	3	0
30min		100	34	3	0	0
6min	100	13	4	0	0	0

Figure 2: Method to constrain continuous rainfall: (a) annual maximum adjustment factors; (b) annual maximum rainfall for 6 minute rainfall; (c) relative error after a single recursion; and (d) percentage of dependence of higher duration annual maximum rainfall on lower duration.

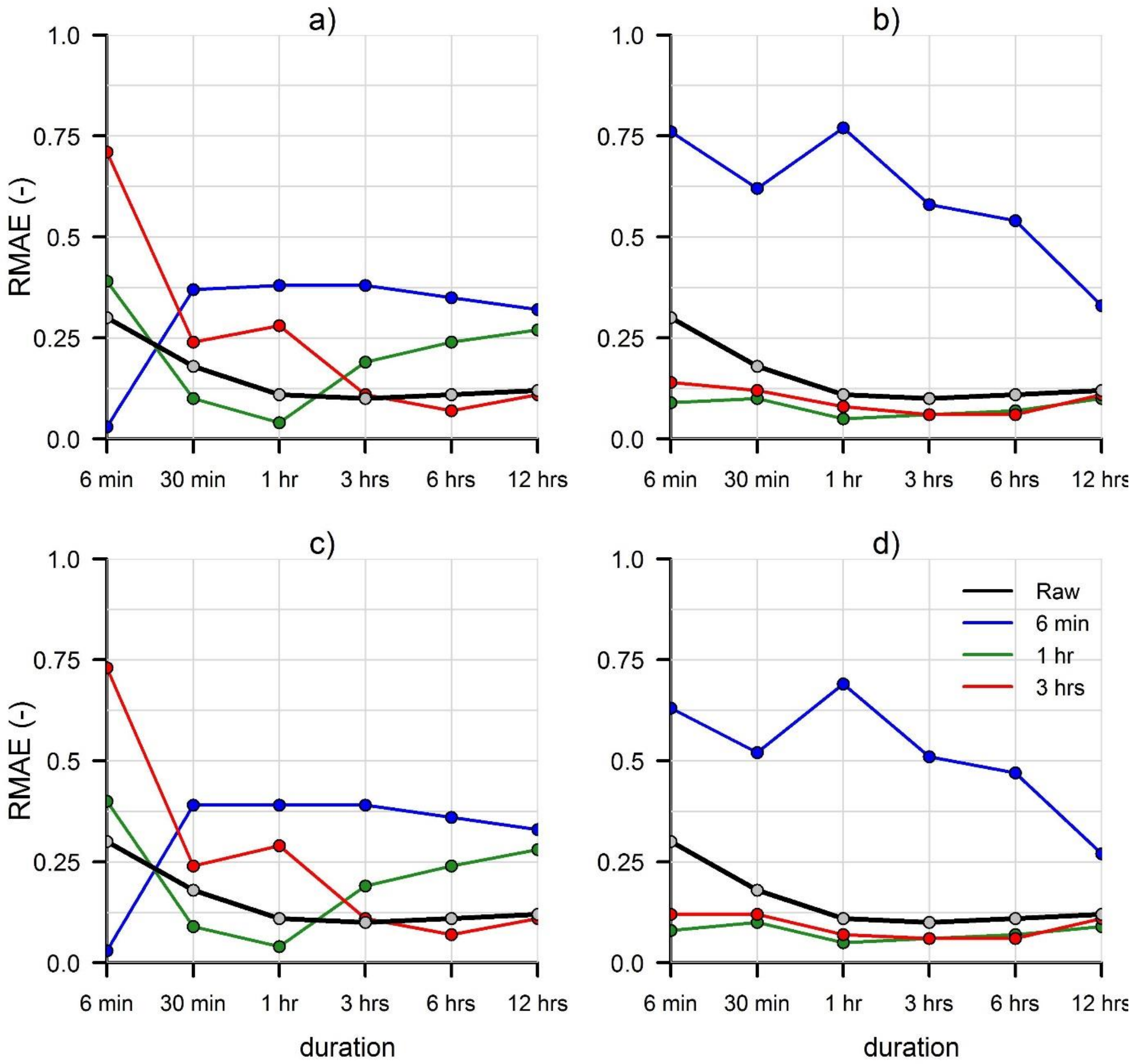


Figure 3: Relative mean absolute error (RMAE) at the Alice Springs station for raw and bias corrected data for three target durations (6min, 1 hr and 6 hrs): (a) recursion 1 and 10 realisations; (b) recursion 2 and 10 realisations; (c) recursion 1 and 50 realisations; and (d) recursion 2 and 50 realisations. RMAE estimates for Sydney, Cairns, Perth and Hobart stations are presented in the Supplementary material S3.

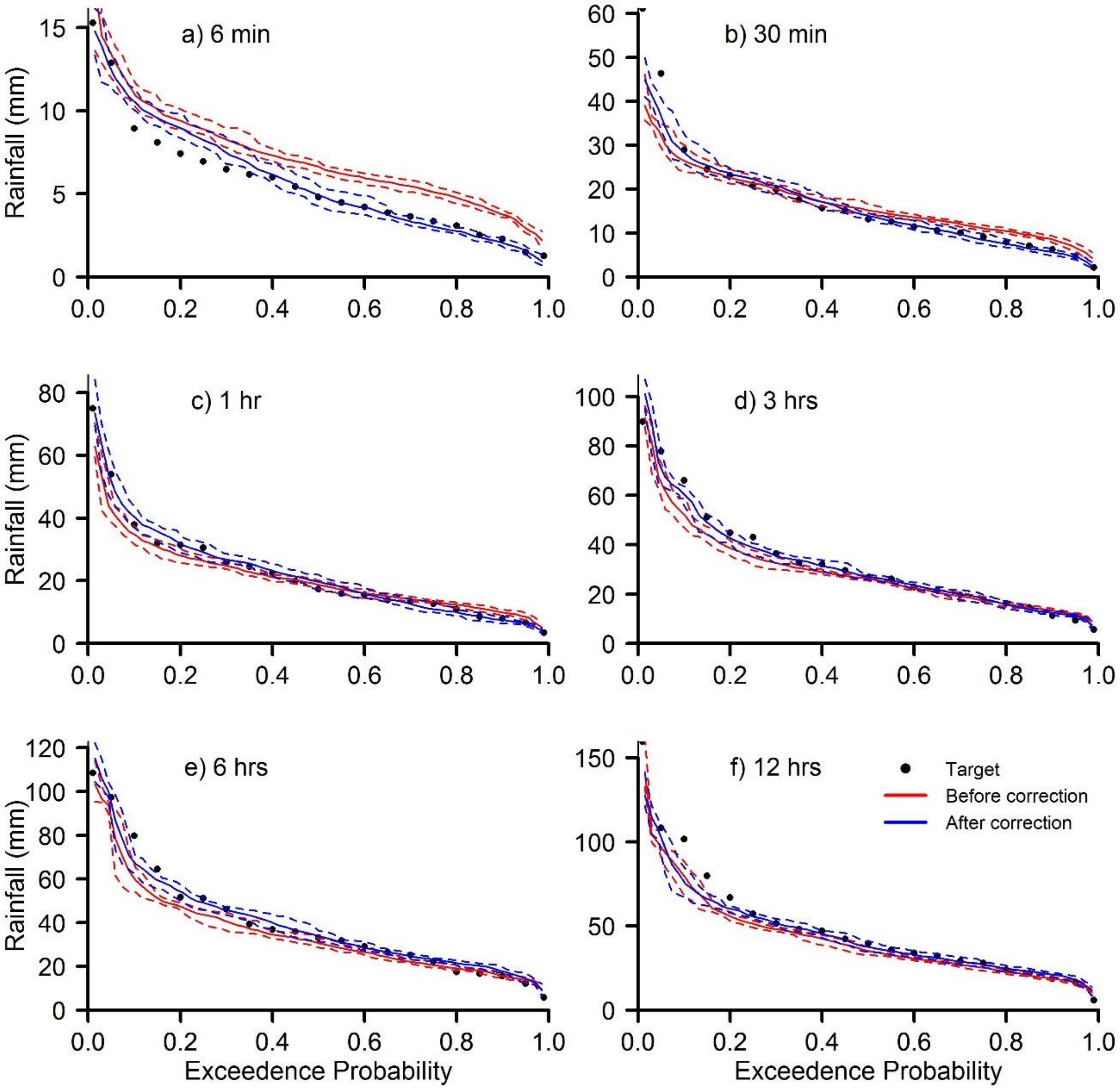


Figure 4: Intensity-duration-frequency (IFD) relationships for target and simulated rainfall before and after bias correction for the best recursion and duration (second recursion and 1 hr duration) at the Alice Springs station using 10 realisations. The broken lines (red and blue) indicate the 5 and 95 percentiles for raw and bias corrected data, respectively. IFD relationships for Sydney, Cairns, Perth and Hobart stations are presented in the Supplementary material S4.

Table 1: Root mean absolute error (RMAE) for two recursions and two approaches of target durations. The lowest RMAE value is underlined in each case.

Station/ Target Duration		**Alice Springs**	**Sydney**	**Cairns**	**Hobart**	**Perth**	**Alice Springs (50 realis.)**	**Hobart (100 realis.)**
	raw	0.15	0.19	0.1	0.28	0.12	0.15	0.27
Recursion-1	6min	0.31	*0.13*	*0.06*	0.29	0.11	0.32	0.28
	60min	0.21	0.18	0.19	0.23	0.11	0.21	0.22
	360min	0.25	0.20	0.25	0.29	0.10	0.26	0.25
Recursion-2 (approach-a)	6min	0.6	0.42	0.07	0.35	0.09	0.52	0.38
	60min	*0.08*	0.19	0.07	*0.13*	0.09	*0.08*	*0.14*
	360min	0.1	0.22	0.14	0.19	*0.08*	0.09	0.18
Recursion-2 (approach-b)	30 min	0.17	0.16	0.07	0.35	0.16		
	180min	0.17	NA	0.07	0.13	0.11		
	720min	NA	NA	NA	NA	NA		