­A hydrological calibration procedure for stochastic rainfall model

# Abstract

# Introduction

Stochastic rainfall modelling involves the generation of sequences of rainfall at a scale of interest (e.g., sub-daily, daily, monthly, annual, multi-annual) that is statistically similar to observed rainfall timeseries, typically measured at rain gauges. Simulated rainfall is a primary input to hydrological model, for simulating streamflow. The simulated streamflow is then used to assess risks such as floods and droughts. Stochastic rainfall models (SRMs) are commonly fitted to observed rainfall data. However, when simulated rainfall data are used as input for hydrological models, it is possible that the simulated rainfall will not be translated to realisations of streamflow that is statistically similar to the observed one due to, for example, limited understanding of the rainfall-runoff process or the incapability of SRMs to capture important rainfall attributes. This paper introduces a new hydrological calibration procedure that allows SRMs to help capture streamflow statistics that cannot be achieved with common calibration approach (fitting with observed rainfall statistics) when SRMs are used to generate rainfall input for continuous hydrological simulation.

In catchment hydrology, the term continuous simulation is the simulation of the wet and dry condition of a catchment by estimating the loss in rainfall and generating streamflow at daily, hourly, or sub-hourly time scales. Generally, the process of continuous simulation requires a rainfall-runoff model with sequences of meteorological inputs such as rainfall, evapotranspiration or temperature depending on the specification of the model ([Beven, 2012](#_ENREF_8)). Continuous simulation for catchment process has an advantage to the popular event-based approach by eliminating the assumptions of initial and continuing losses. Continuous simulation also allows the generation of long sequences of streamflow from which important flood or drought statistics can be extracted for the establishment of appropriate mitigation strategies, early warning, or long-term projection ([Linsley and Crawford, 1974](#_ENREF_26); [Adams and Howard, 1986](#_ENREF_1); [Boughton and Hill, 1997](#_ENREF_11); [Arnaud and Lavabre, 2002](#_ENREF_3); [Blazkova and Beven, 2002](#_ENREF_9); [Lamb, 2005](#_ENREF_24); [Viviroli et al., 2009](#_ENREF_39); [Berk et al., 2017](#_ENREF_7); [Rowe and Smithers, 2018](#_ENREF_33)).

The type of rainfall-runoff model component is selected depending on different purposes of the hydrological assessment. Based on the spatial resolution, for example, rainfall runoff models can be categorised into lumped, semi-distributed and distributed models. There have been a numerous developments and reviews of lumped rainfall runoff models ([Burnash et al., 1973](#_ENREF_12); [Perrin et al., 2003](#_ENREF_29); [Boughton, 2004](#_ENREF_10); [Croke et al., 2006](#_ENREF_16); [Chiew, 2010](#_ENREF_13)) as well as semi-distributed and distributed rainfall-runoff model [ref]([Knightes, 2017](#_ENREF_23)). Different rainfall-runoff models have their own strengths and weaknesses, however by definition, they are all simplifications of the catchment characteristics and processes such as soil properties, topography, vegetation, water and energy balance ([Beven, 2012](#_ENREF_8); [Gupta et al., 2005](#_ENREF_20)). Overlooking the assumptions accompanied with rainfall-runoff models could hamper the performance of continuous simulation.

In terms of rainfall time series, a primary input to rainfall-runoff model, can be (1) the observed rainfall data collected at a rain-gauge or a network of rain-gauges or (2) generated from a rainfall model. There has been a substantial amount of study on rainfall model development to capture both the temporal pattern including daily ([Richardson and Wright, 1984](#_ENREF_32); [Semenov and Barrow, 1997](#_ENREF_34); [Sharma and Lall, 1999](#_ENREF_35); [Srikanthan and McMahon, 2001](#_ENREF_36)), sub-daily ([Gupta and Waymire, 1993](#_ENREF_21); [Khaliq and Cunnane, 1996](#_ENREF_22); [Cowpertwait, 2006](#_ENREF_14)), year to year variation ([Thyer and Kuzera, 1999](#_ENREF_38); [Srikanthan and Pegram, 2009](#_ENREF_37)), as well as the spatial pattern ([Wilks, 1998](#_ENREF_40); [Qian et al., 2002](#_ENREF_30); [Leonard et al., 2008](#_ENREF_25); [Rasmussen, 2013](#_ENREF_31); [Baxevani and Lennartsson, 2015](#_ENREF_4); [Bennett et al., 2018](#_ENREF_5); [Evin et al., 2018](#_ENREF_17)) of the observed rainfall. However, one of many challenges to the continuous simulation approach is to assess the impact of uncertainties in rainfall data on rainfall-runoff models response. Poor understanding of the effect of rainfall variability or uncertainties in rainfall data on the output of rainfall-runoff models will hamper the capability of continuous simulation in providing reliable hydrological assessment ([Michaud and Sorooshian, 1994](#_ENREF_27); [Faurès et al., 1995](#_ENREF_18); [Andréassian et al., 2001](#_ENREF_2); [Cristiano et al., 2017](#_ENREF_15)). The sensitivity of rainfall-runoff models to the spatial variability of rainfall input has become an attention to researchers. [Wilson et al. (1979)](#_ENREF_41) found that poor spatial representation of rainfall input causes significant errors to the estimated hydrograph through an experiment on a small-sized catchment (68.6 km2). Similarly, [Michaud and Sorooshian (1994)](#_ENREF_27) examined the effect of rainfall sampling errors on peak-flow estimations on a 150 km2 semi-arid catchment and concluded that poor spatial representation of rainfall (inadequate rain-gauges network in point sampling) accounts for 58% underestimation in observed peak-flow. However, [Nicótina et al. (2008)](#_ENREF_28) pointed out mixed conclusions in the effect of rainfall spatial variability on rainfall-runoff models response from multiple mesoscale catchments, where some catchments tend to dampen the effect of spatial distributions while others tend to amplify it and concluded that the sensitivity of runoff response to the spatial distribution of rainfall is also affected by catchment characteristics such as hillslope and routing time distribution.

Sources of simulated streamflow deficiencies have also been reported to be caused by the deficiencies of simulated rainfall in different time periods. In particular, poor simulated streamflow within a month could be the result of rainfall deficiencies in the concurrent month, the preceding month, or a contiguous block of month ([Bennett et al., 2019](#_ENREF_6)). It was also found that in some cases, “good” simulated rainfall can create “poor” streamflow estimations while “poor” simulated rainfall can create “good” streamflow estimations ([Bennett et al., 2019](#_ENREF_6)). The case of “good” rainfall - “poor” streamflow has also been reported in ([Gao et al., 2020](#_ENREF_19)), in which a single site SRM was developed and was shown to capture well a range of rainfall statistics including the wet and dry spell distributions, the lower and the upper tails. However, when the model is used to generate rainfall input for a rainfall-runoff model, the streamflow estimation was shown to have relatively large underestimation in the high flow ranges (from the 90th to the 99th percentiles, with increasing magnitude of underestimation). It is evident that a SRM should not only be able to preserve observed rainfall attributes but also be able to capture observed streamflow characteristics for practical hydrological application. Hitherto, studies on SRMs development generally considered observed rainfall statistics as benchmarks without any consideration on streamflow statistics. Hence, the aim of this paper is to develop a new approach to SRMs development that considers both rainfall and streamflow statistics.

The three key objectives of this paper are:

1. Present the hydrological calibration procedure for SRMs.
2. Demonstrate scenarios where simulated rainfall categorised as “good” translated to simulated runoff categorised as “bad”. A range of catchments within Australia are examined with the use of a SRM and lumped conceptual rainfall runoff model.
3. Disccuss on the improvements that the hydrological calibration procedure provided to the SRM through examining different rainfall and runoff statistics.

This paper is structured as follows. Sect. 2 introduces the hydrological calibration procedure for SRMs. Sect. 3 presents the case studies that are used to demonstrate the hydrological calibration procedure. Results, discussion, and conclusion are in sect. 4, sect. 5, sect. 6 respectively.

# Hydrological calibration of SRMs

## Overview

A typical calibration procedure for SRMs involves computing some observed rainfall statistics which are then used as model parameter to generate simulated rainfall. Fig. 1 illustrates the general process of SRMs development.

Diagram

Description automatically generated

Figure 1. Schematic of SRMs development with observed rainfall data.

For example, the popular WGEN models ([Richardson and Wright, 1984](#_ENREF_32)) has a daily rainfall generator component that requires 4 rainfall statistics: the probability of dry-wet event (PDW), the probability of wet-wet event (PWW), the shape (α) and rate (β) parameters of the gamma distribution. The first two probabilistic parameters PDW and PWW control the wet/dry pattern of the rainfall using a 1st order Markov chain while parameters α and β controls the amount of rainfall occurs on wet days. These parameters can be computed directly from the observed rainfall and used for simulating rainfall estimates.

Calibrating with observed rainfall data allows SRMs to preserve the observed rainfall statistics. The simulated rainfall time series can be used as input for hydrological models to produce streamflow time series for hydrological assessment. However, it is not necessarily given that simulated rainfall time series will translate to streamflow time series that preserve the properties of observed streamflow data.

Therefore, another approach to SRMs development is to calibrate model parameters with streamflow statistics. Fig. 2 illustrates a schematic of the hydrological calibration procedure for stochastic rainfall models. [culley]

Diagram

Description automatically generated

Figure 2. Schematic of the hydrological calibration for SRMs with observed runoff

In comparison to the typical procedure of SRMs development, the hydrological calibration of SRMs requires an additional rainfall-runoff model component to simulate runoff estimates and observed streamflow data. The proposed steps for the hydrological calibration procedure are as follows.

1. Generating a sequence of simulated rainfall from the SRM with a pre-defined set of parameters.
2. Generating a sequence of simulated runoff using the rainfall runoff model with the simulated rainfall as input.
3. Computing a pair of statistics from the simulated runoff and the observed runoff (e.g., the flow duration curve).
4. Constructing an objective function with the simulated and observed runoff statistics (e.g., the sum of squared errors)
5. Finding the SRM parameters set that optimizes the objective function.

Diagram

Description automatically generated

Figure 3. Schematic of the hydrological calibration for SRMs with virtual observed runoff.

## Step 1 – rainfall simulation

**Estimating stochastic rainfall model and rainfall-runoff model parameters**:

The occurrence parameters PDW and P­WW are computed using the following equations:

Where nDW is the number of wet days given a dry occurred previously, nDD is the number of dry days given a dry day occurred previously, nWW is the number of wet days given a wet day occurred previously and nWD is the number of dry days given a wet day previously.

The parameters α and β is computed by assuming the amount of rainfall on wet days has a gamma distribution. Then the parameters can be estimated using the maximum likelihood (MLE) approach or simply using the method of moment (MoM).

After obtaining the required parameter on a monthly basis (i.e., 4 parameters for each of the 12 month) sequences of daily rainfall can be simulated. The complete procedure are provided in ([Richardson and Wright, 1984](#_ENREF_32)).

To initiate the experiment, the stochastic rainfall model will be calibrated with at-site observed rainfall data; while the rainfall-runoff model will be calibrated with at-site observed runoff data. This procedure will allow the stochastic rainfall model to simulate rainfall data that are similar to the condition at the site which could avoid potential divergence to the hydrological calibration procedure at later stages. While the set of parameters for the rainfall-runoff model will be fixed throughout the process after they are calibrated and evaluated with the observed runoff.

## Step 2 – streamflow simulation

**Simulating streamflow with simulated rainfall input:** the sequences of simulated rainfall will be used as input to the (already calibrated) rainfall-runoff model to generate sequences of simulated streamflow. Note that a separate aim will investigate the influence of the hydrological model on the overall method.

**Simulating virtual-observed streamflow with observed rainfall input**: A sequence of observed rainfall data will be used as input to the same rainfall-runoff model to generate a sequence of virtual-observed streamflow. This approach removes the possibility of errors from observed streamflow influencing the comparison

## Step 3 – objective function

Sum of square errors

Relative errors

## Step 4 – optimization

**Comparing simulated streamflow and virtual-observed streamflow**: The flow duration curve (FDC) will be the subject of the comparison. The FDC is computed from the streamflow sequences produced in the previous stage. The simulated FDC and the virtual observed FDC will be compared against each other forming an objective function using the sum of squares error (SSE) metric. The value of the objective function will be used to inform the calibration of the stochastic rainfall model parameters (i.e. minimizing the SSE by changing stochastic rainfall model parameters).

**Evaluating stochastic rainfall model performance**: To ensure the performance of the stochastic rainfall model in simulating rainfall input that preserves streamflow characteristics, the model will be verified with a virtual-observed FDC at a different time period (split-sample validation)

# Case study

# Results

# Discussion

* Rainfall attributes

# Limitations and opportunities

* Rainfall runoff models
* Objective function
* Feasibility – runtime
* Other Rainfall model (extend WGEN to capture seasonal pattern - harmonic function)

# Conclusions

* Limitation and future opportunities

*Data availability.* All the data used in this study can be requested by contacting the corresponding author Thien Nguyen at truonghuythien.nguyen@adelaide.edu.au.

*Author contributions.*

*Competing interest.* The authors declare that they have no conflict of interest.

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