Development and Evaluation of Stochastic Rainfall Models for Urban Drought Security Assessment

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Professor Garry Willgoose

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List of Symbols and Notations

The following is a description of the symbols and notation commonly used in this thesis.

Symbol	Description	Unit
$P_{00,i}$	Probability of dry-to-dry day for month *i,* for January, *i* = 1	–
$P_{11,i}$	Probability of wet-to-wet day for month *i*	–
μ_i	Mean of wet day rainfall depths for month *i*	mm
σ_i	Standard deviation of wet day rainfall depths for month *i*	mm
$r_{c,i}$	Coefficient of correlation between log μ_i and log σ_i values for month *i*	–
$\lambda_{\mu,i}$	Mean of log μ_i values for month *i*	mm
$\zeta_{\mu,i}$	Standard deviation of log μ_i values for month *i*	mm
$\lambda_{\sigma,i}$	Mean of log σ_i values for month *i*	mm
$\zeta_{\sigma,i}$	Standard deviation of log σ_i values for month *i*	mm
E	Elevation	m
r_0	Coefficient of correlation between Elevation and Parameters of MC model	–
r_{ts}	Coefficient of correlation between rainfall timeseries in pairs of pixels	–
Z	Z score	–

Abbreviations

The following abbreviations are commonly used in this thesis:

BoM	Bureau of Meteorology
NARCliM	NSW/ACT Regional Climate Modelling
RCM	Regional Climate Model
AWAP	Australian Water Availability Project
ECL	East Coast Low
MC	Markov Chain
APMC	Average Parameter Markov Chain
DPMC	Decadal Parameter Markov Chain
CDMC	Compound Distribution Markov Chain
HMC	Hierarchical Markov Chain
DHMC	Decadal and Hierarchical Markov Chain
MMKD	Modified Markov Kernel Density

Abstract

The key objective of this study is to develop a stochastic daily rainfall model, which can be used in streamflow and reservoir water simulation for urban drought security assessment. After critically reviewing the existing rainfall simulation techniques, this study has developed a Markov Chain (MC) model for stochastic generation of daily rainfall. The MC model uses a two-state MC process with two parameters (wet-to-wet and dry-to-dry transition probabilities) to simulate rainfall occurrence and a Gamma distribution with two parameters (mean and standard deviation of wet day rainfall) to simulate wet day rainfall depths. One of the major focuses of the study is to evaluate the ability of the stochastic model to preserve the rainfall variability and autocorrelation at daily, monthly and multiyear resolutions. Preserving monthly to multiyear variabilities in a daily rainfall model is always challenging, while those longer-term variabilities are critically important for the drought security analysis of reservoirs as the reservoir water levels usually vary in monthly to multiyear resolutions. The traditional models usually underestimate the monthly to multiyear variability, which results in the overestimation of reservoir reliability. On the other hand, the daily variability is also important in many parts of the world to take the influence of short-term extreme rainfall events into account (e.g. East Coast Lows in eastern Australia, which may occur for a few days or weeks, but substantially contribute to the reservoir water level).

Five variants of the MC model with different parameterisation techniques have been tested in this study. The first model, referred to as the Average Parameter Markov Chain (APMC) model, uses deterministic parameters of MC and Gamma distribution, that is, the same parameter set is used to simulate the rainfall in all years. The second model, referred to as the Decadal Parameter Markov Chain (DPMC) model, also uses deterministic parameters of MC and Gamma distribution, but the parameters vary for each decade. The third model, referred to as the Compound Distribution Markov Chain (CDMC) model, uses deterministic parameters of MC (same as APMC) and stochastic parameters of the Gamma distribution by sampling the mean and standard deviation of wet day rainfall depths from fitted distributions for each month. The fourth model, referred to as the Hierarchical Markov Chain (HMC) model, uses stochastic parameters of both MC, by sampling wet-to-wet and dry-to-dry transition probabilities from fitted distributions, and Gamma distribution (same as CDMC). The fifth and final model, referred to as the Decadal and Hierarchical Markov Chain (DHMC) model, uses decade-varied parameters of MC (same as DPMC) and stochastic parameters of Gamma distribution (same as CDMC).

To calibrate the model parameters and compare their performance, this study has used dynamically downscaled rainfall data produced by the NSW/ACT Regional Climate Modelling (NARCliM) project (reanalysis data for three Regional Climate Models (RCMs)), gridded data by the Australian Water Availability Project (AWAP), and ground-based data of raingauge stations. The MC models have been assessed in five catchments of coastal NSW – (i) Goulburn River site (ii) Williams River site (iii) Sydney site (iv) Richmond River site and (v) Bega River site using the NARCliM and AWAP datasets. In addition, raingauge data for 12 raingauge stations around Australia and 30 stations around Sydney have been used to compare the MC models with an existing model. To compare the model performance for streamflow generation, this study has used area-averaged rainfall data of NARCliM and AWAP in a SimHyd hydrology model for three sub-catchments of the Williams River site (i.e. Hunter Water System).

The APMC satisfactorily reproduces the variability of rainfall depths and wet periods at daily resolution only, and significantly underestimates the variability at monthly to multiyear resolutions. The DPMC also significantly underestimates the variability of rainfall depths at monthly to multiyear resolutions, but mostly preserves the variability of wet periods at monthly to multiyear resolutions. The CDMC satisfactorily reproduces the variability of rainfall depth at daily to multiyear resolutions, but significantly underestimates the variability of wet periods at multiyear resolution. The performance of CDMC for wet period variability is consistent with the respective performance of APMC, as both models use the same deterministic parameters of the MC process. The HMC also satisfactorily reproduces the variability of rainfall depths at daily to multiyear resolutions, which is consistent with CDMC as both models use the same stochastic parameters of Gamma distribution. However, the HMC can preserve the variability of wet periods at multiyear resolutions, but significantly overestimates the variability of wet periods at monthly resolution. The DHMC performs better than the other four models, and satisfactorily reproduces the variability of rainfall depths and wet periods at all resolutions, although it significantly underestimates the variability of wet days at shorter multiyear resolutions. For mean of rainfall depths and wet periods, all five MC models perform satisfactorily, although the CDMC, HMC and DHMC show a slight tendency to underestimate the mean of rainfall depths, particularly at multiyear resolutions. For month-to-month autocorrelations of monthly rainfall depths and monthly wet days, all five models perform satisfactorily, except the HMC shows a tendency to underestimate the autocorrelations. The above results suggest the following conclusions:

- The models with deterministic parameters of Gamma distribution (e.g. APMC and DPMC) cannot reproduce the monthly to multiyear variability of rainfall depths. Stochastic parameters of Gamma distribution (e.g. CDMC, HMC and DHMC) are useful for satisfactorily reproducing the short and long-term variability of rainfall depths.
- Deterministic parameters of MC (e.g. APMC and CDMC) underestimate the multiyear variability of wet periods, while stochastic parameters of MC (e.g. HMC) overestimate the monthly variability of wet periods. Decadally varied parameters of MC (e.g. DPMC and DHMC) are better to satisfactorily reproduce the variability of wet periods at monthly to multiyear resolutions.
- The stochastic parameters of Gamma distribution (e.g. CDMC, HMC and DHMC) yield a slight underestimation of mean rainfall depths.
- The MC models are adequate to reproduce the autocorrelations of monthly rainfall depths and monthly wet days. The underestimation of the autocorrelations in HMC might be linked with the overestimation of wet period variability.

This study has compared the performance of CDMC, HMC and DHMC with an existing Modified Markov Kernel Density (MMKD) model by Mehrotra and Sharma [2007]. The MMKD uses a modified MC process with memory of past periods to simulate rainfall occurrence and resamples rainfall depths for wet days from observed records using a kernel-density estimation. The MC models are methodologically simple and straightforward in comparison with the relative complexity of the MMKD. Despite the methodological simplicity, the DHMC shows comparable satisfactory performance as MMKD to reproduce the distribution and autocorrelations of rainfall depths and wet periods at daily to multiyear resolutions. The other two MC models, CDMC and HMC, also show comparable performance to reproduce the distribution of rainfall depths at all resolutions, but fail to preserve the distribution of wet periods at all resolutions. However, MMKD tends to overestimate the mean of rainfall depths at all resolutions, which might be caused by the resampling of wet day rainfall depths using kernel-density estimation.

The performance of CDMC, HMC, DHMC and MMKD have also been compared for streamflow generation. The performance of each model for streamflow generation is consistent with their respective performance for the rainfall depths. The MC models perform similarly and slightly better than the MMKD to reproduce the distribution and autocorrelation of streamflow volume.