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Research papers

Short time step continuous rainfall modeling and simulation of extreme events

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ABSTRACT

The design, planning, operation and overall assessment of urban drainage systems require long and continuous rain series in a high temporal resolution. Unfortunately, the availability of this data is usually short. Nevertheless a precipitation model could be used to tackle this shortcoming; therefore it is in the aim of this study to present a stochastic point precipitation model to reproduce average rainfall event properties along with extreme values. For this purpose a model is proposed to generate long synthetic series of rainfall for a temporal resolution of 5 min. It is based on an alternating renewal framework and events are characterized by variables describing durations, amounts and peaks.

A group of 24 stations located in the north of Germany is used to set up and test the model. The adequate modeling of joint behaviour of rainfall amount and duration is found to be essential for reproducing the observed properties, especially for the extreme events. Copulas are advantageous tools for modeling these variables jointly; however caution must be taken in the selection of the proper copula. The inclusion of seasonality and small events is as well tested and found to be useful. The model is directly validated by generating long synthetic time series and comparing them with observed ones. An indirect validation is as well performed based on a fictional urban hydrological system. The proposed model is capable of reproducing seasonal behaviour and main characteristics of the rainfall events including extremes along with urban flooding and overflow behaviour. Overall the performance of the model is acceptable compared to the design practice. The proposed model is simple to interpret, fast to implement and to transfer to other regions, whilst showing acceptable results.

1. Introduction

Stochastic modeling of precipitation consists of conceptually representing the natural process through some mathematical relationships to generate synthetic series for different purposes, e.g. planning and design, deriving long extended time series or regionalization of rainfall to areas without measurements. Among the existing models, the following can be mentioned: Markovian process-based (e.g. Markov chains), data driven generators (e.g. resampling and disaggregation), and event based methods such as point and cluster process-based (e.g. Neyman-Scott, Barlett-Lewis) or alternating-renewal models. The spatio-temporal scale of the precipitation model is determined by the hydrological application and becomes more challenging for high temporal resolutions, which is required for urban applications. For sub-daily resolution the complexity of some models increases, as is the case of chain dependent processes which result in more parameters (see Verhoest et al., 1997), and their performance declines as a result of the difficulty to reproduce historical properties. Thus many investigations focus on the generation of daily precipitation time series, whereas models for hourly or sub-hourly time series are less frequent.

Nevertheless clear progress has been made with the aim of improving existing models for high temporal applications. A brief review of some of them is presented here, with a special focus on their performance regarding extreme events. Some examples of data driven models were developed by Bárdossy (1998), Licznar et al. (2011) and Beck (2013). Results show either overestimation or underestimation especially for very extreme events. Several works explore the capability of modified versions of Barlett-Lewis (BL) model to reproduce high resolution precipitation, see e.g. Rodriguez-Iturbe et al. (1988), Verhoest et al. (1997), Cowpertwait et al. (2007), Vandenberghe et al. (2011), Pham et al. (2013), Kaczmarska et al. (2014), Vernieuwe et al. (2015). Some of these models show to underestimate the number of extreme events and annual maxima for short durations, in some cases the over-clustering of events fails to preserve the extreme

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characteristics. Unfortunately none is able to reproduce the extreme value behaviour of rainfall for short durations. Models based on Alternating Renewal processes can be found in Bernardara et al. (2007), Haberlandt et al. (2008) and Haberlandt and Radtke (2014). Results show overestimation of extreme events that cause overestimation of maximum annual flows according to the runoff modeling included in the last work. Other event based models are proposed by Gyasi-Agyei and Charles (2012), Vernieuwe et al. (2015) and Zhang and Switzer (2007). In the two first works the extreme values are over- and underestimated for short and long durations. The third work shows acceptable modeling of maximum intensities; however this model needs to be further combined with a frequency model to simulate continuous rainfall series.

The performance of event based models depends on the proper modeling of the event characteristics. Several studies state the fact that as these characteristics are generated by the same physical phenomenon, their statistical dependence structure should be included. Joint probability distributions are able to model these structures, in particular copula functions. Copulas have the advantage of modeling the dependencies of random variables independently of their marginal distributions (see e.g. Nelsen, 2006; Genest and Favre, 2007; Salvadori et al., 2007). Some application of copulas to model joint behaviour of variables describing storm characteristics can be found in Grimaldi and Serinaldi (2006), Salvadori and De Michele (2006), Vandenberghe et al. (2010), Balistrocchi and Bacchi (2011), Gyasi-Agyei and Charles (2012), Ariff et al. (2012), Serinaldi and Kilsby (2013) and Vernieuwe et al. (2015). Many of these applications focus on the modeling of single storm events, i.e. the occurrence of rainfall is neglected and thus a continuous modeling is not considered.

The overview of the existing literature leaves some open questions: Is it possible to reproduce average event properties and extreme value statistics of observed rainfall with one single model? Is it possible to fulfill both requirements for a high temporal resolution? It is the aim to address these questions by setting up a stochastic continuous point rainfall model. The objective is to contribute to the possibility of obtaining long rainfall series that can properly reproduce different characteristics of the observed ones, whilst keeping the model as simple as possible. For this reason an alternating-renewal model is tested, due to the fact that it is event based and is considered easy to interpret and transfer to new regions of interest. For the mathematical background of the model the readers can refer to Ross (1996) or Grimmett and Stirzaker (1992). Given that the model is stochastic the evaluation is performed on the basis of ensembles of many long synthetic time series. Since a high temporal resolution is to be assessed, synthetic time series are evaluated based on hydrological modeling using fictional urban systems. Fictional catchments have been used in the past for assessing rainfall input influence (see e.g. Arnaud et al., 2002; Kim and Olivera, 2012). The same fictional network is used for different locations to keep all external factors besides precipitation constant and be able to assess the difference of rainfall inputs.

The model presented here is based on an existing one which was developed by Haberlandt (1998) for a different region. The existing model is further developed by focusing on the following aspects:

- Inclusion of seasonality and improving the simultaneous simulation of mean and extreme characteristics,
- Inclusion of small events and assessment of its effect on mean and extreme statistics,
- Introduction of copulas to better mimic the join behaviour of rainfall amount and duration,
- Analyzing the effect of different copula structures, not only in terms of rainfall characteristics, but also regarding an urban hydrological application,
- Assessing the advantage of availability of long continuous time series compared to current design practice, i.e. event based, in terms of extreme events.

In the ‘‘Methods” section the development of the precipitation model is described along with the different criteria used for validating it. The ‘‘Study area and data” section consists of a brief description of the study area, along with the main characteristics of the rainfall series used for updating and evaluating the model. The urban hydrological system is presented as well. In ‘‘Results” the existing model and the proposed alternatives to improve it are compared in terms of reproducing average properties and extreme values, along with the validation based on hydrological modeling. Finally in the last section ‘‘Discussion and Conclusions” main findings are discussed regarding the improvements and ability of the model to reproduce the main rainfall characteristics along with the current status of investigation.

2. Methods

2.1. Precipitation model

The aim of the proposed model is to generate long synthetic 5-min time series based on the simulation of variables describing rainfall events. These events are described by i) time between two events or dry spell duration (DSD), ii) time of event in which rain occurs or wet spell duration (WSD), iii) total volume of rainfall falling during the event or wet spell amount (WSA), iv) wet spell intensity (WSI) which is the ratio of WSA divided by WSD, v) intensity of the peak (WSPeak) and vi) the time of occurrence of the peak (WSTpeak). Defining rainfall events from the continuous series requires the setting of the following minimum values: wet spell intensity (WSImin = 0.01 mm/5 min), wet spell amount (WSAmin = 1 mm) and dry spell duration (DSDmin = 5 min). These criteria provide events which have continuous rainfall within the WSD and result in the exclusion of small events that are later added back to the model.

The model is based on the theory of renewal processes. Rainfall is described as two structures: external and internal. The external structure is the succession of independent rain events, each one described by a wet and a dry spell along with the total amount of rainfall within the wet spell, whereas the internal structure describes the distribution of the total rainfall within the wet spell (see Fig. 1).

In this study the external structure is modeled by probability distributions which are fitted to the following variables: DSD, WSD and WSA. The WSI is estimated from pairs of WSA and WSD. Seasonality is included by modeling the marginal behaviour of the different variables separately for summer and winter events. Several distribution functions are tested for modeling the different variables describing rainfall events. The final components of the model are listed in Table 1.

As described in Table 1, the internal structure is modeled by a a double exponential function. Integration of this function over WSD leads to an equation described by: WSA, WSD, WSPeak and WSTpeak (for further details see Haberlandt, 1998). WSI is used for estimating WSPeak, whereas WSTpeak is modeled by a simple uniform distribution that generates a value between 0 and 1, which is then multiplied by the WSD to derive the value of the time to peak. Experiments have shown that profiles with rainfall concentrated around the peak produce flood events which occur in very short periods of time and therefore lead to overestimation of flooding. For this reason the parameter (λ) of the exponential function is estimated considering an intensity lower than the WSPeak (see right image of Fig. 1); this way the volume of rainfall