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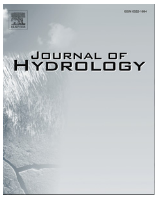

An efficient causative event-based approach for deriving the annual flood frequency distribution

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SUMMARY

In ungauged catchments or catchments without sufficient streamflow data, derived flood frequency methods are often applied to provide the basis for flood risk assessment. The most commonly used event-based methods, such as design storm and joint probability approaches are able to give fast estimation, but can also lead to prediction bias and uncertainties due to the limitations of inherent assumptions and difficulties in obtaining input information (rainfall and catchment wetness) related to events that cause extreme floods. An alternative method is a long continuous simulation which produces more accurate predictions, but at the cost of massive computational time. In this study a hybrid method was developed to make the best use of both event-based and continuous approaches. The method uses a short continuous simulation to provide inputs for a rainfall-runoff model running in an event-based fashion. The total probability theorem is then combined with the peak over threshold method to estimate annual flood distribution. A synthetic case study demonstrates the efficacy of this procedure compared with existing methods of estimating annual flood distribution. The main advantage of the hybrid method is that it provides estimates of the flood frequency distribution with an accuracy similar to the continuous simulation approach, but with dramatically reduced computation time. This paper presents the method at the proof-of-concept stage of development and future work is required to extend the method to more realistic catchments.

1. Introduction

Flooding is one of the most frequently occurring natural hazards worldwide, and often causes major damage to our society. For example, every year in Australia, floods incur millions of dollars damage to critical infrastructure and threaten humans lives. Appropriate designs of flow regulation structures, such as dam spillways, bridges, pipelines and flood detention basins are vital for flood mitigation and the protection of important domestic and commercial resources. These designs rely on the estimation of both the frequency and the magnitude of extreme flow events. However, due to the highly variable and complex climatic and hydrological processes that drive flood extremes, it is a major challenge to provide reliable predictions.

Existing flood estimation methods can be broken down into two major groups: flood frequency analysis and derived flood frequency methods (Moughamian et al., 1987).

1.1. Flood frequency analysis

Flood frequency analysis involves fitting a distribution model to streamflow data so that the flow magnitude associated with a certain occurrence probability can be calculated using the mathematical equation of the fitted distribution. The success of the analysis depends on achieving a reliable fit for the distribution, which requires a sufficiently long and high quality streamflow record. Unfortunately it is not available in the vast majority of catchments. Furthermore if the catchment has undergone significant land-use or climate changes in the past, the historical record cannot support an accurate estimation of the flood frequency distribution.

1.2. Derived flood frequency methods

Derived flood frequency methods have been developed to overcome the limitations of flood frequency analysis. These approaches use meteorological data (rainfall, potential evapotranspiration) as inputs for a rainfall-runoff (RR) model to generate streamflow data. In general, historical rainfall data are longer and have more reliable records than streamflow data and only a relatively short streamflow record is required to calibrate the RR model. Furthermore,

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to provide projections of the impact of climate change, a weather generator can be used to simulate the meteorological data for a certain climate scenario. The simulated meteorological data is then input into the RR model to generate streamflow data, from which the flood frequency distribution (FFD) under the projected climate condition can be derived. Derived flood frequency methods are, therefore, generally preferred over flood frequency analysis, and have been developed as both analytical and simulation approaches.

Analytical methods were initiated in the early 70 s by Eagleson (1972). The author derived the peak streamflow distribution from the distributions of catchment and climate characteristics using a kinematic runoff model in an idealised V-shaped flow plane. Further development of the analytical methods was achieved by other researches, e.g., Hebson and Wood (1982); James et al. (1986) and Raines and Valdes (1993).

Recently, numerical simulation methods for deriving flood frequency distribution have undergone considerable development. These simulation techniques can be classified into two groups: continuous simulation (CS) (Calver et al., 2000) and event-based (EB) approaches (e.g. Rahman et al., 2002). CS runs a weather generator and a RR model in parallel continuously to produce a time series of streamflow data from which the flood frequency curve can be derived, while EB approaches focus on the events of interest. These usually include rainfall events and catchment wetness conditions that drive extreme flood events and are sampled from their distributions to serve as inputs for the RR model that runs in an event-based fashion. The average return intervals (ARI) of the generated flood events are associated with the ARI of the input events based on certain assumptions.

In the following, two mainstream event-based (EB) approaches, i.e., the design storm and the joint probability approaches will be reviewed, followed by a brief discussion of continuous simulation (CS).

1.2.1. Design storm approach

Among the EB methods, the most widely adopted one in the guidelines of the world practicing water resource institutions (for example, Australian Rainfall and Runoff AR&R Pilgrim, 1987) can be attributed to the design storm (DS) approach, mainly because of its simplicity. This approach involves design event rainfall generation, runoff production and hydrograph formation. It assumes that a design rainfall event of a given ARI can be converted to a design flood of the same ARI and it relies on the specification of a rainfall loss (aka antecedent soil moisture deficit) as an indicator of the catchment wetness condition. A fixed value, typically the median, is taken to represent the rainfall loss/soil moisture deficit (AR&R Pilgrim, 1987), which ignores its variability. This assumption (also referred to as the ARI neutrality assumption) can lead to significant prediction errors, as the rainfall-runoff process is basically a joint probability problem (Kuczera et al., 2003). For example, a 1 in 100 year flood can be caused by a 1 in 50 year rainfall event falling on a wet catchment or by a 1 in 200 year rainfall event falling on a dry catchment (Michele and Salvadori, 2002). Thus it is important to capture the interactions of antecedent soil moisture conditions and extreme rainfall events.

In order to overcome the problems of the ARI neutrality assumption, Camici et al. (2011) proposed to calibrate the antecedent soil moisture to the value that produces a flood with the same ARI as that of the input rainfall event. For each return period of the flood, a design soil moisture value is calibrated using the result of a long-term CS as a reference. The design soil moisture values are then regionalised as a function of the geo-morphological characteristics of the catchment so that they can be applied to ungauged catchments with similar characteristics. Given the popularity of the DS approach and its major problem of defining the antecedent soil moisture condition, the attempt to find the critical soil moisture value that maintains ARI neutrality during the transformation from rainfall to runoff seems to be practical. Walsh et al. (1991) undertook a similar study for New South Wales in Australia. However the regionalisation showed huge variability. This indicates the success of this method strongly depends on the strength of regionalisation and the quality of the data. The other significant limitation of this approach is that the design soil moisture is likely to undergo significant change under climate change conditions. The regionalised design soil moisture inputs are therefore likely to produce unreliable estimates of the FFD.

1.2.2. Joint probability approaches

To account for the joint probability nature of the estimation of extreme flood events, event-based Monte Carlo simulation techniques have been developed (Rahman et al., 2002), in which the values of the input variables, e.g., rainfall depth and antecedent soil moisture amount are sampled from either their joint or independent distribution and input into the RR model to generate a range of streamflow events. Using the *total probability theorem* the exceedance probability of these events can be estimated (Rahman et al., 2002). To reduce the computational time, stratified Monte-Carlo (SMC) techniques are used in Nathan et al. (2003), where the sampling procedure of the input variables focuses selectively on the probabilistic range of interest.

The major challenge of these techniques is to obtain the correct input distributions from the causative events of the annual maximum extreme flows that are of interest. These are very difficult to obtain because long-term historical records with many extreme events are not readily available. Moreover, catchment soil moisture conditions are not routinely measured, which requires calibrating a RR model to flood events. Currently, practical guidelines (e.g., RORB by Laurenson et al., 2010) recommend using the distribution of annual maximum rainfall and some documented rainfall loss distribution (e.g. Hill et al., 1997) estimated from short historical data to derive the annual FFD. Part of this study will evaluate the use of these practical guidelines in the EB approaches for estimating the annual FFD.

As these procedures use the annual maximum rainfall as input and take into account the joint probability of rainfall and catchment antecedent soil moisture condition, we will collectively name these methods as AMXJP methods hereafter, where *AMX* stands for annual maximum rainfall and *JP* stands for joint probability.

1.2.3. Continuous simulation

In contrast to event-based approaches, continuous simulation (CS) (Calver et al., 2000; Heneker et al., 2003) seems to solve all the problems mentioned above, under the assumption that the applied weather generator and RR model adequately simulate the rainfall-runoff process. It does not postulate ARI neutrality between rainfall and runoff, nor does it require estimation of the input distributions for an EB procedure. It simply runs a weather generator coupled with a RR model in a continuous manner to simulate a long time series of streamflow data, from which the annual maximum flows can be extracted and in turn the annual FFD can be derived.

The major limitation of the CS approach is that it is computationally demanding. For instance, as will be shown in Section 4.4.2, to get an estimate of the exceedance probability of 1 in 100 year flood with a prediction error less than 20%, the minimum length of the simulated streamflow data needs to be more than 9500 years at a daily time step. If a complicated RR model, such as a distributed and/or physically based model is required, the computational time can be prohibitive.

1.3. Contribution of this work

The main contribution of this paper is to develop a hybrid event-based approach which overcomes the limitations of current