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An objective method for partitioning the entire flood season into multiple sub-seasons

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SUMMARY

Information on flood seasonality is required in many practical applications, such as seasonal frequency analysis and reservoir operation. Several statistical methods for identifying flood seasonality have been widely used, such as directional method (DS) and relative frequency (RF) method. However, using these methods, flood seasons are identified subjectively by visually assessing the temporal distribution of flood occurrences. In this study, a new method is proposed to identify flood seasonality and partition the entire flood season into multiple sub-seasons objectively. A statistical experiment was carried out to evaluate the performance of the proposed method. Results demonstrated that the proposed method performed satisfactorily. Then the proposed approach was applied to the Geheyan and Baishan Reservoirs, China, having different flood regimes. It is shown that the proposed method performs extremely well for the observed data, and is more objective than the traditional methods.

1. Introduction

Floods are amongst the most frequent and costliest natural disasters in terms of human hardship and economic loss. More than 90 percent of the damage related to all natural disasters is caused by floods and associated debris flows. Knowledge of flood seasonality is important for flood protection and water resources management. Information on flood seasonality is often used in seasonal frequency analysis, regional frequency analysis and seasonal reservoir operation. In seasonal frequency analysis, the first step is to segment the whole year or flood season into seasons or sub-seasons (e.g. Fang et al., 2007; Chen et al., 2010). In regional flood frequency analysis, similarity measures in flood seasonality have become increasingly popular in identifying hydrologically homogeneous regions (e.g. Burn, 1997; Castellarin et al., 2001; Cunderlik and Burn, 2002; Ouarda et al., 2006; Cunderlik et al., 2004a,b). In reservoir operation, the flood season is divided into multiple sub-seasons and then different reservoir operation policies are employed in different sub-seasons (Chen et al., 2010). This practice can produce greater benefit in hydropower and navigation, and help operate reservoirs more effectively without increasing flood risk (e.g. Fang et al., 2007; Chen et al., 2010).

In the following, the reasons why the seasonal reservoir operation polices are needed in China are presented. According to the Chinese Flood Control Act, the water level of a reservoir should not be higher than the flood control water level, if there is no large flood occurring. This policy ensures that the reservoir can provide adequate storage for flood control during the flood season. However, if we want to generate more electricity, the higher water level of reservoir is better. Therefore, there is a conflict between flood control and electricity generation.

In order to resolve the conflict between flood control and electricity generation, considering the hydrometeorological characteristics, a seasonal reservoir operation policy in flood season was proposed. Usually the flood season in China is from May (or June) to September. Large or annual maximum flood mainly concentrates in some periods of the flood season (e.g. July and August), and median or small flood occurs during other periods (e.g. May, June and September). Therefore, the whole flood season can be divided into multiple sub-seasons, such as three sub-seasons, namely pre-flood season, main-flood season and post-flood season (Ngo et al., 2007; Liu et al., 2010; Chen et al., 2010). In each sub-season, a different reservoir operation policy, i.e. different flood control water level, can be used. This method

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can enhance economic benefits of reservoirs without increasing flood risk during the flood season.

The seasonal reservoir operation during the flood season gives rise to a new problem, that is, how to partition the flood season into sub-seasons. There are several approaches for the identification of flood seasonality. Ouarda et al. (1993) proposed a graphical method for the identification of river flood seasons using peaks-over-threshold (POT) data. This method consists of plotting the mean annual number of exceedances against a time interval t for each station. The behavior of these plots, such as the change of slope, indicates significant seasons. A widely used method for identifying seasonality is the relative frequency (RF) method. In the RF method, dates of flood occurrences are usually grouped into months and relative frequencies of flood occurrences are calculated for each group (Black and Werritty, 1997; Cunderlik et al., 2004b; Ouarda et al., 2006). For example, Black and Werritty (1997) described flood seasonality by means of relative frequencies of flood occurrences in six two-month long seasons. In addition, flood seasonality can be described in terms of directional statistics (Mardia, 1972). The directional statistics (DS) method consists of defining the mean date of flood (directional mean) and the flood variability measure (Magilligan and Graber, 1996; Black and Werritty, 1997; Burn, 1997; Ouarda et al., 2006). Bayliss and Jones (1993) described flood seasonality in Great Britain by means of seasonality indices derived from directional statistics. Burn (1997) measured similarities in the timing and seasonality of floods for catchments via the mean direction and mean resultant vector. Relative frequency (RF) and directional statistics (DS) methods are widely used because of their relative simplicity and ease of calculation. Cunderlik et al. (2004a) indicated that the graphical method, DS method, and RF method identified flood seasons subjectively by assessing the temporal distribution characteristics of flood occurrences at the site of interest. Based on the DS and RF methods, Cunderlik et al. (2004a) introduced a new objective method for the identification of flood seasons, in which they translated the flood occurrence data into directional statistics and assumed that the flood occurrence date followed a circular uniform distribution. A hypothesis test based on a bootstrap method was carried out to evaluate the validity of this assumption by comparing the observed relative frequencies of flood occurrences with theoretical relative frequencies obtained from the circular uniform distribution.

However, for partitioning the flood season into sub-seasons, there are some difficulties. First, the temporal distribution characteristics of flood occurrences do not coincide with calendar months. Second, the flood season only lasts for nearly 150 days (May to September) at most. If we group the flood season into months, the unit is too large and it is inaccurate. Therefore, in this study, we propose a method which can partition the flood season at a specific day instead of a month.

The objective of this paper therefore is to develop a new approach, which is inspired by Cunderlik's method, to partition the flood season into several sub-seasons and determine the segmentation points. A statistical experiment is carried out to evaluate the performance of the proposed method. The Geheyan Reservoir in the Qing River Basin and Baishan Reservoir in the Songhua River Basin of China are selected as case studies to test the applicability of the proposed method.

2. Methodology

First, the sampling method is given. Second, the distribution of flood occurrence dates is presented. Third, the observed relative frequency is calculated. Fourth, the confidence interval of uniform distribution is obtained. Finally, the segmentation points are determined by comparing observed and computed confidence intervals of uniform distribution.

2.1. Sampling method

The Annual maximum (AM) sampling method is widely used for flood frequency analysis, in which the annual maximum flood event is sampled for every year in the observation period. For seasonal reservoir operation, we need to pay attention to large floods, therefore the AM sampling method was used in this study. The annual maximum flood events include the information on magnitudes and occurrence dates. For the identification of seasonality, we paid much more attention to flood occurrence dates. The AM flood series constitutes a data set, called AM series.

2.2. Distribution of flood occurrences dates

Usually, dates of flood occurrences can be expressed using directional statistics (DS), such as the DS method. First, the date of AM series is converted to the directional data, namely an angular value α_i

$$\alpha_i = D_i \frac{2\pi}{T}, \quad 0 \leqslant \alpha_i \leqslant 2\pi \tag{1}$$

where T is the length of flood season; and D_i is the date of flood occurrence.

If there is no seasonality characteristic in the data set, the PDF of flood occurrence dates can be expressed by a circular uniform distribution, which is a probability distribution on the unit circle whose density is uniform for all angles. The PDF of circular uniform distribution is defined as

$$f(\alpha_i) = \frac{1}{2\pi} \tag{2a}$$

The CDF of the circular uniform distribution is defined as:

$$F(\alpha_i) = \frac{\alpha_i}{2\pi} \tag{2b}$$

In this uniform distribution, a flood can occur, with the same probability, on any given day of the year (or flood season). If there is seasonality existing in the data set, the data set cannot obey the circular uniform distribution.

2.3. Calculation of relative frequency (RF)

2.3.1. Calculation of RF value

In order to test whether the AM data set follows a circular uniform distribution, dates of flood occurrences are grouped into each sub-season and the relative frequencies (RF) of flood occurrences are calculated for each sub-season. The RF value for sub-season j is calculated by

$$\mathrm{RF}_j = \frac{N_j}{N} \quad (j = 1, 2, \ldots, n) \tag{3}$$

where RF_j represents the relative frequency of the jth sub-season; N_j is the number of floods occurring in the jth sub-season; N is the total number of floods; and n is the number of sub-seasons.

If the data set obeys the circular uniform distribution, the RF values for each sub-season with the same length should be more or less the same. Since each sub-season may be not with the same length, an adjustment must be applied. Mardia (1972) proposed a method for adjusting the frequencies in such a way that all sub-seasons have the same length. The adjusted RF is calculated as

$$\mathrm{RF}'_j = \mathrm{RF}_j \cdot \frac{N/n}{n_j} \quad (j = 1, 2, \ldots, n) \tag{4}$$