Journal of Hydrology 527 (2015) 234–250

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Return period and risk analysis of nonstationary low-flow series under climate change

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ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form 3 April 2015
Accepted 20 April 2015
Available online 7 May 2015
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Peter F. Rasmussen, Associate Editor

Keywords:
Return period
Risk
Nonstationarity
Low-flow
General Circulation Models (GCMs)

SUMMARY

Return period and risk of extreme hydrological events are critical considerations in water resources management. The stationarity assumption of extreme events for conducting hydrological frequency analysis to estimate return period and risk is now problematic due to climate change. Two different interpretations of return period, i.e. the expected waiting time (EWT) and expected number of exceedances (ENE), have already been proposed in literature to consider nonstationarity in return period and risk analysis by introducing the time-varying moment method into frequency analysis, under the assumption that the statistical parameters are functions only of time. This paper aimed at improving the characterization of nonstationary return period and risk under the ENE interpretation by employing meteorological covariates in the nonstationary frequency analysis. The advantage of the method is that the downscaled meteorological variables from the General Circulation Models (GCMs) can be used to calculate the nonstationary statistical parameters and exceedance probabilities for future years and thus the corresponding return period and risk. The traditional approach using time as the only covariate under both the EWT and ENE interpretations was also applied for comparison. Both approaches were applied to annual minimum monthly streamflow series of two stations in the Wei River, China, and gave estimates of nonstationary return period and risk that were significantly different from the stationary case. The nonstationary return period and risk under the ENE interpretation using meteorological covariates were found more reasonable and advisable than those of the EWT and ENE cases using time alone as covariate. It is concluded that return period and risk analysis of nonstationary low-flow series can be helpful to water resources management during dry seasons exacerbated by climate change.

1. Introduction

Statistical inference is used in hydrological frequency analysis under the assumption that hydrological events such as flood and drought are randomly distributed through time. A precondition for traditional frequency analysis of hydrological variables is the assumption of stationarity, which means that the controlling environmental factors such as climate and land cover act to generate or modify the hydrological variable of interest in the same way in the past, present and future (Gilroy and McCuen, 2012; Katz, 2013; Benyahya et al., 2014; Charles and Patrick, 2014). However, under the conditions of climate change, land use change and river regulation, acting individually or together, the assumption of stationarity is suspected, and existing methodology may no longer be valid (Katz et al., 2002; Xiong and Guo, 2004; Milly et al., 2005, 2008). To overcome this problem, various approaches have been developed for conducting nonstationary hydrological frequency analysis (Khaliq et al., 2006). The concept of event return period (or recurrence interval) and the associated risk of occurrence, with potential consequences of loss of life, social disruption, economic loss and ecological disturbance, are critical considerations in the management of water resources, especially with regard to design and operation of hydraulic structures in rivers. Under nonstationary conditions, estimates of return period and risk are ambiguous unless the temporally changing environment is explicitly considered in the analysis.

The most common way of handling nonstationarity in hydrological time series is the method of time-varying moment, which assumes that although the distribution function type of the

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http://dx.doi.org/10.1016/j.jhydrol.2015.04.041
0022-1694/

hydrological variable of interest remains the same, the statistical parameters are time-varying (Strupczewski et al., 2001; Coles, 2001; Katz et al., 2002; Villarini et al., 2009; Gilroy and McCuen, 2012; Jiang et al., 2015a). With the method of time-varying moment, it is not difficult to derive a value of a hydrological variable for a return period, with a specific design quantile (Olsen et al., 1998; Villarini et al., 2009), i.e. $T_t = 1/p_t = 1/(1 - F_Z(z_{p_0}, \boldsymbol{\theta}_t))$, where T_t and p_t are the annual return period and exceedance probability, respectively, of the given design quantile z_{p_0} with fitted annual statistical parameters $\boldsymbol{\theta}_t$, and F_Z is the cumulative distribution function of the hydrological variable of interest. However, for many planning and design applications, a measure of return period that varies from one year to the next is impractical. To deal with this issue, various studies have been carried out for return period estimation and risk analysis that consider nonstationary conditions (Wigley, 1988, 2009; Olsen et al., 1998; Parey et al., 2007, 2010; Cooley, 2013; Salas and Obeysekera, 2013, 2014). Among these various studies two different interpretations of return period have already been proposed. The first is that the expected waiting time (EWT) until the next exceedance event is T years (Wigley, 1988, 2009; Olsen et al., 1998; Cooley, 2013; Salas and Obeysekera, 2013, 2014), and the second is that the expected number of exceedances (ENE) of the event in T years is 1 (Parey et al., 2007, 2010; Cooley, 2013).

Wigley (1988, 2009) used the EWT interpretation to consider how nonstationarity can be included in the concepts of return period and risk of extreme events. A normal distribution with a linear increasing trend in the mean was assumed, and the changes in the return period and risk were derived by the technique of stochastic simulation. Building on the work of Wigley (1988), Olsen et al. (1998) presented a more rigorous mathematical examination of the effect of nonstationarity on the concepts of return period and risk, also using the EWT interpretation. Parey et al. (2007, 2010) introduced the ENE interpretation into the nonstationary framework to derive return levels of air temperature in France. A detailed review and comparison of the two interpretations of return period can be found in Cooley (2013). Recently, Salas and Obeysekera (2013, 2014) extended the geometric distribution to allow for changing exceedance probabilities over time, considering the cases of increasing, decreasing and shifting extreme events. Although these studies vary considerably in their scope and the methodologies employed, they have in common the assumption that the statistical parameters are functions only of time. However, this carries the unreasonable implication that the identified pattern of nonstationarity in a hydrological time series will continue indefinitely. Also, while runoff can follow inter-year cyclical patterns, the lack of a direct physical link between time and runoff means that time alone is not quite sufficient as an explanatory variable.

The time-varying moment method can be extended to perform covariate analysis by replacing time with any physical factors that are known to be causative of the hydrological variable of interest. Using meteorological variables as covariates could be more effective and have clearer physical meaning for modelling return period and risk under nonstationary conditions than simply using time as covariate. This physical covariate analysis approach has previously been explored for nonstationary frequency analysis of extreme events (Coles, 2001; Villarini et al., 2010; López and Francés, 2013), but to our knowledge it has not been incorporated with either the EWT or ENE interpretation of return period in estimating return period and risk of extreme events under nonstationary conditions.

Like many other places around the world, hydrological processes in China are under the influence of climate change, so the assumption of stationarity of river flow series is not valid for many rivers (Zhang et al., 2011). The Wei River, the largest tributary of the Yellow River, is the major source of water supply for the economic hub of Western China – the Guanzhong Plain. The Wei River basin is one of the most important industrial and agricultural production zones in China. However, in recent decades the Wei River basin has suffered a significant decrease in streamflow (Song et al., 2007; Zuo et al., 2014), which threatens industrial and agricultural production and socioeconomic development. The increasing scarcity of water resources under conditions of climate change is a serious concern not only in the Wei River basin, but also across the entire nation. There is an urgent need to provide water resource managers and policy makers with reliable information on the return period and risk characteristics of the low-flow component of the flow regime of the Wei River under the prevailing nonstationary conditions.

For those reasons, the main goal of this paper is to define and apply an integrated approach for understanding and quantifying the differences in calculating the nonstationary return period and risk of extreme low-flow resulted from using time as the sole covariate and using meteorological variables as covariates in the nonstationary frequency analysis of the low-flow series. Note that the economic development and human activities might have partially contributed in the nonstationarity of extreme hydrological events as identified in other studies (Xiong et al., 2014; Jiang et al., 2015b). Thus, in addition to climatic factors, anthropogenic factors, such as irrigation area, population, and industrial consumption, should be considered as covariates in investigating the causes of nonstationarity of low-flow events. However, these anthropogenic factors have not, for the moment, been incorporated in this paper in investigating the nonstationary exceedance probabilities of low-flow events for future years for the reason that the values of these anthropogenic factors in the future years are very difficult to be determined, or the estimated values have too big uncertainties even compared to the GCMs estimates of climatic factors. So, in the present study we would like to limit the explanatory factors of future low-flow nonstationarity to just climatic factors.

When using meteorological covariates, GCMs outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) provide the statistical parameters of the nonstationary low-flow distribution by substituting downscaled future meteorological variables into the derived optimal nonstationary model to extend the exceedance probabilities into the future. The EWT interpretation of return period requires infinite (or as long as possible) future exceedance probabilities (Cooley, 2013) but the GCMs outputs are temporally finite (most of the GCMs just provide continuous large-scale daily predictors to the year of 2100) (Riahi et al., 2011; van Vuuren et al., 2011), so the meteorological covariates cannot be incorporated in estimating return period and risk of extreme events under nonstationary conditions with the EWT interpretation. However, the ENE interpretation of return period requires just finite future exceedance probabilities, which can be fully provided by the GCMs outputs, and thus the meteorological covariates are adopted in the nonstationary return period and risk analysis with the ENE method. Besides, the traditional approach using time as the only covariate under both the EWT and ENE interpretations is also applied in this study for the purpose of comparison with the approach using meteorological covariates under the ENE interpretation. The practical application of this approach is illustrated using a case study of the Wei River basin.

This paper is organized as follows. The next section describes the Wei River basin and the available data sets used in the study. Then the methods for determining the return period (under the EWT and ENE interpretations) and risk under stationary and nonstationary conditions are described, along with a brief outline of the methods of nonstationary frequency analysis of low-flow series