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A non-stationary cost-benefit based bivariate extreme flood estimation approach

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ABSTRACT

Cost-benefit analysis and flood frequency analysis have been integrated into a comprehensive framework to estimate cost effective design values. However, previous cost-benefit based extreme flood estimation is based on stationary assumptions and analyze dependent flood variables separately. A Non-Stationary Cost-Benefit based bivariate design flood estimation (NSCOBE) approach is developed in this study to investigate influence of non-stationarities in both the dependence of flood variables and the marginal distributions on extreme flood estimation. The dependence is modeled utilizing copula functions. Previous design flood selection criteria are not suitable for NSCOBE since they ignore time changing dependence of flood variables. Therefore, a risk calculation approach is proposed based on non-stationarities in both marginal probability distributions and copula functions. A case study with 54-year observed data is utilized to illustrate the application of NSCOBE. Results show NSCOBE can effectively integrate non-stationarities in both copula functions and marginal distributions into cost-benefit based design flood estimation. It is also found that there is a trade-off between maximum probability of exceedance calculated from copula functions and marginal distributions. This study for the first time provides a new approach towards a better understanding of influence of non-stationarities in both copula functions and marginal distributions on extreme flood estimation, and could be beneficial to cost-benefit based non-stationary bivariate design flood estimation across the world.

1. Introduction

Extreme floods could be devastating and can cause huge socio-economic impacts, and have received much attention globally (Perron et al., 2016; Wells et al., 2016; Zhou et al., 2016; Blöschl et al., 2017; Song et al., 2017). In recent years, extreme flood estimation obtained from cost-benefit analysis has been proved to be equivalent to estimates from conventional Flood Frequency Analysis (FFA) method with assumptions of linear damage and cost functions; new approaches have been developed by incorporating cost-benefit analysis into FFA to estimate cost-effective design flood values (Botto et al., 2014; Qi et al., 2016a; Qi, 2017).

Non-stationarity and dependence in design variables (such as, flood peaks and flood volumes) are two key issues in design flood estimation (Milly et al., 2008; Strupczewski et al., 2009; Bender et al., 2014). In FFA, influence of non-stationarity on extreme flood estimation has been investigated by many studies (Olsen et al., 1998; Villarini et al., 2009; Bender et al., 2014; Qi et al., 2016b; Read and Vogel, 2016). Regarding dependence in design variables, efforts have been made to investigate its influence, for example, return period definition (Salvadori and De Michele, 2010; Salvadori et al., 2011; Salvadori et al., 2013), design hydrograph estimation (Gräler et al., 2013; Candela et al., 2014; Mojca et al., 2015), hydrologic dam design (Klein et al., 2010; Requena et al., 2013), structure-based framework for hydraulic design (Volpi and Fiori, 2014; Salvadori et al., 2015), flow distribution estimation from climatic variables (Xiong et al., 2014), modelling uncertainty of flood quantiles in ungauged sites (Santillán et al., 2014; Grimaldi et al., 2016) and non-stationary design flood estimation (Bender et al., 2014; Cong et al., 2015). Copula functions were commonly utilized in the prior studies to represent dependence between design variables (Salvadori and De Michele, 2004; Genest and Favre, 2007; Salvadori and De Michele, 2010; Salvadori et al., 2011; Gräler et al., 2013; Salvadori et al., 2013; Fu and Butler, 2014).

In cost-benefit based extreme flood estimation approaches, previous studies have been based on stationary approaches (Botto et al., 2014; Qi et al., 2016a). Recently, Qi (2017) developed a

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non-stationary cost-benefit based extreme flood estimation method. However, this new non-stationary method is based on univariate analysis. The univariate approach is adequate when only one variable is significant in a design process, but cannot provide a complete assessment of occurrence probabilities of design floods (Callau Poduje et al., 2014). Even worse, the use of a number of variables (viz., a multivariate approach), where possible dependencies are not correctly assessed (e.g., the variables are considered as independent when they are not), may yield fake estimates of the design values: see, e.g., the case study presented in Salvadori et al. (2015). Hydraulic structure design is usually based on full hydrograph which is characterized by flood peak and volume (Renard and Lang, 2007; Callau Poduje et al., 2014; Parent et al., 2014), and these two variables are usually dependent (Salvadori and De Michele, 2004). Thus, it is necessary to develop a non-stationary cost-benefit based bivariate extreme flood estimation approach. However, to the best of the authors' knowledge, such an approach has not been developed.

The overall objective of this paper is to develop a Non-Stationary Cost-Benefit based bivariate design flood Estimation (NSCOBE) approach. This approach can consider non-stationaries in both copula functions and marginal distributions in a framework integrating cost-benefit analysis and copula functions. A river basin with 54-year discharge data is used to illustrate applications of NSCOBE. Six copula functions are tested to select the best one based on the Cramér-von Mises statistic and the Cross-Validation Copula Information Criterion (xv-CIC) (Gronneberg and Hjort, 2014). These copula functions are Gumbel, Clayton, survival Gumbel, survival Clayton, Frank and *t*-student. In this paper, there are three advancements from the present state of knowledge. First, a non-stationary cost-benefit based bivariate design flood estimation approach is developed. Second, a risk calculation approach is proposed based on non-stationarities in both copula functions and marginal distributions. Third, trade-offs are found in risk estimation between copula functions and marginal distributions. Here, the 'risk' refers to the probability of exceedance, not potential damage, which has also been utilized in previous research (e.g., Rootzén and Katz (2013); AghaKouchak et al. (2014); Condon et al. (2015); Sarhadi et al. (2016a)). This study provides a new approach towards a better understanding of the influence of non-stationarity on design flood estimation involving multiple design flood variables.

2. The NSCOBE approach

Fig. 1 shows the flowchart of the NSCOBE approach. It includes three main steps: (1) test significance of non-stationarity of observed data and select copula and marginal distribution functions if non-stationarity is significant; (2) calculate expected total cost criterion values on the basis of a return period of interest, which includes the expected flood damage cost and construction cost; (3) select design variables on the basis of calculated risk and the maximum probability criterion. Fig. 1 shows the flowchart of the developed NSCOBE approach. Details of the proposed new approach are explained in the remainder of this section.

2.1. Selecting copula functions

When there are two dependent variables, joint cumulative distributions F is defined based on marginal distributions $u = F_X(x)$ and $v = F_Y(y)$, and a copula **C** via Sklar Theorem (for a theoretical introduction to copulas see Nelsen (2006), Joe (2014), Durante and Sempi (2015); for a practical approach see Salvadori et al. (2007)). In this study, X and Y represent flood peaks and flood

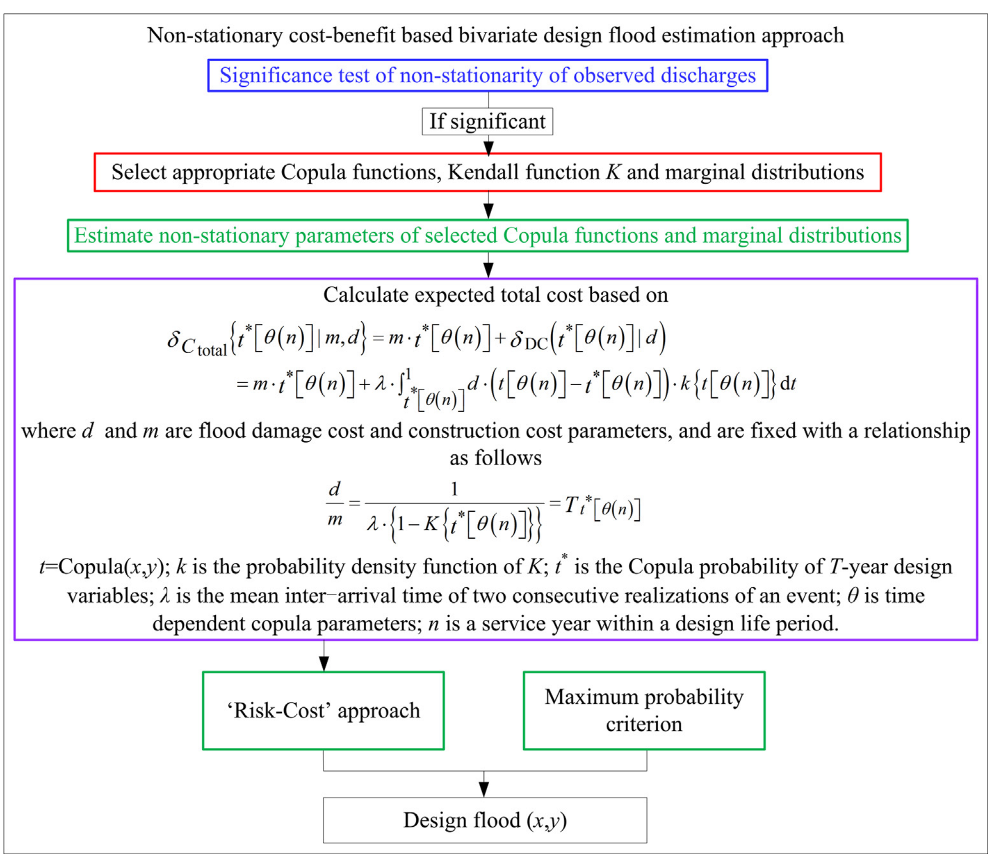

Fig. 1. Flowchart of the Non-Stationary Cost-Benefit based bivariate design flood Estimation (NSCOBE) approach.