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Coastal flooding: A copula based approach for estimating the joint probability of water levels and waves

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A B S T R A C T

An accurate joint probability assessment of water levels and waves is of primary importance for effective coastal flooding management even in microtidal environments subjected to severe storm surge events. A copula based approach is presented for modeling the joint distribution derived from almost six years of sea levels and waves at a site suffering from coastal flooding. The evaluation of the upper tail dependence coefficient represents an unavoidable step in the copula selection process since it provides indications on extreme dependence that cannot be neglected to reliably estimate the probability of marine inundation. Based on the results of various statistical tests and estimation of the upper tail dependence coefficient, a one-parameter extreme value copula is selected to model the dependence structure of events representing conditions at peak water levels, including wave height, incoming wave direction and season of occurrence. The joint distribution obtained is subsequently used for reliability analysis. A particular simplified application case is described for the Ravenna coast (Italy) and the probability of failure/inundation is estimated through the direct integration method. Since the failure function employed involves the wave runup depending on wave period, the joint distribution of wave height and wave period is also assessed. The study highlights the importance of taking into account all the variables involved in the flooding phenomenon for a reliable flood probability estimate. The presented methodology can be applied to the assessment of flood probability at coastal sites at risk of inundation due to the combined impact of waves and water levels.

1. Introduction

Storm related coastal flooding events are mainly caused by high water levels (WLs), due to a combination of astronomical tide and storm surge, and high and long waves incident on the coast, through the effects of wave setup and runup. Both are generated by common meteorological conditions, characterized by strong onshore winds and low atmospheric pressure systems, which can cause elevated sea level and high wave conditions, resulting in a significant positive correlation between the variables.

A number of research studies have outlined that univariate frequency analysis cannot provide a complete assessment of the occurrence probability of extremes if the underlying event is characterized by a set of interrelated random variables (Chebana and Ouarda, 2011). Therefore, accounting for all variables characterizing the sea state conditions and their possible interdependence is fundamental to determine realistic exceedance probabilities in design and safety evaluation of coastal and offshore structures and in assessing coastal flooding and storm erosion risks.

Several analyses highlighted relationships existing among the main oceanographic variables and proposed bivariate methods for modeling the probability distribution of simultaneous conditions (Ferreira and Guedes Soares, 2002; Galiatsatou and Prinos, 2007; Nerzic and Prevosto, 2000).

For assessment of sea defenses an approach to joint probability analysis was developed by Hawkes et al. (2002). The method involves the separate fitting of marginal distributions to significant wave heights (SWHs), WLs and wave steepnesses, the fitting of a single or a mixture of two bivariate normal distributions to represent the dependence between SWHs and WLs and between SWHs and wave steepnesses, and a Monte Carlo (MC) simulation approach to estimate the probability of the combinations which cause failure.

The copula function, i.e. the probability that a pair of variables $\{X_1,X_2\}$ are both less than current values $\{x_1,x_2\}$ expressed as functions of the probabilities that the single variables are separately less than the current values, provides a useful tool to represent the dependence characteristics of random variables enabling great flexibility in modeling multivariate distributions, since no hypothesis is made on univariate distributions while preserving the capacity to describe dependence exhibited by variables. Since the late 1990s copula models have been

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widely used in financial, insurance, econometrical, risk management and actuarial analyses (e.g. Cherubini et al., 2004; Frees and Valdez, 1998; Jaworski et al., 2010). More recent and very numerous are copula applications within the field of hydrology for characterization of extreme rainfalls (De Michele and Salvadori, 2003; Salvadori and De Michele, 2004; Zhang and Singh, 2007) and droughts (De Michele et al., 2013; Janga Reddy and Ganguli, 2012; Shiau, 2006), flood frequency analysis (Favre et al., 2004; Karmakar and Simonovic, 2009), precipitation and runoff analysis (Zhang and Singh, 2012), risk of flooding in river systems (Chen et al., 2012; Sunyer Pinya et al., 2009) and design or checking adequacy of hydraulic structures (De Michele et al., 2005; Requena et al., 2013; Volpi and Fiori, 2014). One of the main reasons for the increasing popularity and recent extensive use of copulas is related to the possibility of separately modeling the univariate marginal distributions, without imposing on them any restriction, and, in a second step, the dependence structure among the random variables.

More recently, the flexibility of the copula approach has been exploited to investigate the joint occurrence of combined critical sea state conditions for coastal and ocean engineering applications. De Waal and van Gelder (2005) proposed a Burr-Pareto-Logistic copula to model the joint distribution of extreme wave heights and periods during severe storms. De Michele et al. (2007) outlined a copula based multivariate model for the sea storm variables, SWH, duration, direction and inter-arrival time. Wahl et al. (2011) highlighted that in performing integrated risk analyses it is necessary to include the temporal evolution of WLs during storm surge events in addition to the maximum WL; thus, the complete storm surge profile, constituted by the storm surge peak and two adjacent high tides, was considered in generating storm surge scenarios at the German Bight. Then, the Gumbel-Hougaard copula was selected by Wahl et al. (2010) to represent the dependence structure of the two storm surge parameters peak WL (PWL) and "intensity", defined as the time integral of the storm surge hydrograph exceedance over the German ordnance datum, and to derive occurrence probabilities of extreme storm surge events having high and long lasting peaks. PWLs and areas of storm surge hydrographs were also considered by Salecker et al. (2011) in a bivariate analysis for the German Baltic Sea coast. To perform more reliable and realistic integrated coastal flood risk analyses, Wahl et al. (2012) extended the bivariate statistical model proposed for the storm surge parameters to a trivariate fully nested Archimedean copula model by additionally incorporating the SWH parameter. In testing flood defenses at the Dutch North Sea coast, Diermanse and Geerse (2012) analyzed the influence of various bivariate correlation structures, including homoscedastic and heteroscedastic models, De Haan method, and Frank, Clayton, Gumbel and Gaussian copulas. Chini and Stansby (2012) incorporated a Gumbel copula within an integrated modeling system to investigate overtopping discharge at a seawall in Walcott (UK) due to future changes in wave and WL climate. The procedure outlined by Salvadori et al. (2011) for calculating return periods and design quantiles in a multivariate framework was applied by Salvadori et al. (2012) to the pair SWH and storm duration. By using wave data from a buoy near Durban (South Africa), Corbella and Stretch (2013, 2012a) investigated the dependencies between the storm parameters SWH, peak wave period (PWP), duration, inter-arrival time and WL, and tested multivariate techniques for simulating storm events by applying a copula based statistical model to quantify storm induced long term trend in dune erosion under changing climatic conditions. Furthermore, Corbella and Stretch (2012b) showed that the method proposed by Salvadori et al. (2011) for selecting the "most-likely design realization" for a specified exceedance probability is purely statistical in its original form, and the lack of any direct link to the underlying physical processes limits its use for design applications. A method to overcome this limitation could be to use a structural response (failure) function approach. Gruhn et al. (2012) used the Frank copula to estimate the joint occurrence probability of WLs and SWHs and performed MC simulations to derive failure probabilities and fragility curves for dune flood protection at the German Baltic Sea coast.

Yang and Zhang (2013) selected the Gumbel-Hougaard copula to assess the joint probability distribution of extreme winds and simulated SWHs in the Bohai Bay. Analyzing data relative to typhoon processes in Qingdao, Tao et al. (2013) developed a criterion to classify the intensity grade of storm surge by the joint return period of extreme PWL and corresponding SWH, based on four types of Poisson bivariate distributions utilizing the bivariate normal, Gumbel-Hougaard, Clayton and Frank copula. Salvadori et al. (2014) presented statistical techniques with application to wave data for performing multivariate design. Li et al. (2013, 2014) employed a Gaussian copula to model the dependency relation among maximum SWH, storm duration, PWP and PWL derived from data collected in the North Sea and simulate storm events for quantifying, within a MC approach, the potential probability of dune erosion volume and retreat distance under plausible sea level rise scenarios.

Two major issues are encountered in analyzing sea level time series for frequency analysis of extreme events. The first one is related to characterization of event structure in the time domain: the observed sea level process cannot be simply schematized through alternating random peak and calm periods based on a given critical threshold level, as it occurs in representing several hydrometeorological phenomena (rainfall, streamflow, drought) or in the case of sea storms. Furthermore, the temporal evolution of storm surge water levels significantly influences the morphological impacts on sandy beaches.

The second issue is associated with the presence of deterministic and long-term components in the astronomical tidal constituents, that cause significant correlation even at pluriannual lag, see Fig. 3.

Fawcett and Walshaw (2007, 2012) observed that long-period return levels, estimated from serially dependent extremes by using the standard peak over threshold approach, appear highly sensitive to the choice of declustering interval and may result significantly biased. They showed that, by initially ignoring any serial correlation between threshold excesses, bias in parameter estimates is virtually eliminated; however, the strength of serial correlation present in the extremes of the process needs to be taken into account when estimating return levels by selecting a suitable estimator for the "extremal index".

The aim of this paper is to describe an approach for the estimation of the present probability of marine inundation accounting for the interrelationship among the main sea condition variables, WL, SWH, PWP and direction of wave propagation, and their seasonal variability. Season of occurrence and direction of wave propagation are treated as discrete variables. The joint probability distribution of the pair of continuous variables PWL-SWH is estimated by using the copula based approach addressing abovementioned issues, while the joint distribution of SWHs and PWPs is separately derived from all available wave observations due to i) the different acquisition frequency of sea levels and waves and ii) the need for considering the peak sea elevations actually achieved during storm surge events (Masina and Lamberti, 2013). Following Poulin et al. (2007), the degree of association between simultaneous large values of WL and SWH is investigated for realistically estimating the occurrence probability of extreme conditions. The methodology is illustrated with an application to the coastal territory of the Italian Ravenna Province and the probability of inundation is estimated considering a failure function approach accounting for wave runup. The proposed approach aims to update and improve coastal inundation hazard analyses for hotspot areas at risk from combined impact of WLs and waves.

The article is organized as follows. The investigation area and the available data are presented in Section 2. The joint distribution of WLs and wave characteristics is analyzed in Section 3, dealing with event definition, technique for modeling the dependence of bivariate data, upper tail dependence and criteria for selecting the most suitable model to represent the observations. The procedure applied for estimating the probability of coastal flooding is outlined for a particular