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Coupling infrastructure resilience and flood risk assessment via copulas analyses for a coastal green-grey-blue drainage system under extreme weather events

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ABSTRACT

This study sheds light on the coupling of potential flood risk and drainage infrastructure resilience of low-lying areas of a coastal urban watershed to evaluate flood hazards and their possible driving forces. Copulas analyses with the aid of joint probability of simultaneous occurrence help characterize the complexity for hazard classification based on subsequent exposure to inundation under varying levels of adaptive capacity. Adaptive measures of consideration include traditional flood proofing structures and low impact development facilities for a coastal urban watershed - the Cross Bayou watershed, near Tampa Bay, Florida. Findings indicate that coupling flood risk and infrastructure resilience is achievable through the careful formulation of flood risk associated with a resilience metric, which is a function of the predicted hazards, vulnerability, and adaptive capacity. The results also give insights into improving existing methodologies for municipalities in flood management practices such as incorporating a multi-criteria flood impact assessment that couples risk and resilience in a common evaluation framework.

1. Introduction

1.1. Background

In May 2015, the Florida Legislature passed and the Governor signed into law SB 1094 [https://www.flsenate.gov/Session/Bill/2015/1094] which regards the consideration of future flood impacts in Florida Comprehensive Plans, particularly from a coastal management perspective. These new requirements, which concern development and redevelopment efforts to reduce flood risk, include natural hazards such as high tide events and sea level rise. Risk in this context can be described as the likelihood of a flood hazard occurring with an associated loss or negative impact. The likelihood of associated loss or negative impact is dependent on several factors, such as the flood hazard considered and the level of vulnerability to flooding. The concepts of hazard and vulnerability can be thought of as the physical manifestations or occurrences of adverse events and the propensity or predisposition to be adversely affected or susceptible to harm (IPCC, 2014), respectively, both of which influence flood exposure simultaneously. Flood exposure is dependent upon the spread of hazardous effects given vulnerability such as proximity to waterbodies and/or condition of drainage outfalls. The level of risk, however, can be influenced by the level of resilience through the connection to the adaptive capacity in a region such as a low-lying coastal area. The concept of resilience has expanded from its origins in material science and engineering to ecological resilience (Holling, 1973) and eventually to other disciplines such as the social sciences (social resilience) and psychology (psychological resilience). When considering infrastructure systems, such as drainage under flooding, engineering resilience, which is highlighted in this study, is the ability of such systems to absorb disturbance (i.e., flooding) and recover after a disturbance has occurred, or the ability to continue functionality under adverse conditions (Omer, 2013). While resilience is typically seen as an outcome, it should be viewed as a process which involves adaptation, anticipation, and improvement in basic functions of a considered system (Bahadur et al., 2010).

Coupling flood risk and engineering resilience is by no means an easy task. De Bruijn (2005) defined resilience, in terms of flood risk management, as the ability of a system to recover from floods.

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Quantitatively, this can be represented via several indicators such as the amplitude or magnitude of the reaction to disturbances, the graduality of reaction(s) under increasing disturbances, and recovery rate (De Bruijn, 2005). A resilient system results in a lower amplitude of reaction to disturbances, low graduality of reaction to increasing disturbances, and a higher recovery rate. Analogously this can be tied to three types of capacity of resilience, proposed by Francis and Bekera (2014), which include absorptive capacity, adaptive capacity, and restorative capacity. The absorptive capacity allows for adequate buffering to absorb or contain hazard effects while adaptive capacity is the ability to adjust or provide the necessary changes in response to adverse impacts such as when absorptive capacity has been exceeded. Restorative capacity is the ability to return to normal function or improved level of performance after a disturbance.

As with many systems, however, the absorptive capacity can fluctuate with changes in hazards, as is the case when considering future flood risk. Thus, adaptive capacity can be seen as a “bridge” to restorative capacity and eventually resilience when absorptive capacity has been exceeded. Adaptive capacity can be understood as the capacity to cope and adapt to adverse effects or, from a systems approach, the extent to which a system can modify its circumstances to move to a less vulnerable condition (Luers et al., 2003). Adaptive capacity also encompasses the ability to plan, prepare for, facilitate, and implement adaptation options (Klein et al., 2003), which first depend upon the nature of the disturbances or potential disturbances. Subsequently, additional factors such as scale of adaptation (individual to systemic), policy, and constraints must also be considered. Klein et al. (2003) has argued for the use of adaptive capacity as an umbrella concept that includes the ability to prepare and plan for hazards, as well as to implement technical measures before, during, and after a hazard event. All the while, the strategy for adaptive capacity must be flexible with respect to both risk and resilience (De Bruijn, 2005) in order to reduce rigidity in case of disruptive events (Park et al., 2013).

While adsorptive capacity can provide an “initial gauge” of resilience, failure is imminent when the adsorptive capacity is exceeded unless adaptive measures are taken. This is particularly concerning for system design based upon a particular risk event as opposed to system design adaptive to various levels of risk. Essentially, as Park et al. (2013) argued, the risk-based approach considers developing resistance to identified threats as opposed to resilience-based approaches which embrace uncertainty and failure due to possible threats via anticipation and adaptation. However, in this regard, risk and resilience cannot be applied individually but must work together. Risk provides a starting point for identifying potential problems or threats at hand; however, resilience considers how the progression can be maintained in the face of potential problems or threats.

1.2. Review of methods

When considering flooding in risk analysis and resilience assessment in particular, flooding can be caused by any combination of hazards which would impact both risk and resilience. This is particularly important for coastal communities, which are typically low-lying and can face heavy rainfall, high tide events, and sea level rise within the same time period. Subsequently, there exists a level of uncertainty of any combination of hazards occurring with corresponding consequence(s). Joint probability analysis is useful in this regard for determining the probability of potential flooding hazards occurring simultaneously rather than in isolation. A univariate analysis alone cannot provide a complete assessment of the occurrence probability of potential flooding hazards or scenarios, particularly if they are interdependent (Chebana and Ouarda, 2011). However, with typical multivariate analyses, one condition is for the variables in question to be independent from one another (Wahl et al., 2012). A univariate analysis also lacks consideration of flooding under multivariate hazards, particularly for coastal communities, when worst case flooding can occur under combined heavy rainfall and high tide events (Xu et al., 2014). The choice of multivariate analysis must take into consideration that the variables in question could be interdependent, may not be under the same family of marginal distributions, and are not normally distributed.

Both Bayesian networks and copulas have been utilized for analyzing multivariate problems (Cleophas and Zwinderman, 2013; Nelsen, 2006). However, Bayesian networks require the need for prior information or knowledge for defining conditional probability distributions and the structure of the network. Depending on the level of detail needed to build such networks, the computational demand can be quite large (Uusitalo, 2007) compared to copulas. For this reason, copulas can be particularly useful. While copulas have wide applications across several disciplines such as finance and insurance, the application of copulas within hydrology in particular is important since hydrological processes are typically multidimensional in nature and indicate certain levels of interdependence (De Michele et al., 2007). Several applications of copulas in hydrology (Table 1) consisted of analyzing the joint behavior of several hydrological variables during storm events while capturing important statistical dependences (De Michele and Salvadori, 2003; Salvadori and De Michele, 2004; Balistrocchi and Bacchi, 2011), modeling multivariate hydrological extremes (Favre et al., 2004; Zhang et al., 2011), rainfall frequency analysis (Zhang and Singh, 2007), flood frequency analysis (Wang et al., 2009) and hydraulic structural design for flooding (De Michele et al., 2005). Particularly for inland coastal areas, copulas have been useful in analyzing coastal hazards (Table 2) with underlying hydrological and hydrodynamic processes (De Michele et al., 2007; Wahl et al., 2012; Corbella and Stretch, 2013; Xu et al., 2014; Trepanier et al., 2014).

Table 1
Applications of copulas for varying hydrology topics.

Topic of Concerns	Copula Variables	References
● Rainfall Characteristics	● Storm intensity and duration^1 ● Rainfall volume and duration^2	● De Michele and Salvadori (2003)^1 ● Salvadori and De Michele (2004)^1 ● Balistrocchi and Bacchi (2011)^2
● Extremes	● Peak flows and volumes	● Favre et al. (2004)
● Rainfall Frequency Analysis	● Rainfall duration and intensity ● Rainfall depth and intensity ● Rainfall duration and depth	● Zhang and Singh (2007)
● Flood Frequency Analysis	● Peak flow (confluence)	● Wang et al. (2009)
● Structural Design (Flood Risk)	● Flood peak and volume	● De Michele et al. (2005)

Note: The superscripts in the second and the third columns link the respective copula variables in the second with their respective references in the third column.