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Modelling coastal flood vulnerability: Does spatially-distributed friction improve the prediction of flood extent?

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A R T I C L E I N F O

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A B S T R A C T

This paper examines whether the application of spatially-distributed versus static friction in hydrodynamic modelling increases the accuracy of predicted coastal flood extent using Pigeon Point, southwest Tobago, as a case in point. A two-dimensional hydrodynamic flood model is created from acquired and surveyed bathymetric, topographic and tidal data via the LISFLOOD-FP model code. Using a Landsat 8 image of the study area, a Maximum Likelihood (ML) supervised classification was performed to distinguish different land cover classes within the study site. The classified Landsat 8 image was further processed by assigning friction values to each land cover class to create a spatially-distributed friction file in ASCII format for use in LISFLOOD-FP. Using the flood model developed, simultaneous simulations were performed to assess the impact of storm surges (varying levels) on coastal flood extent at Pigeon Point utilising a static friction value, which broadly defined the area (i.e., 0.02), and the spatially-distributed friction file generated. Model outputs were compared to determine the extent of difference in flood prediction obtained from the application of static versus spatially-distributed friction through a Geographic Information System (GIS) based analysis. The flood model developed was subsequently applied to simulate an observed spring tide event using both static and spatially-distributed friction value(s) defined and model performance in each case was evaluated using the Root Mean Squared Error (RMSE) approach. Collated results indicated that using spatially-distributed over static friction do not increase accuracy of predicted coastal inundation extent, nor improve model performance. However, it appears to provide more insight on flood timings, which can be useful for coastal management.

1. Introduction

With global sea-levels (Cazenave & Le Cozannet, 2014; Stocker, Qin, & Plattner, 2013) and the frequency of extreme storm surges (Ding & Wei, 2014; Grinsted, Moore, & Jevrejeva, 2013;) set to increase, under climate change, Coastal Flood Vulnerability Assessments (CFVA) are needed, particularly for low lying coastal areas in Small Island Developing States (SIDS), due to their small size, densely populated coasts, and economic dependency on coastal tourism and resources. These assessments are critical for informing decision making in coastal management and, therefore, must be carried out with precision. There are two approaches to CFVA: (1) Using GIS and (2) Hydrodynamic Modelling.

The GIS approach to CFVA is primarily a function of topography, where flood vulnerable areas are found using a simple calculation procedure to determine areas lower in elevation than that of floodwater at some level. For this reason, the GIS method is termed the 'bathtub' technique and only requires the use of a Digital Elevation Model (DEM) representing the terrain of the land of the area of interest (Cooper, Fletcher, Chen, & Barbee, 2013; Gallien, Sanders, & Flick, 2014). On the other hand, hydrodynamic models enforce the laws of physics to describe the flow of water in the coastal environment by solving the governing equations of fluid flow (Abbot & Basco, 1989). These are usually the Navier-Stokes equations, which have been derived from Newton's second law of motion applied to fluids (Kantha & Clayson, 2000). For hydrodynamic modelling, these equations are scaled down to match the specific properties of the coastal ocean being studied and the resulting equations are called the shallow water equations (Chen, Navon, & Fang, 2009). These equations are based on the principles of conservation of momentum and mass (Chen et al. 2009; Kantha & Clayson, 2000). As a result, hydrodynamic models can take into account an array of factors that can potentially influence floodwater flow (i.e., friction, Coriolis force, atmospheric pressure,

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wind, natural and artificial barriers etc.). Therefore, they can provide a more precise output of coastal flood vulnerability (Gallien et al. 2014).

While hydrodynamic models may be better suited to demonstrating coastal water dynamics, input parameters for the assessment of coastal flood vulnerability need to be carefully defined, such as the specification of bottom friction, to ensure the accuracy of outputs. The incorporation of carefully-defined friction values in coastal modelling is important, since friction plays a key role in influencing the flow of floodwaters. Friction refers to the resistance that an object encounters when moving over another. Each type of land use and cover is assigned a specific friction value based on the level of influence they exert on floodwater flow. For example, flood waters will spread quickly over a flat, low lying, smooth surface, cleared of vegetation rather than over a mangrove, or forested area, since there will be no structure or barrier to impede the flow of water. In this case, a smooth surface and a forested area will have a low (i.e., 0.01 for concrete) and high (i.e., 0.1 for dense forest) friction value, respectively. The need for the incorporation of friction in coastal modelling is indirectly implied by Zhang et al. (2012) and Ferrario et al. (2014).

Zhang et al. (2012) applied the Coastal Estuarine and Storm Tide (CEST) model to indicate the role of mangroves in attenuating storm surges using the Gulf coast of south Florida as a case in point. The numerical model demonstrated that mangroves are more effective at limiting water levels associated with fast (rather than slow) moving storm surges. The CEST model also indicated that the decrease in water level is non-linear with the largest reduction in storm surge height occurring close to the seaward edge of the mangrove area. Similarly, McIvor, Spencer, Moller, and Spalding (2012) found that mangroves can lessen storm surge water levels by limiting water flow and reducing surface waves. They showed that mangroves can reduce storm surge water levels by up to 50 cm/km width of mangrove. Further to this, they proved that more than 1 km of mangroves can reduce greater than 75% of surface wind waves. As a result, they inferred that mangroves can play an important role in coastal defence either by itself or in conjunction with other risk reduction initiatives, such as sea walls or early warning systems. Mangroves ability to reduce the impact of storm surges is due in part to their root morphology (Ellison, 2014; Lacambra, Daniel, Spencer, & Moller, 2013), which exerts a significant influence on bottom roughness and, in turn, friction (Anthony, 2009).

Furthermore, Ferrario et al. (2014) performed a meta-analysis of more than twenty past studies that assessed how coral reefs across the globe dissipated wave energy in conditions ranging from normal surf to hurricane level waves. Their analyses revealed that coral reef crests and flats dissipated disproportionately further wave energy as incident wave energy amplified. Through non-linear regressions, they demonstrated that for reef crests and flats, wave energy reduction reached asymptotes of 91% and 67%, respectively. Further to this, their analyses indicated that coral reef platforms lessened on average 97% of wave energy, which would otherwise impact shorelines, whereas the reef crests alone dissipated more than 80% of said energy. Coral reefs, as a natural defence system, persist in shallow waters and exert a strong influence on bottom roughness and, therefore, friction (Cochard, 2013). For this reason, incoming waves break and dissipate their energy on reef areas, thereby sheltering the adjacent coastline from the full impact of storm surges.

While studies by Zhang et al. (2012), McIvor et al. (2012) and Ferrario et al. (2014) indirectly implied that the incorporation of friction in CFVA is important, standard modelling practice typically involve the use of a static friction value, which is usually modified in the calibration of flood models to provide the best fit between observed and predicted inundation extent (Horritt & Bates, 2002; Wilson & Atkinson, 2007). However, the use of a static friction value does not realistically represent friction and can lead to an overestimation of coastal flooding. In extreme sea-level events, it is possible that flood extent generated will be more of a function of topography rather than friction (Chini & Stansby, 2015). For instance, in cases where storm surge levels are particularly high, friction may exert a minimal or no influence on floodwater attenuation, since the depth and flow rate of the water can overcome these natural defences. In such instances, topography may be the deciding factor with regards to inundation extent. In this regard, the use of a static friction value for the assessment of flood vulnerability in hydrodynamic models is perhaps acceptable. While this may be a practical assumption, it was evident from the studies aforementioned that natural defence systems, such as mangroves and coral reefs, play an important role in reducing storm surge impact, including hurricane level waves (Ferrario et al. 2014). Therefore, it is possible that the use of spatially-distributed friction, to account for all land cover classes in the study site, might improve the representation of coastal flood inundation. Using this as a point of departure, this paper examines whether the use of spatially-distributed friction in coastal modelling 'significantly' improves the accuracy of predicted inundation extent. This is achieved using simultaneous modelling of storm surge impact at varying levels on the coastal floodplain at Pigeon Point, southwest Tobago, by applying both static and spatially-distributed friction via the LISFLOOD-FP model code.

2. Study site characteristics

Tobago is situated in the southern end of the Caribbean in a north-easterly direction from Venezuela, and is the smaller of two islands, which form the Republic of Trinidad and Tobago (Fig. 1). It is located on latitude 11°N, longitude 60°W. Pigeon Point is positioned on its southwest coast, and is the growth point of an accumulation feature, which is the result of an interrelationship between current directions, water depth, wave energy and sediment supply (Deane, 1993). Further, Pigeon Point is classified as a sand spit (i.e., a depositional landform created by longshore drift) and, most of its aerial extent, is sheltered by a fringing coral reef system called the Buccoo Reef Complex (Fig. 2).

Pigeon Point has been selected for this study because it is part of a multifaceted system that is comprised of mangroves and a coral reef system (Fig. 2). In addition, it is situated in close proximity to a densely populated and heavily commercialised region of southwest

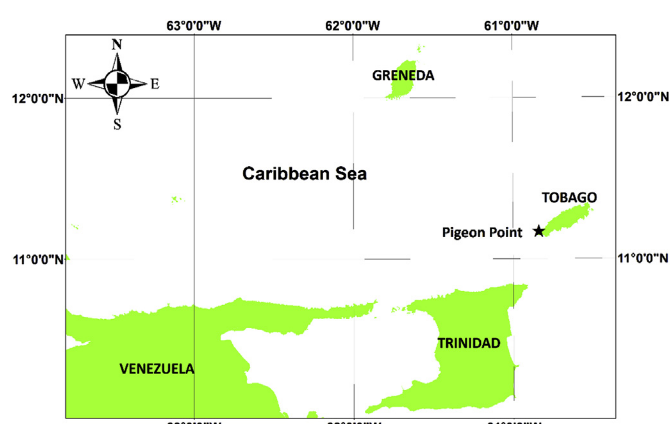

Fig. 1. Location of Pigeon Point, southwest Tobago.