Applied Geography 98 (2018) 22–33

Contents lists available at ScienceDirect

Applied Geography

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

Assessing tropical cyclone risks using geospatial techniques

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ARTICLE INFO

Keywords:
Tropical cyclone
Natural disaster
Hazard
Vulnerability
Risk
Analytical hierarchy process

ABSTRACT

Tropical cyclones are one of the most catastrophic natural disasters, regularly affecting coastal areas across the world. The intensity and extent of impacts by these disasters have remained very high throughout history. An appropriate mapping approach is essential for producing detailed risk assessments to plan for, and reduce the future impacts of cyclones on people, property and the environment. This study developed and evaluated a spatial multi-criteria approach for mapping the risk levels of areas to tropical cyclone impacts using remote sensing, field data and spatial analysis at a local scale covering $< 1000\,\text{km}^2$. We used the Sarankhola Upazila ($151\,\text{km}^2$), a local government area, from coastal Bangladesh to test the applicability of this approach. Three risk components: vulnerability and exposure; hazard; and mitigation capacity, and their 14 relevant criteria were considered. Thematic raster map layers were prepared for every criterion and weighted using an Analytical Hierarchy Process (AHP). A weighted overlay technique was used for generating individual maps for every risk component and then risk map was produced from them. The resulting maps successfully identified the spatial extents and levels (very high, high, medium, low, and very low) of risk. Our results indicate that eastern, south and south-western parts of the study area are likely to be subject to higher risk from tropical cyclone's surge height, strong wind and intensive rainfall than other parts. The approach provided was validated by confidence level assessment and a map of past cyclone impacts. Our preliminary findings indicate this approach has the potential to assess risks from tropical cyclone impacts in the affected countries by producing risk maps able to be used by policymakers and administrators.

1. Introduction

Tropical cyclones are one of the most catastrophic hydro-meteorological natural disasters in coastal environments (Li & Li, 2013). These deadly disasters are associated with strong winds, heavy rainfall and large storm surges resulting in widespread human, economic, social and environmental losses (Hoque, Phinn, & Roelfsema, 2016a; Puotinen, 2007). The occurrences and impacts of tropical cyclones are very common in many coastal areas across the world (Peduzzi et al., 2012). According to the statistics, at the global level, 637 tropical cyclones were reported during the period of 1970–2010 (Weinkle, Maue, & Pielke, 2012). Over the last two centuries, about 1.9 million people have lost their lives due to tropical cyclones worldwide (Shultz, Russell, & Espinel, 2005). Tropical cyclones cause the largest economic and environmental losses compared to the other hydro-meteorological natural disasters (Pielke et al. 2008; Hoque, Phinn, Roelfsema, & Childs, 2016b). Tropical cyclone disasters in the Gulf and east coast of the United States cause, on average, nearly US 5 billion dollars damage per year (Burroughs, 2007). Moreover, it is predicted and expected by recent studies that the intensity and frequency of tropical cyclones will increase enormously under future climate change scenarios (Deo & Ganer, 2014; Krishnamohan, Mohanakumar, & Joseph, 2014; Mendelsohn, Emanuel, Chonabayashi, & Bakkensen, 2012; Yin, Yin, & Xu, 2013). Consequently, coastal lives, resources and environments will be under constant threats in the future (Hoque, Phinn, & Roelfsema, 2017a).

Prevention and reduction of tropical cyclone disaster impacts are core disaster management activities (Yin et al., 2013). The key infrastructure and areas at risk in relation to spatial location, level of risk and factors liable for risk are required information in the context of finding suitable cyclone mitigation options (Gao et al., 2014; Li, Ahuja, & Padgett, 2011). This type of information is usually derived from risk assessments. Risk assessments are the essential groundwork to prevent and reduce the impacts of cyclones (Birkmann, 2007; Hoque, Phinn, Roelfsema, & Childs, 2017b). An effective risk assessment procedure includes the mapping of potential hazards, along with their resultant

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https://doi.org/10.1016/j.apgeog.2018.07.004
Received 9 March 2017; Received in revised form 22 June 2018; Accepted 2 July 2018

vulnerability and exposure levels, and the capacity of existing mitigation (Cutter, Boruff, & Shirley, 2003; Dewan, 2013a). Hazards are events (Blaikie, Cannon, Davis, & Wisner, 2014) which affect life, property, and the environment (Dewan, Islam, Kumamoto, & Nishigaki, 2007; Rashid, 2013). Vulnerability is linked to the exposure of element at risk and the extent to which a community and environment are likely to be affected by a hazard (Eckert, Jelinek, Zeug, & Krausmann, 2012; Rashid, 2013; Turner et al., 2003). Exposure is proportional to the population and property value located in hazard-prone areas. Mitigation capacity involves structural and non-structural initiatives (e.g. cyclone shelter, warning system) used to reduce the impacts of tropical cyclone hazards (Coppola, 2006; Khan, 2008). While vulnerability, exposure, and hazard act simultaneously to contribute the risk of natural hazard, but mitigation capacity reduces the risk. The maps produced by risk assessment have been used by policymakers and administrators to devise effective management plans with targeted prevention and reduction measures (Mahapatra, Ramakrishnan, & Rajawat, 2015; Masuya, Dewan, & Corner, 2015; Yin et al., 2013). Thus, the risk assessment procedure can minimise disaster losses and even provide protection from disaster occurrence.

Several studies were conducted using remote sensing and spatial analysis for mapping the hazard, vulnerability and risk of tropical cyclone disasters using different approaches by Li and Li (2013); Yin et al. (2013); Rafiq, Blaschke, and Zeil (2010); Yin et al. (2010); Kumar and Kunte (2012); Saxena, Purvaja, Suganya, and Ramesh (2013). Accurate and detailed tropical cyclone risk information is determined by the selection of appropriate and sufficient criteria, scale as well as components of risk (Dewan, 2013a; Rashid, 2013). Adequate criteria selection under each of the risk components (e.g., hazard, vulnerability and exposure, and mitigation) and their processing serve as a foundation to assess the risk in a more reliable way (Birkmann, 2007). Similarly, the size of the study area (local or regional scale) is a vital issue in deriving detailed risk information (Wang, Li, Tang, & Zeng, 2011). Detailed local level risk information is required to identify the type of risk accurately as well as to select the best mitigation options in the process of appropriate management plans (Blaikie et al., 2014). However, most available studies have been conducted based on limited criteria and were at the regional scale.

Another fundamental issue with risk assessment is the selection of risk components. Generally, risk is considered as the product of vulnerability, exposure and hazard (Birkmann, 2007). The evaluation of actual risk to a particular community, resources and the environment not only depends on the level of vulnerability, exposure and hazard, but also on the existing mitigation capacity to prevent and reduce the disaster impacts (Cutter, 1996; Frazier, Thompson, & Dezzani, 2013a). To assess the actual risk information, it is essential to incorporate mitigation capacity in the risk assessment procedure (Cutter et al., 2003). Currently, very few studies are available in the existing literature focusing on multi-criteria integrated tropical cyclone risk assessment at the local scale covering $< 1000\,\text{km}^2$ and incorporating mitigation capacity using remote sensing and spatial analysis.

Geospatial techniques using remote sensing and spatial analysis are efficient and accurate tools for deriving the information sources required for tropical cyclone risk assessment (Rafiq et al., 2010; Taramelli, Melelli, Pasqui, & Sorichetta, 2008; Yin et al., 2013). Remote sensing provides a capability to deliver maps of environmental features at repeated time frames from spatial scales of a few meters to entire continents. This essential environmental information enables the spatial risk assessment of natural hazards (Mahendra, Mohanty, Bisoyi, Kumar, & Nayak, 2011; Martino, Ulivieri, Jahjah, & Loret, 2009). Spatial analysis supports data collection and analysis as well as the integration of spatial and aspatial data for spatial decision making (Cutter et al., 2003; Dewan, 2013a; Kunte et al., 2014).

The spatial decision making processes weighting and ranking are required to integrate multi-criteria of risk components in the risk assessment process (Roy & Blaschke, 2013). Analytical Hierarchy Process (AHP) is an effective tool for combining a larger number of input variables, for example on hazard and vulnerability, in a multi-criteria decision making process to derive risk assessments (Malczewski, 1999). AHP allows for the analysis of the spatial multi-criteria layers through the generation of a hierarchical structure providing weighting and ranking to support the spatial decision making process with the views of experts and user (Dewan, 2013b). A weighted overlay technique is used to integrate weighted and ranked spatial criteria together. AHP has been successfully used for mapping hazards, vulnerability and risk of other natural disasters such as floods, landslides, and earthquakes, hence it is considered suitable for tropical cyclone risk assessment (Abella & Van Westen, 2007; Chen, Ito, Sawamukai, & Tokunaga, 2015; Panahi, Rezaie, & Meshkani, 2013; Roy & Blaschke, 2013).

This study developed and examined a risk mapping approach for tropical cyclone impacts using AHP to combine information derived from remote sensing, field data and spatial analysis at a local scale. The study was divided into three specific objectives: (1) develop a spatial AHP based multi-criteria integrated risk mapping approach for tropical cyclone impacts; (2) examine the developed approach for mapping tropical cyclone risk at the local scale covering $< 1000\,\text{km}^2$ in Sarankhola upazila, Bangladesh; and (3) assess the validation of the risk mapping approach.

2. Study area

The study was carried out in Sarankhola Upazila, a local government area, (about 151.24 sq. km) of Bagerhat District which is located in coastal Bangladesh (Fig. 1). The study area was chosen as tropical cyclones are the most common disaster in coastal Bangladesh, striking the country almost every year with a varied scale (Choudhury, Paul, & Paul, 2004; Islam & Peterson, 2009). About 508 cyclones originated in the Bay of Bengal in the last 100 years, and out of them 17% struck coastal Bangladesh (Paul, 2009). The selected study area is one of the most tropical cyclone prone coastal Upazilas located on the mouth of the Bay of Bengal in the southern part of the country (Islam, Bala, Hussain, Hossain, & Rahman, 2010; Nadiruzzaman & Paul, 2013). The area is open to the sea surface as well as subject to high storm surges by the coastal Baleshwar and the Bhola River which surround it on both sides. As a lowland and densely populated area, human as well as all kinds of natural and physical resources are highly vulnerable to tropical cyclone impacts by strong winds, flooding and storm surges (Islam et al., 2010). This coastal area is characterised by a humid climate and annual rainfall is 2200 mm. Tropical cyclones typically originate and strike the area in the period of March–July and September–December due to the dominance of humid air in the nearby ocean (Islam & Peterson, 2009).

3. Materials and methods

3.1. Overview

The geospatial multi-criteria assessment technique in the form of AHP is adopted in this study to integrate many natural and anthropogenic criteria in the risk assessment process. This approach can integrate and aggregate many criteria easily and can present output in very simple manure (Dewan, 2013b; Yin et al., 2013). Several risk equations are available for risk mapping for any kind of natural or man-made hazard. A well-developed and complete risk equation with its components gives a better risk evaluation. On the basis of reviewing existing literature, the following risk equation has been considered for evaluation of tropical cyclone risk in this study:

$$\text{Risk} = \text{hazard} \times \text{vulnerability} \times \text{exposure}/\text{mitigation capacity} \quad (1)$$

The processes used in this study are summarised in Fig. 2.