DETERMINING URBAN FLOOD VULNERABILITY USING AN INDICATOR BASED APPROACH

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Abstract

With increase in urbanisation and climate change, urban flood (UF) is becoming more frequent and intense – surpassing other types of flooding in terms of death and damage to critical infrastructure (CI) buildings. Guwahati, gateway to the eight states of north-east India, is prone to recurring UF – three to four times annually. The lack of an urban drainage network has added to the suffering of the residents. A major portion of the building stock are non-engineered and many new constructions are without UF compliance. Considering that the population and buildings are at risk, this research aims to develop a comprehensive UF vulnerability index (UFVI) as a combination of two indices – human vulnerability index (HVI) and building vulnerability index (BVI). Modified on various concepts of vulnerability assessment for hazards in the developing world, the UFVI has been proposed considering inherent hardships related exclusively to UF. For this purpose, in a prior survey conducted in the 31 municipal wards of the city, relevance of the HVI was checked by choosing residents as survey respondents and the BVI will be conducted based on the concept of rapid visual screening (RVS) of buildings. The HVI stratified the population into five tiers ('very high' to 'very low') and the BVI is expected to stratify the CIs similarly. These two indices will be combined in HAZUS-MH platform to obtain the UFVI ward-wise. This paper puts forward a theoretical explanation of the method that will be incorporated once the BVI is developed and while combining HVI and BVI to develop the UFVI. The composite UFVI that will be obtained will contribute to long-term actions for improving resilience of the existing population and CIs of the city against UF.

Keywords

building vulnerability, critical infrastructure, HAZUS-MH, human vulnerability, urban flood

1. Introduction

Disasters, such as earthquakes, floods, landslides and fires, significantly affect the community and infrastructures. Most of these phenomena are characterised by short action, but their impacts on buildings and other tangible structures, persist for years (Karimzadeh *et al.*, 2014). Some recent disasters in India (e.g. Cyclone Fani 2019, the Kerala floods 2018, the

Uttarakhand flash floods 2013, etc.) or in rest part of the world (e.g. the 2011 Tohoku earthquake in Japan, the 2010 Haiti earthquake, the 2008 Sichuan earthquake in China, etc.), resulted in huge damage to people, buildings and critical infrastructures (CI) (Bach *et al.*, 2013; Upadhyaya, 2018; Senapati, 2019).

Urban floods (UF) are among the most recurring hazards, impacting human lives and causing economic damage throughout the world. (Jha, Bloch and Lamond, 2012) has compiled various case studies from Argentina, Germany, Mozambique, and Indonesia, where UF is an annual issue. And with the onset of climate change, it is apprehended that UF risks will not subside in the future, but its increasing intensity and frequency will threaten many more regions of the world (Jonkman and Dawson, 2012). Casualties and damages are also increasing globally due to (a) haphazard, rapid and unplanned urbanization and (b) the impacts of global change on climate – heavy rains and run-off conditions because there is a direct relationship between urbanization and hydrological characteristics – decreased infiltration, increase in run-off, increase in frequency and flood height (Alaghmand *et al.*, 2010). This scenario implies that urban areas suffer from a comparatively high flood risk due to their high population density and many CIs to cater to this population. Out of the existing body of disaster studies, UF is a comparatively new topic but showing exponential growth in its occurrence in several urban areas of India experiencing rapid development (Sarmah and Das, 2018b).

Different methods to assess or determine hazard, risk and vulnerability to UF have evolved in recent decades (Hartanto *et al.*, 2011; Xia *et al.*, 2011; Gichamo *et al.*, 2012). CIs can be interrupted by a variety of threats. Hence the vulnerability assessment of these buildings and the dependency of the population on these CIs are essential to “build back better” (Bach *et al.*, 2013). In this context, if CIs are affected by flood, it has to be resilient enough to still function or be quickly restored to normalcy (Mcbain, Wilkes and Retter, 2010). Focussing on this, the present study has tried to combine a human vulnerability index (HVI) and a building vulnerability index (BVI) – both developed by the authors in a prior work – to form a composite UF vulnerability index (UFVI) to understand the criticality of UF on the people and buildings in the city of Guwahati – the financial capital of north-east India. Disaster in these north-eastern states has a broader significance because it is graded as seismic zone V of India (Rajendran and Rajendran, 2011) and is situated in the flood prone valley of the indomitable Brahmaputra River. Guwahati, the largest urban area of the region, narrowly connects the seven north-eastern states to the mainland via road, rail and airways. Any critical issues in Guwahati can hamper this connectivity and the lifeline of the entire north-east region will be cut-off (Sarmah and Das, 2018a) thus causing disruption to transport, power and telecommunication and as a result damage to life.

2. Literature Review

This section outlines the direct impacts of UF on the primary receptors – people and buildings (more precisely CI) – and the integration of these two for a holistic UF management scenario.

2.1. Human Vulnerability

UF poses a serious challenge to the lives of people, especially the urban poor of the rapidly growing urban areas in developing countries (Jha, Bloch and Lamond, 2012). These people residing in the informal settlements or slums are frequently at highest risk of UF. (Du *et al.*, 2010) mentioned that more deaths occur during a UF or flash flood event as compared to slower riverine floods. Different authors have noted different death causing reasons in the developing countries such as Bangladesh, Vietnam, etc. In 1990 the United Nations Development Programme (UNDP) along with economist Mahbub-ul-Haq and Nobel Laureate Amartya Sen defined human development in a comprehensive way through the concept of Human Development Index (HDI) (UNDP, 2006), where life expectancy, education and per capita income were used as indicators to rank countries into four tiers ('very high', 'high', 'medium', 'low'). In the same vein, over the years many researchers have developed several context-specific customised indices (Cutter, Mitchell and Scott, 2000; Khan and Salman, 2012; Ghislandi, Sanderson and Scherbov, 2019). As a response to the large and unexpected shock brought by any disaster people's behaviour changes in relation to the magnitude and negative shock and it has been studied how people with different socio-economic backgrounds (the poor), age (the elderly and the youngest members) and gender (the women folk) cope with the losses (Sawada and Shimizutani, 2008; Jha, Bloch and Lamond, 2012). Against this background the authors in a prior study has tried to deal with the losses that communities suffer during and after UF by developing an index depicting human vulnerability.

2.2. Building (Critical Infrastructure) Vulnerability

CIs are often interconnected systems that are so essential to our day-to-day life that any interruption to these services can cause significant disturbance to societies (Bach *et al.*, 2013). Different countries have adopted different definitions of CIs according to their respective requirement. In the United States (US), "CI is defined as systems and assets, whether physical or virtual, so vital to the US that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" (Riedman, 2016). Similar definitions have been adopted by Australia, Germany and the European Union. United Kingdom has categorised the CIs according to their uses in UF vulnerability as essential CI, highly vulnerable, more vulnerable, less vulnerable and water compatible development (CPNI, 2016). India till date has no official definition for CIs.

The direct impacts of UF on the buildings affect the basement floors, underground utilities, corrodes metal elements and overall affect the structure that will require repairs and refurbishment (Riedman, 2016). The indirect impacts include the loss of business processes (Jha, Bloch and Lamond, 2012). Hazards can however affect CIs in various ways. In 2005 hurricane Katrina made the drinking water infrastructure in the city of New Orleans inoperable due to power outage in the excessive wind and flood water inundation followed by contamination issues for a prolonged period (Bach *et al.*, 2013). In 2011 river and flash floods in Brazil combined with landslides posed serious risks when the key infrastructures such as electricity, running water and phone lines were affected (Jha, Bloch and Lamond, 2012). India's capital city Delhi suffered from severe water crisis in 2012 where most middle-class households did not have a dependable source of clean water due to extreme heat waves (Bach *et al.*, 2013). Against this background, in an ongoing study by the authors, has

tried to deal with the losses that CIs suffer during and after UF by developing an index depicting building vulnerability.

Current methods of UF vulnerability assessment of buildings are lengthy and detailed processes. It is measured in terms of depth, duration or quality of water, among which the first one is the most common. These are further used for evaluating the cost of damage (Jha, Bloch and Lamond, 2012). (Godfrey *et al.*, 2015) assessed the vulnerability of different building typologies to multi-hazard using depth-damage curves from existing literatures, though very few publications describe the derivation of the depth-damage function in detail. (Kelman, 2002) gave an overview of damages by “slow-rise” flood water based on the depth and duration. (Pistrika, Tsakiris and Nalbantis, 2014) developed a depth-damage curve for an area in Athens, Greece, by using actual flood data and compared the same to the functions of other areas with similar conditions; whereas (Martina *et al.*, 2015) used a synthetic approach to develop a damage model for the buildings of Italy.

Of the many vulnerability assessment methods, Rapid Visual Screening (RVS) is a quick, simple and inexpensive method without performing any structural calculations or instrumentations. Based on sidewalk visual survey a data form is filled up to determine the probable damages caused by a disaster to a structure. Though RVS is mostly used for seismic assessment (IRC-NRC, 1993; JBDPA, 2001; Jain *et al.*, 2010; FEMA, 2015), RVS sheets can be customised based on the context (Lang, 2002) and can be used for other disasters such as cyclone (Dutta and Mukhopadhyay, 2012; Mukhopadhyay and Dutta, 2012). RVS is used to find out if a particular building requires simple precautionary measures during a hazard or it requires detailed investigation. In this manner a homogeneous region can be selected and accordingly ratings can be done to find the recovery measures specific to that area. Moreover, because the synthetic depth-damage curve estimates the potential damage of a building and RVS indicates the level of retrofitting under the disaster, both uses similar principles and hence can be logically combined. (Jha, Bloch and Lamond, 2012) has suggested five restoration steps for buildings which get flooded but remain structurally sound – assess damage, clear and remove standing water and decontaminate, determine appropriate treatment, drying phase and repair phase.

2.3. Linkage between Human and Building Vulnerability

Taking human and infrastructure vulnerability as a whole is an integrated approach to UF management. Most of the losses caused by disasters are due to interaction between the physical environment and the social-demographic features. Determining and considering both the factors enables the identification of points which are highly vulnerable in various aspects, giving a holistic idea of the disaster and the affected area (Yucel and Arun, 2012). Adequate operation and maintenance of the CIs with continuous communication with the people to keep them prepared are two major principles for integrated UF management (Jha, Bloch and Lamond, 2012). Furthermore, the CI itself can become a hazard, as failure of one can have cascading effect on other buildings or even injure people. UF damage to CI is a considerable concern as it affects the ability of the people to respond during the event and recover after it. The UF hazard map of the study area of Guwahati city created by the authors in a prior study, along with the two indices and plotted on map, is a valuable aid to decision-making. The composite index created will also be plotted on map because they are visual tools for communicating the hazard situation (Jha, Bloch and Lamond, 2012).

Approaches such as vulnerability assessment or vulnerability index will help the city to be resilient and reduce the recovery time, allowing business-as-usual to continue.

Human and building vulnerability have been linked by different approaches ranging from global models such as Prompt Assessment of Global Earthquake for Response (PAGER) operated by United States Geological Service (USGS) or local (case-based) models such as HAZards United States – Multi Hazards (HAZUS–MH). HAZUS–MH is applicable for estimating potential losses due to earthquakes, floods and hurricanes, on a regional basis (FEMA, 2015). This hazard analysis tool was developed by the Federal Emergency Management Agency (FEMA), United States in 1997 and over the years has undergone many modifications. It graphically illustrates the identified high-risk locations, in ArcGIS, due to different hazards. Users can then visualize the spatial relationships between population and buildings with the geographic conditions for the specific hazard being modelled.

(Singh, 2005) used HAZUS to estimate building damages (structural and non-structural) and assessed that there is a strong relation between the damage and the number and severity of casualties. An area where buildings are of poor quality and has high concentration of people, there the vulnerability is very high. The author used both the top-down (HAZUS based) and bottom-up (community based) approaches to determine the building and population loss estimation. On the other hand, (Petal, 2004) put forward that although HAZUS categorises buildings and population into four tiers of damage each, it does not give the variation in casualty rates across the building types; but relationship between building damage and casualties can be calculated using seven parameters. In another study on Dehradun city, India, (Gulati, 2006) found that there is a direct relationship between the damage to buildings to the number of people affected. HAZUS, as a tool developed in the United States, its applicability was checked for analysing the buildings and population in the Indian scenario, by (Gulati, 2006), and found that it did not give very realistic results when ward-wise data was considered. But the method gave good results in the city level evaluation. Thus it was inferred that HAZUS method needs modifications so that it gives more accurate results in the Indian context.

3. Methodology

The proposed methodology (Figure 1) aimed to combine the two indices – HVI and BVI – which define the UF hazard profile of Guwahati city and to develop a composite UFVI using HAZUS – MH. After Guwahati became the state capital in 1971, there has been a manifold rise in its population (38.6% decadal growth from 1971) (MHA, 2011). The Guwahati Municipal Corporation (GMC) underwent divisional changes from 34 wards in 1974, 60 wards till 2013 and at present constitutes of 31 wards.

Figure 1: Proposed methodology

In a prior study conducted by the authors, an UF hazard map was developed for the city by taking opinions from experts working on UF. Using analytic hierarchy process or AHP (Saaty, 2008), they compared seven causative factors of Guwahati UF using the conventional 9-point scale (1= equal importance; 9= extreme importance). These factors collated from detailed literature review were – contour and slope; rainfall distribution; soil type; choking of natural drainage; land-use; population density; road network. These seven thematic layers were created using remote sensing data and geo-informatics system to derive the final hazard map of Guwahati. Accordingly, 31 wards were divided into five hazard groups, namely, ‘very high’ (9 nos.), ‘high’ (7 nos.), ‘medium’ (10 nos.), ‘low’ (3 nos.) and ‘very low’ (2 nos.). Further, in order to find the vulnerability of the population, ward-wise questionnaire survey was done by taking feedbacks from the residents living with the recurring UF. The questionnaire was developed based on the HDI and other vulnerability indices and modified to suit the current context. It had questions grouped under six key constructs namely, household, education, health, income, dependency on public infrastructure (drinking water, sanitation, waste disposal) and some special conditions during UF. The responses recorded were scored accordingly and HVI was calculated for all the 31 wards. The range between the maximum possible HVI to the minimum possible HVI was equally divided under five HVI groups. The ‘very high’, ‘high’ and ‘medium’ zones had 7 wards in each. And the ‘low’ and ‘very low’ zones had 5 wards in each. The result was fairly different from UF hazard map of Guwahati city developed by the authors. It defied the general custom to take flood hazard as flood vulnerability.

In a second study conducted by the authors, the CIs located in the 216 sq. km. of GMC area were surveyed for UF vulnerability assessment using RVS. The sample survey consisted of reinforced cement concrete (RCC) buildings, confined masonry buildings and the typical Assam-type (Ikra houses). This sampling was done from GMC tax records. A combined list of CIs was collated from a list noted by the city local bodies and various literatures. The same was modified to suit the Indian context in the UF scenario (CIs vital for rescue-recovery, essential and others). The authors developed a RVS sheet for assessing the performance of

three types of common building typologies against UF. Each of the parameters contributing to building vulnerability has a 'score modifier' which determines which parameter has a positive or negative influence on the 'base score' or 'overall score' of the building type. Relevant parameters based on their role in defining building vulnerability against UF were collated from literature.

Thereafter, HVI and BVI can be joined in GIS-based HAZUS-MH by running the model with the dataset of the human and building vulnerability parameters. This will give the loss estimation for the population in terms of number of people and for the building stock in monetary terms. The ratio of loss estimated and the vulnerable population will be R_{Human} and the ratio of loss estimated and the vulnerable building stock will be R_{Building} . Using weighted average of both, the composite index (i.e. UVFI) can be calculated. The weights will be calculated using multiple-criteria decision analysis technique.

4. Key Findings and Discussions

After measuring the human vulnerability and the ongoing work of measuring the building vulnerability, it was found by the authors that these two have strongly co-related variables that increase UF vulnerability. Such as education, age, gender, income, past disaster experience, poverty, isolation, lack of social security services, funds for disaster prevention and mitigation, location of buildings, material of buildings, maintenance, unprecedented population growth, CIs providing services, health services, etc. In this study the HVI and BVI will be combined in HAZUS—MH interface to arrive at a common UVFI, because according to (NDMA, 2010; Jha, Bloch and Lamond, 2012) vulnerability maps are based on two major factors – the buildings and CIs at risk and the vulnerability of the users. A total of six constructs in case of HVI and 20 parameters in case of BVI will be considered. The combined UVFI will give a composite index that will represent overall performance of the city during UF. This will categorise the 31 wards of the city into five tiers of UF vulnerability ('very high' to 'very low'). When CIs are situated in UF prone areas and the existing population also cannot be relocated, the composite index will help in enhancing decision-making procedures; for example, investments in the cities can be assigned in the best form. This index after being developed for Guwahati city can be used to determine which wards in the city are most vulnerable to UF.

5. Conclusion

Studies on UF hazard, human vulnerability and building vulnerability have become substantial for CIs since these buildings are used by the entire population. The direct and indirect effects that these CIs face, can severely affect societies and become a threat to the urban areas. The city of Guwahati is submerged in UF waters 3-4 times annually. The present study combines the vulnerability indices of humans and buildings (CIs) to UF in the city of Guwahati, using remote sensing data and geo-informatics. This will identify the city resources (both human and buildings) under threat and thus prioritize the assistance by concentrating efforts in those locations and channelling resources. This is an example of a local scale study which proposes a holistic approach by combining the two approaches (population and CIs). The study is limited only to the CIs of the city and overlooks the possible effects of other

disasters. For instance, Guwahati lies in the flood-prone Brahmaputra valley, which is so mighty and is known as a moving ocean. The entire north-east region is located in the seismic zone V in the earthquake hazard zones of India. Buildings on stilts are good for UF but open storey buildings are dangerous for areas in high seismic zones. Similar method can be adopted for the residential buildings. This is a generic method which can be applied for other disasters such as riverine floods, earthquakes and hurricanes, by considering area specific human and building vulnerability parameters. This study is a novel approach to combine the vulnerability of the human and the building component which defines the structure of any city in a developing country like India.

6. References

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