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Waterlogging risk assessment: An undervalued disaster risk in coastal urban community of Chattogram, Bangladesh

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Abstract

In recent years, rainfall-induced waterlogging has become a common hazard in the highly urbanized coastal city of Chattogram, Bangladesh resulting in high magnitude of property damage and economic loss. Therefore, the primary objective of this research is to prepare a waterlogging inventory map and understand the spatial variation of the risk by means of hazard intensity, exposure, and vulnerability of waterlogging. In this research, the inventory map and factors influencing waterlogging hazard were determined from a participatory survey and other spatial data including land elevation, population, and structural data were collected from secondary sources. Analytical Hierarchy Process was applied to measure the hazard intensity and the exposure and vulnerability were estimated by overlaying the spatial data onto the hazard intensity map. A total of 58 locations in 22 wards have been identified as waterlogging affected, which covers ~8.42% of the city area. Obtained waterlogging vulnerability index map suggests that ward no. 5, 6, 16, 17, and 33 are greatly vulnerable to waterlogging in terms of their social, infrastructure, critical facilities, economic and environmental vulnerability. We show that ~2.71% of the study area is at very high risk, while the risk score is considerably higher for ward no. 5, 8, 17, 19, and 33.

Keywords: waterlogging, vulnerability, risk, participatory survey, GIS, Chattogram

1. Introduction

Urban waterlogging caused by heavy rainfall has become an increasingly prevailing problem for the city dwellers and is creating adverse economic, physical, social, and environmental consequences in major Asian cities such as Tokyo, Beijing, and Dhaka (Islam & Das, 2014). Rapid population growth, unplanned urbanization, and climate extremes are the major triggering factors for making this disaster more frequent in recent years (Sun et al., 2020). Unlike other disasters, waterlogging-induced human losses are not common, billions of dollars in damage are inflicted upon city's infrastructure every year by this event. For example, The Ministry of Land, Infrastructure, Transport and Tourism of Japan had shown that 86% of total economic flood damage in the Tokyo metropolitan during 1998–2007 was only due to waterlogging (MLIT, 2008). From 2001 to 2018, there was an average of more than 40 million people affected by waterlogging and caused more than the US $10 billion economic losses each year in urban areas of Eastern China (Sun et al., 2020). Although a massive investment in the improvement of waterlogging control infrastructures has been made, it remains a major disaster risk throughout the Asian countries and the case of urban areas in Bangladesh is also similar. Along with the reasons above, Bangladesh is greatly susceptible to waterlogging due to two-thirds of its' land is less than five meters above sea level (Dasgupta et al., 2011; Islam & Das, 2014). In particular, 2009-14 period, waterlogging disasters caused yearly 2677 million BDT (Bangladesh currency) in property damages at the household level. It is estimated that if there was no such economic loss in that period, GDP volume could be increased by 0.02% per year (Bangladesh Disaster-related Statistics, 2016). These exemplify the importance of assessing waterlogging risk for alleviating its' impact on society and development works.

Waterlogging generally brings shallower inundation depth and slower flow velocity than floods but causes severe disruption of regular city life, including traffic paralysis, infrastructure damage, health, and environmental problems in Bangladesh (Subrina & Chowdhury, 2018). At present major urban areas such as Dhaka, Chattogram, and Khulna have been suffering from waterlogging almost every year in the monsoon season. In 2014, more than 65,000 households were affected by rainfall-induced waterlogging disasters in southern coastal districts only (Bangladesh Disaster-related Statistics, 2016). Sarkar et al., 2020 reported that 38% of coastal inhabitants in southern Khulna city experience short-term waterlogging every year. More recently, Chattogram, the most prosperous economic region of Southern Bangladesh, suffered its highest recorded economic damage of 6000 million BDT caused by several waterlogging events in the single financial year of 2017 (Quddusi, 2017). Although disaster risk management practitioners widely investigate water disasters, mostly in assessing fluvial flooding risk, less attention has been paid to the sufferings caused by the waterlogging disasters (Islam & Das, 2014).

Risk assessment as a pre-requisite for an effective warning is essential to mitigate the risks to life and property posed by disasters. The Bangladesh Meteorological Department (BMD) has been responsible for monitoring and reporting weather data as well as forecasting rainfall over many years. The BMD issues heavy rainfall warnings when the estimated rainfall within 24 hours over an area is 44 mm or more. This warning has four contents: (1) expected affected area; (2) approximate time of commencement; (3) severity of the heavy rainfall; (4) future status of heavy rainfall condition (Hossain, 2007). On the other hand, Bangladesh Water Development Board utilizes the European Centre of Medium-Range Weather Forecasts rainfall data for forecasting large-scale floods, including fluvial and flash flood (Rahman et al., 2012). However, the authorized department for assessing risk, forecasting, and issuing warnings for urban waterlogging has not been established until now. Mainstreaming waterlogging risk in national disaster risk management is fundamental to achieving reductions in related loss of economy and property damage. Essentially, such improvement can only be achieved through an in-depth understanding of both the physical factors of waterlogging and its degree of risk in a particular area.

Many previous studies have revealed that heavy rainfall is not the only other critical factors can markedly influence waterlogging; others, including land-use changes, unplanned urbanization, low terrain profile, backwater effect, and absence of proper drainage planning and management, also have an impact (Quan et al., 2010; Suriya & Mudgal, 2012; Ning et al., 2017; Akter et al., 2017). Consequently, a range of different risk assessment methodologies for waterlogging has been introduced. For example, Quan, (2014) performed hydrological modeling and GIS spatial analysis for Shanghai city, considering hypothetical heavy rainfall conditions, terrain, building, and drainage system as impact factors. It showed that the water depth, vulnerability, and economic loss tend to increase as rainstorm intensity increases. Employing a similar method but for a small-scale urban area (Jing'an district) in Shanghai, Yin et al., (2011) developed stage-damage curves and explained that for maximum inundation depth of 50 cm, the average annual waterlogging loss could be reached as much as RMB 3.42 million yuan. Shi, (2012) analyzed the risk of a 50-year return period rainstorm waterlogging by integrating a hydraulic model with GIS over the same region. The study found that water depth and population density were the determining factors for the correlation among exposure, vulnerability, and waterlogging risk. Smith et al., (2015) applied a hydrodynamic model in Carlisle, North West England, to assess the impact of sustainable drainage system design for urban flood modeling. Sarkar et al., 2020 utilized a MIKE hydrological model for Khulna, Bangladesh and showed that both the existing drainage area and capacity are inadequate to mitigate waterlogging risk. Inspired by these previous studies of the dependence of waterlogging on the various factors, including meteorological and hydrological, that have advanced the understanding of the waterlogging risk of the many places worldwide, the present study investigated the potential waterlogging risk in Chattogram City, Bangladesh.

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Chattogram is the most populous coastal and well-known port city of Bangladesh. The population of Chattogram City is estimated to be 2.6 million (BBS, 2011). The metropolitan area is located on the Karnaphuli River banks between the Chattogram Hill Tracts and the Bay of Bengal, centered at 22°21'N, 91°50'E (Figure 1). Chattogram City is divided into 41 wards, which are the smallest administrative units of the city, and its total area is around 155.4 sq.km (Chattogram City Corporation, 2021). It has a tropical monsoon climate and a majority of the people along the coastlines living between 0 to 5-meter elevation from sea level (Hoque & Khan, 1996). The city's annual rainfall fluctuates between 2540 mm to 3810 mm, of which an average of 2400 mm occurs only during the monsoon (June-October) (Ahmed & Rubel, 2013; Ahmed, 2015). Using 32 years (1982-2013) of rainfall data, BMD showed a significant increment in precipitation during January to July while the decreasing trend persists from August to December. However, some individual occurrences of uneven rainfall, such as heavy precipitation during July 2009 in contrast to a very low precipitation in July 2010, were reported by Akter et al., (2017). Despite the climatological facts, economic agglomeration with unplanned urbanization leads to change in the hydrological cycle (i.e., uneven distribution of precipitation in time and space) by reducing infiltration capacities. For instance, the declination rate of forest and agricultural lands is 9% and 8%, during 1990-2004, respectively (Hashemi, 2006). In addition, District Fisheries Department in 1991 reported that the number of water bodies in the city was 19250, while this figure changed into 4523 as reported by Chattogram Development Authority (CDA) during 2006-2007 (decreasing rate: 920/year). Thus, along with modified hydrological cycle, the frequency of rainfall-induced waterlogging in Chattogram City has increased remarkably in the last decade or so (M. R. Islam & Das, 2014). A series of field surveys conducted in 2013-14 revealed that some places (i.e., *Kapasgola*, *Badurtala*) in Chattogram City had experienced waterlogging up-to 12 times in a year (Akter et al., 2017). In 2017, the inundation height was reported to be 0.5 – 0.9 m in the commodity hubs

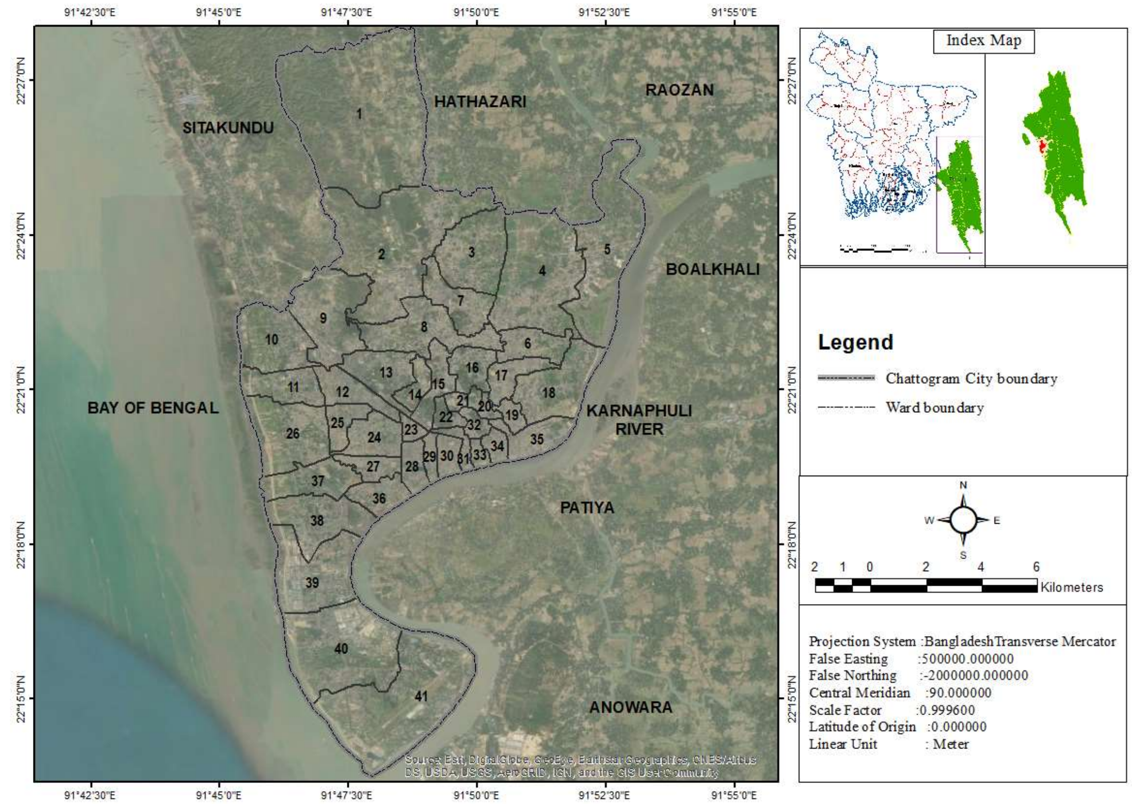

Fig. 1 Location map of Chattogram City

(i.e., *Khatunganj, Chaktai*) that submerged 80% of the warehouses and apparel factories and damaged more than 30% of the city road (Quddusi, 2017). The CDA has spent more than USD 650 million over the last five years for re-excavation, expansion, and development of canals to improve the drainage system of Chattogram City (The Daily Star, 2017). However, waterlogging has remained perennial woe to city dwellers.

To the best of the author's knowledge, the methods of identifying waterlogging affected areas in Chattogram and spatial risk of those areas have not yet been clarified in a published document. Therefore, it is not apparent to which extent the city areas are at risk due to the waterlogging hazard. Ashraf & Chowdhury, (2009) conducted a field survey on the perception of drainage and waterlogging problem in the eastern part of Chattogram City and reported inadequate stormwater drainage, backwater effect, and low terrain profile are the primary influential factors. More recently, Akter et al., (2017) performed an HEC-HMS hydrological modeling and developed a depth-duration-frequency curve for 13 locations in the city. However, no published literature includes inventory maps, causative factors, exposure, vulnerability, and overall risk to waterlogging hazard covering the entire city. Therefore, this present study aims to prepare a waterlogging inventory map and understand the spatial variation of waterlogging risk in Chattogram City. The risk is determined by means of intensity, exposure, and vulnerability of waterlogging.

2. Data and methods

Waterlogging risk index (WRI) presented in this study is estimated with the following basic eq. 1 (Cardona et al., 2012):

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \qquad (1)$$

Using the waterlogging hazard intensity index map developed in Geographic Information System (GIS) environment and GIS database at the city level, the elements at risk are combined to assess the exposure. A vulnerability assessment is carried out using the exposure information. Finally, utilizing the hazard, exposure, and vulnerability assessment, waterlogging risk index map was developed for Chattogram for the first time at the city level. The methodology adopted in this study is summarized in Figure 2. The detailed methods and data collection procedure for waterlogging inventory map, hazard intensity, vulnerability, and risk index are described step by step in the following.

2.1 Preparation of waterlogging inventory

A waterlogging inventory map was prepared from existing literature and field survey. At first, preliminary waterlogging locations were identified from existing literature such as local newspapers, research articles, and Govt. reports (Alamgir, 2008; Islam, 2009; Barua, 2010; Dey, 2013; Quddusi, 2017). An extensive field survey was then conducted employing a participatory survey to confirm the exact location and extent of this hazard. The participatory survey is adopted for increasing the reliability and accuracy of the inventory data, assuming that local people have a better knowledge of waterlogging. Hand GPS (Global Positioning System; Model: Garmin handheld GPS etrex 30x) was used to collect field data. This field survey was first conducted in 2014 and updated in 2019.

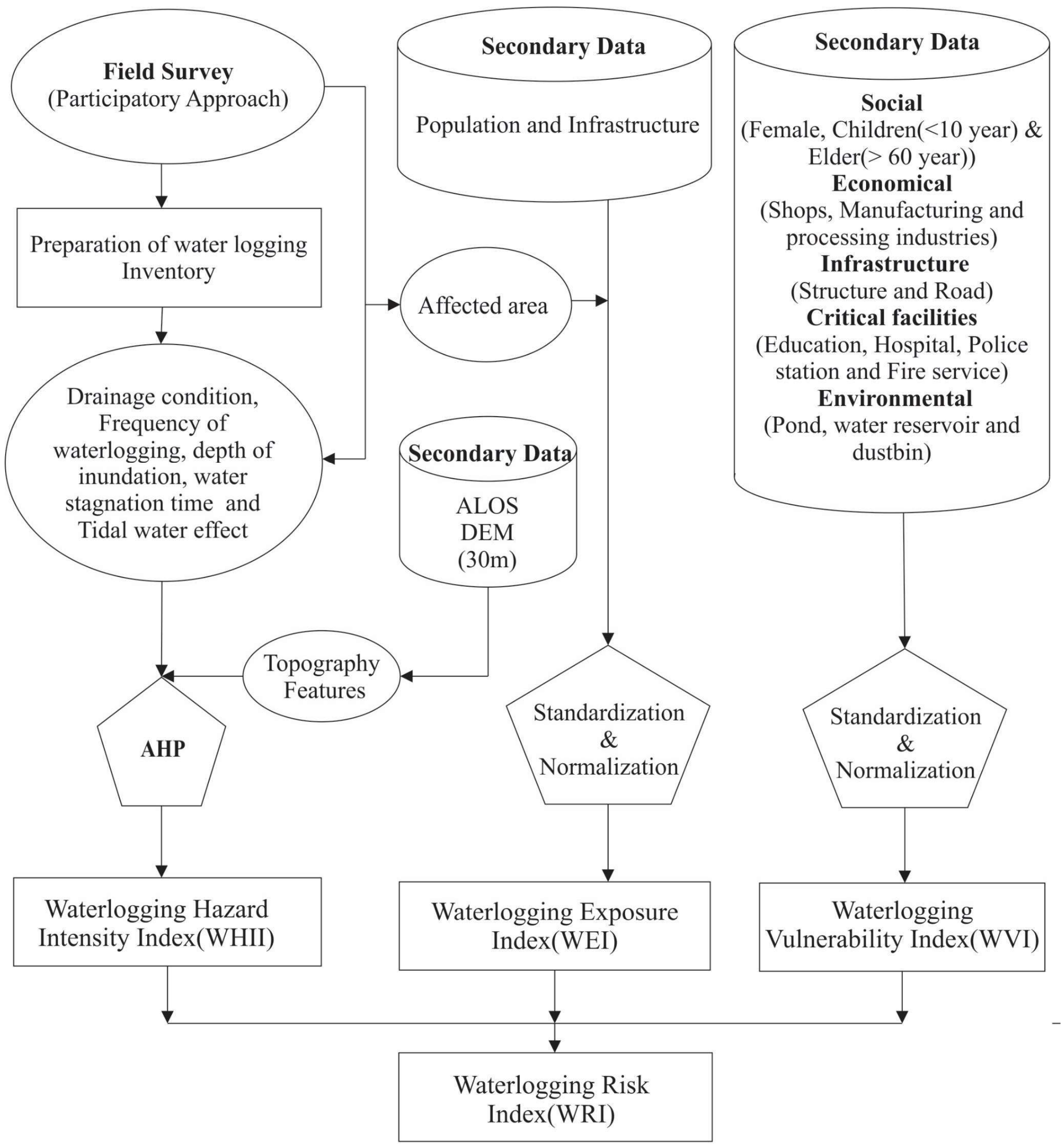

Fig 2. The adopted methodology of the study

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2.2 Preparation of waterlogging hazard intensity index

Based on the inventory map, waterlogging hazard intensity index (WHII) was prepared following two steps: (a) determining major influential factors to waterlogging through the participatory survey; (b) applying the GIS-based overlying technique to combine identified factors into a single composite layer (WHII). At first, local people respective to each identified waterlogging point were asked to identify the reasons behind the water stagnation problem. The collected primary and secondary data (land elevation data: ALOS 30m Digital Elevation Model (DEM); (JAXA, 2021)) were processed and represented spatially - using GIS mapping, which is explained below.

Drainage condition map

In this study, the role of drainage condition on waterlogging hazard was determined based on the local peoples' qualitative judgment and it was generalized by considering the performance of existing local (ward wise) drainage facilities. Residents judged it into three broad categories: unsatisfactory, marginally satisfactory, and satisfactory. The unsatisfactory level of drainage facility denotes waterlogging affected ward with poor operational and maintenance performance; low gravity and capacity of drainage structure; insufficient and inactive natural water bodies; and natural drainage encroachment. Ward having a subsequently better condition of the criteria mentioned above was considered as a marginally satisfactory or satisfactory level of drainage condition.

Tidal water effect map

Some low-lying flat areas in Chattogram City have small or no water level difference with the adjacent tidal canals and river Karnaphuli during high tide, resulting in tidal water entrance in the city on a regular basis (Ashraf & Chowdhury, 2009). Hence, local citizens were asked about the influence of tidal water in the waterlogging situation and four broad categories, including high, moderate, low, and absent, were identified. If the tidal water stands for more than two hours in any waterlogging point, the influence was determined as high. The moderate influence was considered when it stands between one to two hours. The areas that can recede water less than one hour of the high tide without affecting nearby built-up areas were counted with the low influence of tidal water during waterlogging.

Waterlogging frequency map

To portray the importance of rain on waterlogging hazard, we asked residents about the frequency of waterlogging hazard that directly represents the occurrence of rainfall events to cause waterlogging to a specific place in a year. The class ranges between 3 to 24 times, indicates the heterogeneity of waterlogging events in Chattogram City.

Other layers

The depth of inundation and water stagnation time maps were produced using the local experiences recorded during the field survey. Furthermore, an elevation map was generated from a DEM layer.

Analytic hierarchy process analysis

GIS-based overlying technique - Multi-Criteria Decision Analysis (MCDA) was applied to prepare WHII map. MCDA belongs to heuristic analysis, including Analytic Hierarchy Process (AHP), the Weighted Linear Combination, and the Ordered Weighted Average (Feizizadeh & Blaschke, 2013). In this study, AHP (Saaty, 1977) was employed to derive the weights associated with four thematic map layers identified by local people: drainage condition (A_1), waterlogging frequency (A_2), topographical characteristics (A_3), and tidal water effect (A_4). AHP was chosen because it can deal with complex decision-making and useful for checking the consistency of the evaluation measures as suggested by the experts. Thus, it is widely used for vulnerability and risk mapping (i.e., Feizizadeh & Blaschke, 2013; Ahmed, 2015).

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The AHP process requires a pre-defined score or weight to input (Saaty, 1977). In this study, it was assigned from expert opinion surveying. To avoid biases in decision-making, expert opinions from four different backgrounds: planner, engineer, geographer, and disaster risk manager were taken. A normalized set of weights was established to compare alternatives using the factors (A_1-A_4). Next, a pairwise comparison matrix was formed where the number in the ith row and jth column gives A_i's relative importance compared with A_j. Finally, all layers were overlaid together using the eq. 2:

$$WHII = \sum_{i=1}^{n} (Wi * Ri) \qquad (2)$$

Here, WHII is the required hazard intensity index for a specific site; W_i and R_i are factor weight and class weight (or rating value) for factor *i,* respectively. Equal weight was assigned to different classes (R_i) under each factor (A_i). The higher R_i value means the class is more influential to waterlogging hazard. Finally, the WHII stands for each site = weight for A_1 × ("1" for unsatisfactory drainage; "0.66" for marginally satisfactory drainage; "0.33" for satisfactory drainage condition) + weight for A_2 × ("1" for more than eighteen times; "0.75" for thirteen to eighteen times; "0.50" for seven to twelve times; "0.25" for three to six times waterlogging event in a site) + weight for A_3 × ("1" for land elevation less than 6 m; "0.75" for 6 -10 m; "0.50" for 11-15 m; "0.25" for land elevation greater than 15 m from mean sea level) + weight for A_4 × ("1" for high; "0.66" for moderate; "0.33" for low; "0" for no tidal water influence).

After applying the AHP generated weights in the attribute layers, the resulting WHII map was reclassified using the equal interval method (ArcGIS help 10.3, 2015) into five levels: very high, high, moderate, and low, and very low in waterlogging hazard intensity.

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2.3 Preparation of waterlogging exposure index

Exposure was assessed for elements at risk within the affected area of waterlogging hazard where population and infrastructure were identified as elements at risk for this hazard. Population and infrastructure data were collected from Bangladesh Bureau Statistics (BBS, 2011) and (DAP, 2008), respectively. These data include different population information, roads, structures, and water bodies. To prepare the waterlogging exposure index (WEI), first, elements at risk were standardized using eq. 3. The standardized values were summed up and rescaled for normalizing the score between 0 to 1 applying eq. 4. This index value was represented visually by GIS mapping.

$$z = X - \mu\sigma \quad (3)$$

$$X_{new} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4)$$

Where, Z = standardized value, X = observed value, μ = mean value, σ = standard deviation, X_{new} = normalized vale, X_{min} = minimum value of the data set, X_{max} = maximum value of the data set.

2.4 Preparation of waterlogging vulnerability index

The vulnerability assessment was focused on determining the vulnerability of key individual facilities and resources within the city area due to waterlogging. This facilities and resources were broadly categorized in five dimensions (complex variables): a) social; (b) infrastructure; (c) critical facilities; (d) economic; and (e) environmental. We further sub-divided these complex variables into 18 different simple variables, which were determined as sensitive (Flax et al., 2002) to waterlogging. These simple variables were selected based on available attribute information in the spatial data summarized in Table 1. All the sensitive groups of people, infrastructures, critical facilities, economic activities, and environmental data that are in and within proximity to waterlogging affected areas were identified by overlaying the spatial data onto the waterlogging affected area. Finally, the waterlogging vulnerability index (WVI) was estimated similar to WEI (eq. 3, 4) by combining the indices for five complex variables.

Table 1 Description of variables used in vulnerability analysis

No.	Vulnerability dimension (Complex variable)	Simple Variables		Description
1	Social	Female		No. of female populations in the affected area
2		Children (< 10 years)		No. of children less than ten years old in the affected area who are
3		Elder (> 60 years)		No. of older people greater than 60 years old in the affected area
4	Infrastructures	Structure	Kutcha	Foundation: Earthen plinth/brick perimeter wall with earth infill; Wall: CI sheet/part or full brick/Earthen walls; Roof: CI sheet with timber/split bamboo framing
5			Semi-Pucka	Foundation: Concrete/brick; Wall: brick; roof: CI sheet with timber/iron framing.
6			Pucka	Foundation: Reinforced concrete (RC); Wall: brick; Roof: RC
7		Road	Kutcha	Earth filling (km)
8			Semi-Pucka	Herring-bone-bond (HBB: brick made) (km)
9			Pucka	Bituminous & RC (km)
10	Critical facilities	Educational institute		No. of elementary, high school, and college in the affected area
11		Hospital /clinic		No. of hospital and clinic in the affected area
12		Police station		No. of police station in the affected area
13		Fire service station		No. of fire service station in the affected area
14	Economic	Shops		No. of bakery and computer goods shop in the affected area
15		Manufacturing and processing industries		No. of manufacturing and processing industry in the affected area
16	Environmental	Pond		No. of pond in the affected area
17		Water reservoir		No. of water reservoir in the affected area
18		Dustbin		No. of dustbin in the affected area

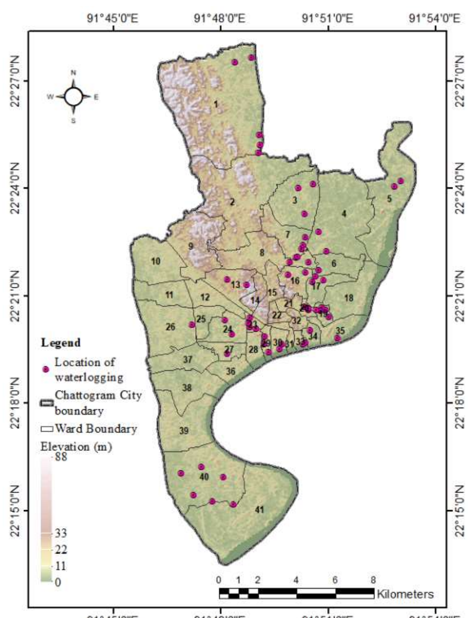
2.5 Preparation of waterlogging risk index

Waterlogging risk index (WRI) for Chattogram City was estimated by multiplying WHII, WEI, and WVI layers (eq. 1). The score was standardized and normalized using eq. 3 and 4, respectively. Finally, the resulting WRI map was reclassified using the equal interval method (ArcGIS help 10.3, 2015) into five levels: very high, high, moderate, low, and very low risk due to waterlogging.

3. Results and Discussion

3.1 Preparation of waterlogging inventory map

A total of 58 waterlogging locations were identified in Chattogram City, where 22 wards among 41 wards have been found as waterlogging affected (Figure 3). The entire size of the affected area is 13.08 sq.km (~8.42% of city area), with the mean size and standard deviation



Ward no.	No. of affected area	Affected area name
1	5	Near South of Aman bazar, Shanti colony, Near south of Vatiyari ring road, Near south of Vatiyari ring road, Mahmudabad & Nondir hat
3	3	Hazipara, Baizid Noar hat, Wazdia,
4	2	Chandgaon residential area & Somser para,
5	2	Moddho mohra & Purbo mohra
6	2	Kapasgola & Badurtola
7	5	Alluminium factory road, Muradpur junction area, Mohammadpur, Nazir para & Tripura khal area
8	2	Solokbahar & Sugandha residential area
13	2	Pahartali & Near railway colony,
16	2	Probartok moore & Katalgonj
17	2	Fultola & KB Amanullah road
19	5	South bakalia, Baria bari, Abdul Karim by lane, Babu bazar & Uzir ali road
20	3	Joynab colony, Machua jharna & Dewanji pukur par
23	4	Bansal, Sultan colony, Chanmiar bil & Dewan hat dighir par
24	2	Muhuri para & Munshi para
26	1	I - block
27	1	CDA residential area
29	3	Near norrth of stand road, Dhaka trunk road, Shuvopur
30	2	Hazi Bari & Maiz Para, Jele & Firingi Bazar
33	2	Yakub Nagar, Tekpara (Bandel canal)
34	1	Brickfield road
35	1	Chaktai Canal area, Cox's Bazar Road
40	6	Maizpara, Dhumpara, South of T.S.P Fertilizer Factory, Hossain Ahmed Para & Colony Jama Mosque

Fig. 3 Ward wise waterlogging inventory map for Chattogram City

of 0.57 and 0.9 sq.km respectively. The extent area respective to each waterlogging location is shown in Figure 4b. Figure 3 shows that most waterlogging locations were found on the east side of the city, adjacent to the *Karnaphuli* river, where the land elevation is between 3 to 6 m from mean sea level and identified as an attributing factor to cause waterlogging by local people. It should be noted that the elevation value in Figure 3 may be showing higher than the actual because of the coarse resolution (30 m) of ALOS DEM. This study reports that some of the waterlogging points locate in the major locations of the city, such as *Kapasgola* and *Badurtola* (ward no. 6), *Muradpur* junction area (ward no. 7), *Solokbahar* (ward no. 8), *Probartok moore,* and *Katalgonj* (ward no. 16), CDA residential area (ward no. 27), *Firingi Bazar* (ward no. 30) and *Chaktai* canal area (ward no. 35). The provided inventory map is the first waterlogging inventory that covers the entire area of Chattogram City.

During the field survey, respondents from 13 wards (out of 22) (Fig. 4a) pointed out that they were unsatisfied with existing local drainage facilities' performance because their places go knee-deep water during a heavy shower. Interestingly, there is no ward where respondents were satisfied with their local drainage facilities, implying that drainage condition is one of the major influential factors to cause waterlogging.

The impact of tidal level on waterlogging in Chattogram City is inevitable. It is found that 23% of waterlogging points experience tidal water influence more than 2 hours (indicated as a high influence in Figure 4b) when heavy rain coincides with high tide. The respondents claimed that improper management and lack of sluice gates on the mouth of different canals connecting with *Karnaphuli* River resulted in tidal water entrance to the built-up areas.

Figure 4c-e depicts the summary of field survey data on frequency-inundation depth-duration for 58 locations. Places in ward no. 5, 27, 33, 34, and 35 experience more frequent waterlogging disasters than other locations (Figure 4c). On the other hand, places (i.e., ward no. 1, 13) far away from the *Karnaphuli* river suffer less frequent waterlogging, indicating the joint influence of rainfall, topography, local drainage facilities and tidal level on waterlogging.

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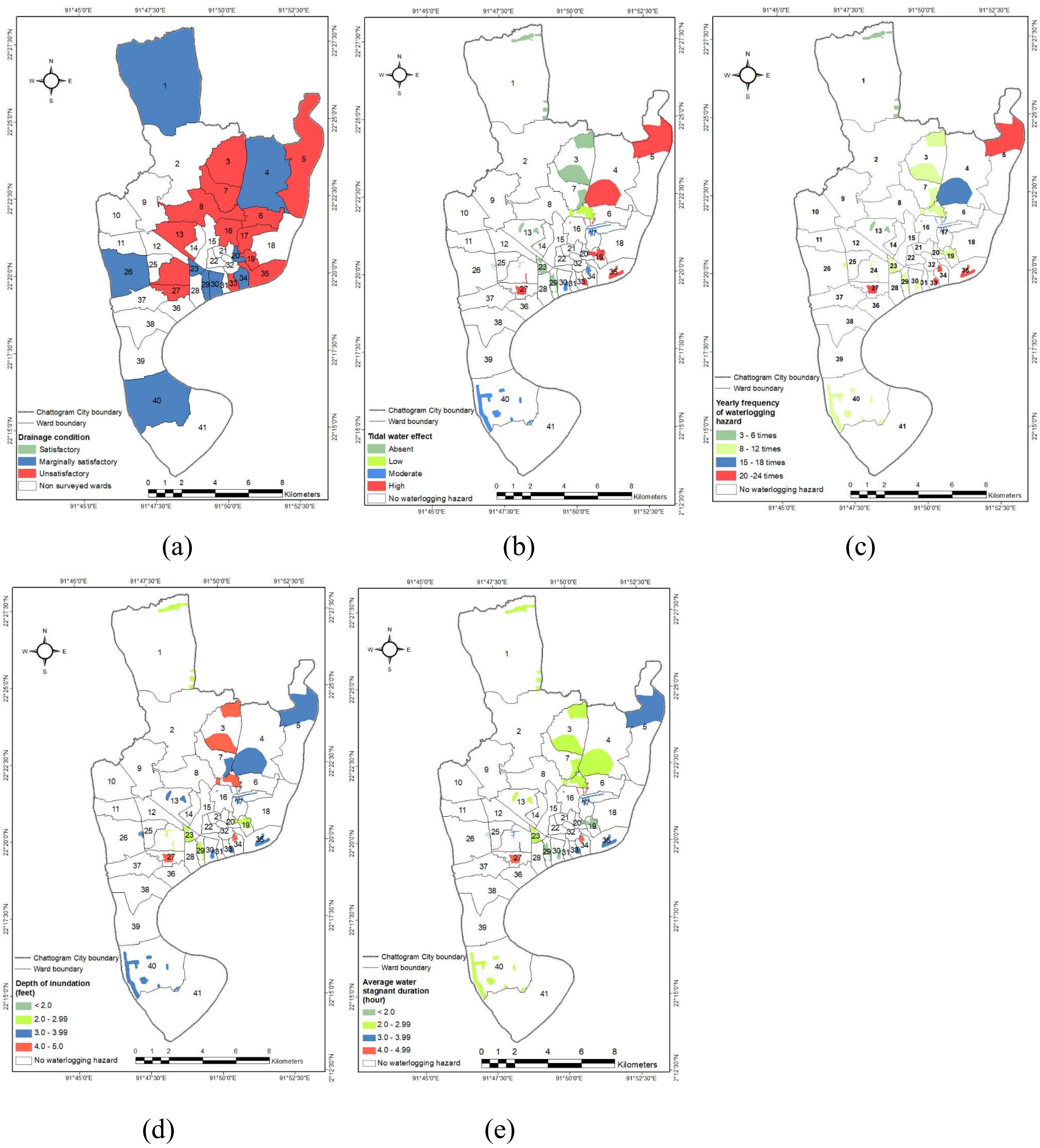

Fig. 4 Ward wise waterlogging hazard attribute layers (a) drainage condition map; (b) tidal water effect map; (c) yearly frequency of waterlogging event map; (d) depth of inundation map; (e) average water stagnant duration map for Chattogram City.

The comparison: Figure 3 (land elevation), 4a-c VS 4d-e shows an association between factors that influence waterlogging and inundation depth-duration in Chattogram City. Major commercial areas such as ward no. 27, 33, 34, 35 are relatively plain (Figure 3) where inadequate drainage (Figure 4a) and the backwater effect from *Karnaphuli* river (Figure 4b) were found significant. These result in greater water depth (3 – 5 feet, Figure 4d) and remains for a longer duration (3-5 hours, Figure 4e) during waterlogging. The Master Plan Organization (MPO) categorized the flood land into five types: F0 (0 – 1 feet), F1 (1.0 – 2.95 feet), F2 (2.95 – 5.9 feet), F3 (5.9 – 9.8 feet) and F4 (over 9.8 feet) (MPO, 1987). This study shows that waterlogging depth reaches an average of 2.95 feet (Figure 4d) during a waterlogging event in Chattogram City. It suggests that as per MPO (1987), waterlogging affected land type ranges from medium low land to above flood level. This finding is consistent with the previous study done by Akter et al., (2017), who showed that water depth reaches around 2.8 feet during a waterlogging event in Chattogram City.

3.2 Waterlogging hazard intensity index

Table 2 shows waterlogging attributing factors weights derived from AHP analysis. The highest weight is assigned to drainage condition. While the yearly frequency of waterlogging, topography, and tidal water effect is given subsequent weight. In this study, the resulting consistency ratio is 0.0829 and less than 0.1, indicating a reasonable consistency in the pairwise comparison that is good enough to recognize the factor weights (Saaty 1977; Feizizadeh and Blaschke 2013).

Table 2 Weights and consistency ratio of data layers

Factors	**Eigen values**
Drainage condition	0.5167
Yearly frequency of waterlogging	0.2406
Topography	0.1320
Tidal water effect	0.0749
Consistency ratio: 0.0829	

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After applying the AHP generated weights in eq. 2, the resulting WHII (Figure 5) is evaluated qualitatively. The very high and high-intensity zone covers 2.63% (4.1 sq.km) of the total Chattogram City, while about 4.17% (6.48 sq.km) area is classified as moderate, and the remaining 2.49 sq.km is classified as low to very low (Table 3). Total 13 waterlogging points and eight wards fall within the very high and high-intensity zones. However, it does not reflect their respective waterlogging risk should also be greater, as shown in the following sections. Figure 5 shows that most of the affected areas with greater intensity (i.e., WHII > 0.78) locate

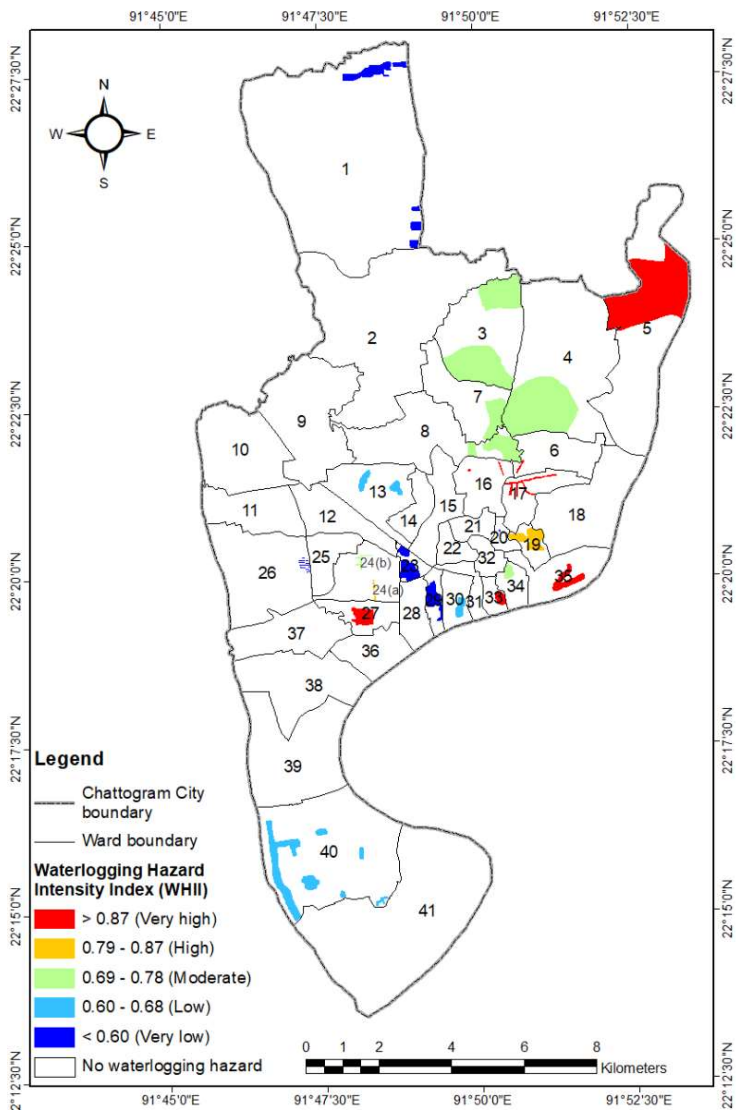

Fig. 5 Ward wise waterlogging hazard intensity index for Chattogram City

in the eastern part of the city adjacent to the Karnaphuli river where inundation height was observed higher (≥ 3 feet, Figure 4d) with a longer stagnant time (≥ 3h, Figure 4e). Overall, AHP generated WHII agrees well with the field survey data.

Table 3 Distribution of area, locations, and affected wards according to the WHII level

WHII	Hazard intensity level	Area (sq.km)	No. of waterlogging locations	Affected wards
> 0.87	Very high	4.06	10	5, 6, 17, 27, 33, 35
0.79- 0.87	High	0.04	3	16, 24(a)
0.69- 0.78	Moderate	6.48	19	3, 4, 7, 8, 19, 24(b), 34
0.60-0.68	Low	1.36	10	13, 30, 40
< 0.60	Very low	1.15	16	1, 20, 23, 26, 29

3.3 Waterlogging exposure index

Figure 6 illustrates waterlogging exposure index (WEI) for Chattogram City. The WEI is equally divided into five categories: very high (> 0.8), high (0.61-0.8), moderate (0.41-0.60), low (0.21-0.4), and very low (< 0.21). Total 20 waterlogging points and six wards fall within the very high and high exposed zone (Table 4). It is clear that except ward no. 5, most of the wards with a greater EI (>0.6) belong to a moderate hazard intensity zone (Figure 5). Table 4 shows that although many waterlogging points fall within the densely populated wards (i.e., 16, 33, 35; BBS 11), their respective EI is found significantly low. It is reasonable as the elements at risk (population and infrastructure) linearly increase with the hazard affected area's spatial size.

Table 4 Exposure of area, locations, and wards as per the level of WEI

WEI	Exposure level	Area (sq.km)	No. of waterlogging locations	Exposed wards

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> 0.80	Very high	9.23	14	3, 4, 5, 8, 19
0.61- 0.80	High	1.05	6	40
0.41- 0.60	Moderate	1.11	12	7, 17, 23, 27
0.21-0.40	Low	0.31	9	13, 16, 20, 33
< 0.21	Very low	1.15	17	1, 6, 26, 29, 30, 34, 35, 24(a), 24(b)

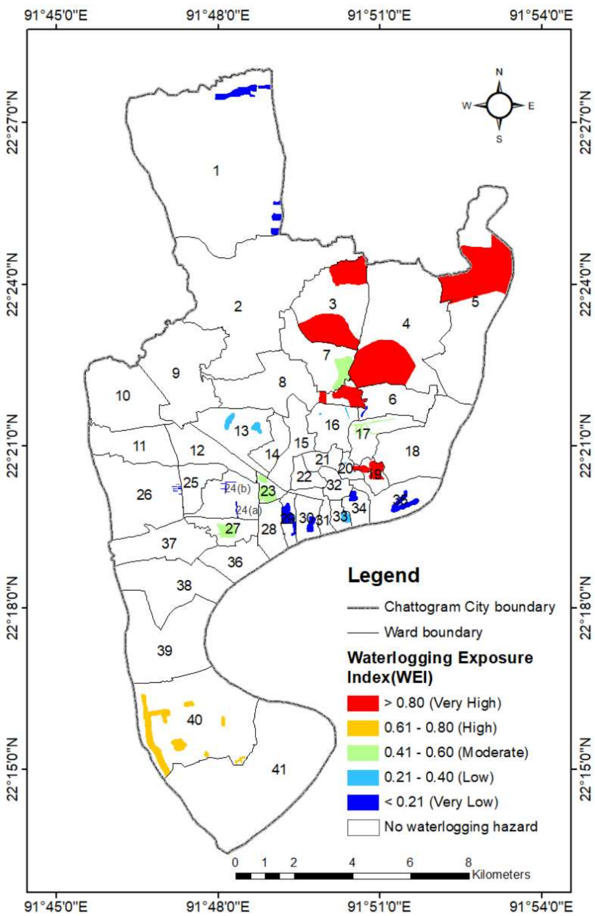

Fig. 6 Ward wise waterlogging exposure index for Chattogram City

3.4 Waterlogging vulnerability index

Figure 7 shows waterlogging vulnerability for Chattogram City. It includes the overall waterlogging vulnerability index (WVI) that combines five different vulnerability dimensions:

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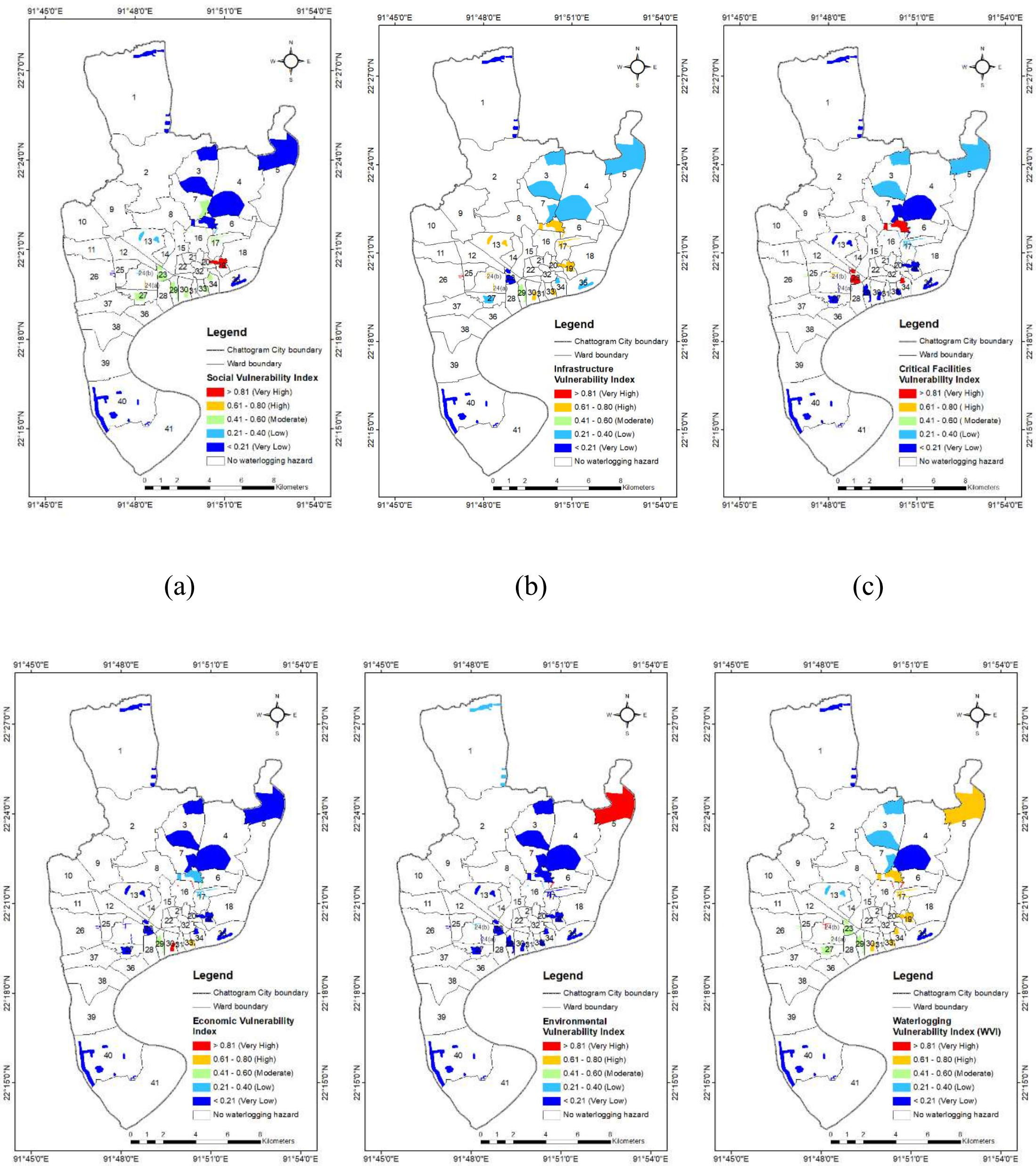
social, infrastructure, critical facilities, economic, and environment (see data and methods section for variables considered in each dimension). It is determined that more than 1,60,000 sensitive group of people (~6.2% of the total population) are vulnerable in the city and ~27% and ~5.9% of them are children (< 10 years) and elderly (> 60 years) population, respectively. Figure 7a illustrates that the city's outer skirt has lower social vulnerability while it is comparatively higher in the city center. Among 22 waterlogging affected wards, ward no. 19 is ranked 1st in its social vulnerability. This map is expected to help decision-makers in providing suitable mitigations and adaption measures depending upon the vulnerable people in an affected area.

Figure 7b shows a sensitive group of structures and roads that are comparatively higher in the city center than the outer skirt. Among the 22 affected wards, infrastructure vulnerability for ward no. 6, 17, and 33 is high along with its' greater WHII (Figure 5). It is identified that over 22,000 residential structures (~14.6% of total residential structures), including *Chandgaon* (ward no. 4; Figure 3) and CDA (ward no. 27; Figure 3) residential area are vulnerable under the five different categories of hazard intensity. The very high and highly vulnerable areas cover more than 1600 *kutcha* structures (see data and methods section for the definition), which are essentially unable to withstand potential hazard damage due to low structural integrity. Additionally, a large number of semi-pucka structure (more than 10000) is found as vulnerable which are not out of damage potential as the wall and foundation are made of less sustainable building materials (i.e., brick). In the context of Chattogram City, *pucka* structures might also be affected by waterlogging due to the corrosive effect of saline water. Such damage could increase the reconstruction costs.

The entire city is served by ~2889 km road while 361.5 km road has been identified as vulnerable to waterlogging hazard. The present study reveals that several important roads, including *Probortok moore* (ward no. 16; Figure 3) and Chattogram-Cox's Bazar connecting



(a) (b) (c)

(d) (e) (f)

Fig. 7 Ward wise (a) Social Vulnerability index; (b) Infrastructure vulnerability index; (c) Critical facilities vulnerability index; (d) Economic vulnerability index; (e) Environmental vulnerability index; (f) Overall waterlogging vulnerability index (WVI) for Chattogram City.

high way (ward no 35; Figure 3), are covered by the very high hazard intensity zone (Figure 5). During the rainy season, these roads go under 3-4 feet of water (Figure 4d), resulting in severe disruption in the major communication system of Chattogram City. It is determined that different categories of hazard intensity zones cover a total of 133 km *semi-pucka* (brick soling) and 44.3 km *kutcha* road (made from mud). The vulnerable pucka road (paved) percentage is ~39% higher than the vulnerable *semi-pucka* road. In Chattogram City, *pucka* roads have a bituminous surface and waterlogging might cause sustained severe damage. On the contrary, *kutcha* roads might also be damaged through topsoil removal. Such damage could affect the natural traffic flow by creating traffic jams with higher delay times, increasing the accident rate, hindering people's daily activities, and increasing the city's financial burden for repairing the damaged roads.

Figure 7c shows critical facilities vulnerability due to waterlogging in Chattogram City. Among the waterlogging affected areas, ward no. 8, 23, and 34 are ranked highest in its' critical facilities vulnerability. It is found that more than 250 educational institutes (~17.7% of total educational institutes in the city) fall within the different vulnerable zones. Thus, academic activities are hampering because students might not attend the classes during the waterlogging events. There are also several hospitals and police stations covered by different vulnerable zones. It is important to protect critical facilities (i.e., through relocating, elevating) to confirm that service interruption is reduced as these facilities play a key role in emergency response and recovery.

Figure 7d exhibits economic vulnerability to waterlogging by identifying major economic sectors: shops and manufacturing and processing industries in Chattogram City. Some major economic centers, including *Katalganj* (ward no. 16; Figure 3) and *Firingi bazar* (ward no 30; Figure 3), are ranked as the highest vulnerable, which might threaten greater economic loss in the country. It is identified that more than 850 economic centers providing various services are located in different vulnerable zones. Chattogram is served as a commercial hub of the country where waterlogging results in loss of income and jobs associated with business interruptions every year. It appears necessary to take advanced hazard mitigation options to prevent or minimize such losses.

Figure 7e shows spatial distribution of environmental vulnerability in Chattogram City due to waterlogging. While ward no. 5 and 6 both are ranked highest for its' environmental vulnerability, most of the affected wards remain very low vulnerable. Several secondary risk sites include ponds (more than 750), waste collection sites and water reservoirs identified, which can trigger further disastrous conditions if waterlogging occurs. Therefore, waterlogging can result in contamination whereby wastes, pesticides, raw sewage, chemicals, hazardous materials are transported through neighborhoods, sensitive habitats, and businesses. Water-borne diseases like diarrhea, skin problems could also break out in an epidemic form. These circumstances can lead to major cleanup and remediation activities, as well as natural resource degradation.

Summing up the five different vulnerability dimensions (7a-e) discussed above yields overall WVI for Chattogram City, as shown in Figure 7f. The variation in WVI is significantly different from the individual vulnerability score at the ward level. Wards at the eastern side of the city show greater vulnerability than the others. Table 5 reports that the very high and high vulnerable zone covers ~3.03% (4.71 sq.km) of the total Chattogram City. The comparison between WVI and WHII (Figure 5) reveals that ward no. 5, 6, 16, 17, and 33 have scored higher in both than other affected wards. It also needs to be noted that although some wards (i.e., ward no. 35) show greater hazard intensity scores, the overall vulnerability score is found less (< 0.41).

Table 5 Vulnerable area, locations, and wards as per the level of WVI

WVI	Vulnerability level	Area (sq.km)	No. of waterlogging locations	Vulnerable wards

> 0.80	Very high	0.07	5	6, 16, 24(b)
0.61- 0.80	High	4.64	16	5, 8, 17, 19, 30, 33, 34
0.41- 0.60	Moderate	1.11	13	20, 23, 24(a), 26, 27, 29
0.21-0.40	Low	3.07	10	3, 7, 13
< 0.21	Very low	4.44	14	1, 4, 35, 40

3.5 Waterlogging risk index

To address the risk potential of Chattogram City under waterlogging condition, WHII, WEI, and WVI were combined using eq.1 and the resulting WRI is spatially presented in Figure

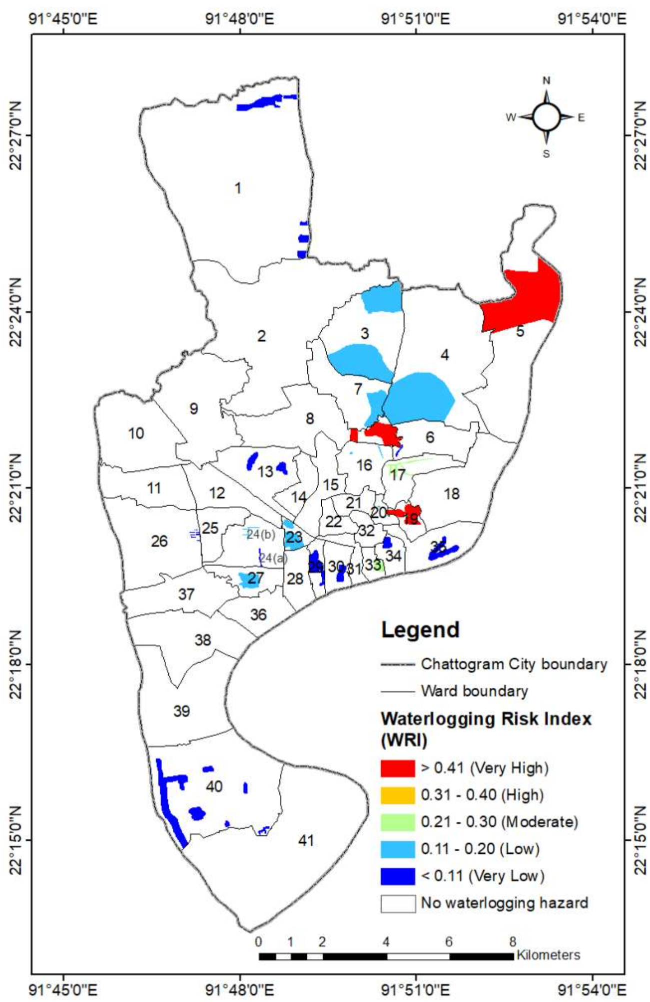


Fig. 8 Ward wise Waterlogging Risk Index for Chattogram City

8. The area, waterlogging points, and wards in each risk level are summarized, as shown in table 6. ~2.71% of the study area is found in very high risk, followed by moderate (0.15%), low (3.89%), and very low (1.67%). The comparison among WHII (Figure 5), WEI (Figure 6), WVI (Figure 7f), and WRI shows that ward no. 5 has scored highest in terms of all indices, followed by ward no. 8, 19, 17, and 33. Although the WHII and WVI scores are comparatively larger for ward no. 6 and 16, the associated WEI score is found less and thus, resulted in low risk (< 0.21) due to waterlogging.

Table 6 Risk area, locations, and wards as per the level of WRI

WRI	Risk level	Area (sq.km)	No. of waterlogging locations	Wards in risk
> 0.40	Very high	4.22	9	5, 8, 19
0.31- 0.40	High	-	-	-
0.21- 0.30	Moderate	0.23	4	17, 33
0.11-0.20	Low	6.05	18	3, 4, 7, 16, 23, 27, 24(b)
< 0.11	Very low	2.59	27	1, 6, 13, 20, 26, 29, 30, 34, 35, 40, 24(a)

4 Summary and conclusion

The analyses presented here to prepare a waterlogging inventory map and assessing waterlogging risk in Chattogram City, Bangladesh. In this regard, participatory survey and GIS-MCDA method – the AHP – were applied to create a WHII map. Finally, utilizing the WHII map and spatial database available at the city level, WEI, WVI, and WRI were prepared. A total of 58 locations in 22 wards have been identified as waterlogging affected, which covers ~8.42% of the city area. Local people addressed four factors: drainage condition, topography, heavy rain, and tidal water effect as primary attributes to cause waterlogging. WHII map shows that most of the affected areas with greater intensity (i.e., WHII > 0.78) locate in the eastern part of the city, where inundation height was also observed higher (≥ 3 feet) than the other places. It needs to be noted that waterlogging affected areas shown in this study do not confirm the complete accuracy because the underlying judgments are subjective and based on local residents' descriptions who are not necessarily technical experts in water disasters. In addition, the AHP method is based on weighting the factors maps and overlaying those layers into a single composite layer. Any incorrect perception of the different criteria' role can be easily conveyed from the expert's opinion into the weight assignment (Kritikos & Davies, 2011). Hence, it can lead to an inaccurate assessment of the final outputs. Nevertheless, the inventory and hazard intensity maps presented in this study should be useful for validating any data-driven model and minimizing the city's waterlogging risk.

The vulnerability analyses combined five major components: social, infrastructure, critical facilities, economic, and environmental vulnerability. The social and infrastructural vulnerability maps show the sensitive group of people, structures, and roads are comparatively higher in the city center than the outer skirt. Obtained WVI map suggests that ward no. 5, 6, 16, 17, and 33 are greatly vulnerable to waterlogging than the other locations in Chattogram City.

Waterlogging risk determined herein combines the hazard intensity, exposure, and vulnerability indices. It suggests that ~2.71% of the study area is at very high risk, followed by moderate (0.15%), low (3.89%), and very low (1.67%). The comparison among WHII, WEI, WVI, and WRI shows that ward no. 5 has scored highest in all indices, followed by ward no. 8, 19, 17, and 33. This risk assessment does not constitute a hydrodynamic or hydrological model to confirm overall waterlogging risk in Chattogram City. Thus, a future study needs to include a quantitative evaluation of a complex urban system's contribution, including the impact of land-use change. Nonetheless, waterlogging risk map presented in this study provides a comprehensive database that can allow disaster risk managers, urban planners, and stakeholders to propose mitigation plans for reducing waterlogging risk in Chattogram City.

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Author contribution

Conceptualization, M.R.I. and D.R.R.; Field Investigation, M.R.I.; Writing—Original Draft Preparation, M.R.I.; Writing—Review, Modifying, and Editing, M.RI. and D.R.R.

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