Waterlogging Risk Assessment: An Undervalued Disaster Risk in Coastal Urban Community of Chattogram, Bangladesh

Md. Rezuanul Islam [1,*] and **Debasish Roy Raja** [2]

[1]   School of Environment and Society, Tokyo Institute of Technology, Tokyo 152-8550, Japan
[2]   Department of Urban and Regional Planning, Chittagong University of Engineering and Technology, Chattogram 4349, Bangladesh; debasishroy@cuet.ac.bd
*   Correspondence: islam.m.ac@m.titech.ac.jp

Abstract: In recent years, rainfall-induced waterlogging has become a common hazard in the highly urbanized coastal city of Chattogram, Bangladesh, resulting in a high magnitude of property damage and economic loss. Therefore, the primary objective of this research was to prepare a waterlogging inventory map and understand the spatial variations of the risk by means of hazard intensity, exposure, and vulnerability of waterlogging. In this research, the inventory map and factors influencing waterlogging hazards were determined from a participatory survey, and other spatial data, including land elevation, population, and structural data, were collected from secondary sources. The 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 were identified as waterlogging affected, which covered ~8.42% of the city area. We showed that ~3.03% of the city area was greatly vulnerable to waterlogging in terms of their social, infrastructure, critical facilities, economic, and environmental vulnerabilities. The obtained waterlogging risk index map suggested that ~2.71% of the study area was at very high risk, followed by moderate (~0.15%), low (~3.89%), and very low (~1.67%). The risk analysis presented in this study was a simple method that can be applied to assess the relative risk of waterlogging in different regions, and the results were applicable to the prevention and mitigation of waterlogging for Chattogram City.

Keywords: waterlogging; vulnerability; risk; exposure; 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 [1]. Rapid population growth, unplanned urbanization, and climate extremes are the major triggering factors for making this disaster more frequent in recent years [2–4]. Unlike other disasters, waterlogging-induced human losses are not common, but billions of dollars in damage are inflicted upon the city's infrastructure every year by this event. For example, The Ministry of Land, Infrastructure, Transport, and Tourism of Japan showed that 86% of the total economic flood damage in the Tokyo metropolitan area during 1998–2007 was only due to waterlogging [5]. From 2001 to 2018, there was an average of more than 40 million people affected by waterlogging and caused the US more than $10 billion economic losses each year in urban areas of Eastern China [3]. Although a massive investment in the improvement of waterlogging control infrastructures has been made, it remains a major disaster risk throughout 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 being less than five meters above sea level [1,6]. In particular, during the 2009–14 period, waterlogging disasters caused yearly US $31 million in property damages at the household level. It is estimated that if there was no such economic loss in that period, the GDP volume could be increased by 0.02% per year [7]. These exemplify

the importance of assessing the waterlogging risk for alleviating its impact on society and development works.

Waterlogging generally brings a shallower inundation depth and slower flow velocity than floods but causes severe disruptions of regular city life, including traffic paralysis, infrastructure damage, health, and environmental problems, in Bangladesh [8]. At present, major urban areas such as Dhaka, Chattogram, and Khulna suffer from waterlogging almost every year during the monsoon season. In 2014, more than 65,000 households were affected by rainfall-induced waterlogging disasters in the southern coastal districts only [7]. Sarkar et al. [9] 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 US $71 million caused by several waterlogging events in the single financial year of 2017 [10]. 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 waterlogging disasters [1].

Risk assessment as a prerequisite 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 h 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, and (4) future status of heavy rainfall conditions [11]. On the other hand, the Bangladesh Water Development Board utilizes the European Centre of Medium-Range Weather Forecasts rainfall data for forecasting large-scale floods, including fluvial and flash floods [12]. However, an authorized department for assessing risk, forecasting, and issuing warnings for urban waterlogging has not been established until now. Mainstreaming the waterlogging risk in national disaster risk management is fundamental to reducing the related loss of economy and property damage. Essentially, such improvements 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 critical factor that can markedly influence waterlogging; others, including land-use changes, unplanned urbanization, low terrain profile, backwater effect, and the absence of proper drainage planning and management, also have an impact [13–16]. Consequently, a range of different risk assessment methodologies for waterlogging has been introduced. For example, Quan [17] performed hydrological modeling and a Geographic Information System (GIS) spatial analysis for Shanghai City, considering hypothetical heavy rainfall conditions, elevation, building, and drainage system as impact factors. The study showed that the water depth, vulnerability, and economic loss tend to increase as the rainstorm intensity increases. Employing a similar method, but for a small-scale urban area (Jing'an District) in Shanghai, Yin et al. [18] developed stage–damage curves and explained that, for a maximum inundation depth of 50 cm, the average annual waterlogging loss could reach as much as US $530 thousand. Shi [19] analyzed the risk of a 50-year return period rainstorm waterlogging by integrating a hydraulic model with the 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. [20] applied a hydrodynamic model in Carlisle, Northwest England to assess the impact of a sustainable drainage system design for urban flood modeling. Sarkar et al. [9] 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 various factors, including meteorological and hydrological, that have advanced the understanding of the waterlogging risk of many cities worldwide, the present study investigated the potential waterlogging risk in Chattogram City, Bangladesh.

Chattogram City experiences waterlogging up to 12 times in a year [16]. In 2017, the inundation height was reported to be 0.5–0.9 m in the commodity hubs (i.e., *Khatunganj* and *Chaktai*), which submerged 80% of the warehouses and apparel factories and damaged more than 30% of the city's road network [10]. The Chattogram Development Authority (CDA) has spent more than US $650 million over the last five years on the re-excavation, expansion, and development of canals to improve the drainage system of Chattogram City [21]. However, waterlogging has remained a perennial woe to city dwellers. To the best of the author's knowledge, the methods of identifying waterlogging affected areas in Chattogram and the spatial risk of those areas have not 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 and Chowdhury [22] conducted a field survey on the perception of drainage and waterlogging problems in the eastern part of Chattogram City and reported that inadequate stormwater drainage, backwater effect, and low terrain profile are the primary influential factors. More recently, Akter et al. [16] performed HEC-HMS hydrological modeling and developed a depth–duration–frequency curve for 13 locations in the city. However, no published literature includes the inventory maps, causative factors, exposure, vulnerability, and overall risk to waterlogging hazards covering the entire city. Therefore, this present study aims to prepare a waterlogging inventory map and understand the spatial variations of the waterlogging risk in Chattogram City. The risk is determined by means of the intensity, exposure, and vulnerability of waterlogging.

2. Study Area

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 [23]. The metropolitan area is located on the Karnaphuli riverbanks 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 [24]. It has a tropical monsoon climate, and a majority of the residents live along the coastlines between 0 to 5-m elevations from sea level [25]. The city's annual rainfall fluctuates between 2540 mm to 3810 mm, of which an average of 2400 mm occurs only during the monsoon season (June–October) [26,27]. Using 32 years (1982–2013) of rainfall data, BMD showed a significant increment in precipitation during January to July, while a decreasing trend persists from August to December. However, some high interannual variability of precipitation, such as heavy precipitation during July 2009 in contrast to very low precipitation in July 2010, were reported by Akter et al. [16]. Despite the climatological facts, economic agglomeration with unplanned urbanization (i.e., changes in land use) leads to change in the hydrological cycle by reducing the infiltration capacity. For instance, the declination rates of forests and agricultural lands were 9% and 8% during 1990–2004, respectively [28]. In addition, the District Fisheries Department in 1991 reported that the number of water bodies in the city was 19,250, while this figure changed to 4523 as reported by the CDA during 2006–2007 (decreasing rate: 920/year) [16]. Thus, along with a modified hydrological cycle, the waterlogging frequency in Chattogram City has increased remarkably in the last decade or so [1].
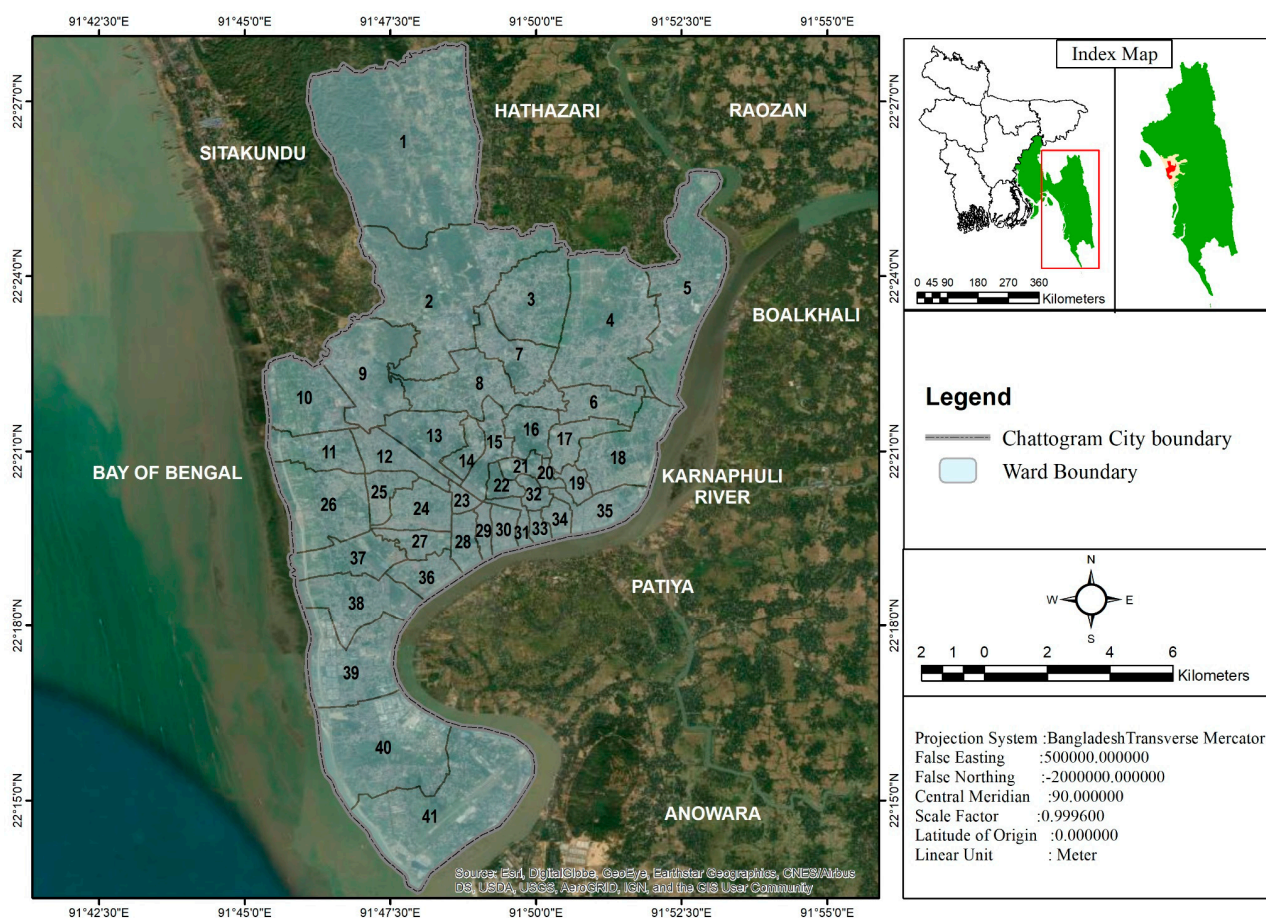
Figure 1. Location map of Chattogram City. Numbers (1–41) represent the respective ward (smallest administrative units) locations in the city.

3. Data and Methods

The waterlogging risk index presented in this study is estimated with the following basic Equation (1) [29]:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{1}$$

Using the waterlogging hazard intensity index map developed in the Geographic Information System (GIS) environment and GIS database at the city level, the elements at risk were combined to assess the exposure. A vulnerability assessment was carried out for the key individual facilities and resources within the waterlogging affected area. Finally, utilizing the hazard, exposure, and vulnerability assessments, a 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 the waterlogging inventory map, hazard intensity, vulnerability, and risk index are described step-by-step in the following sections.
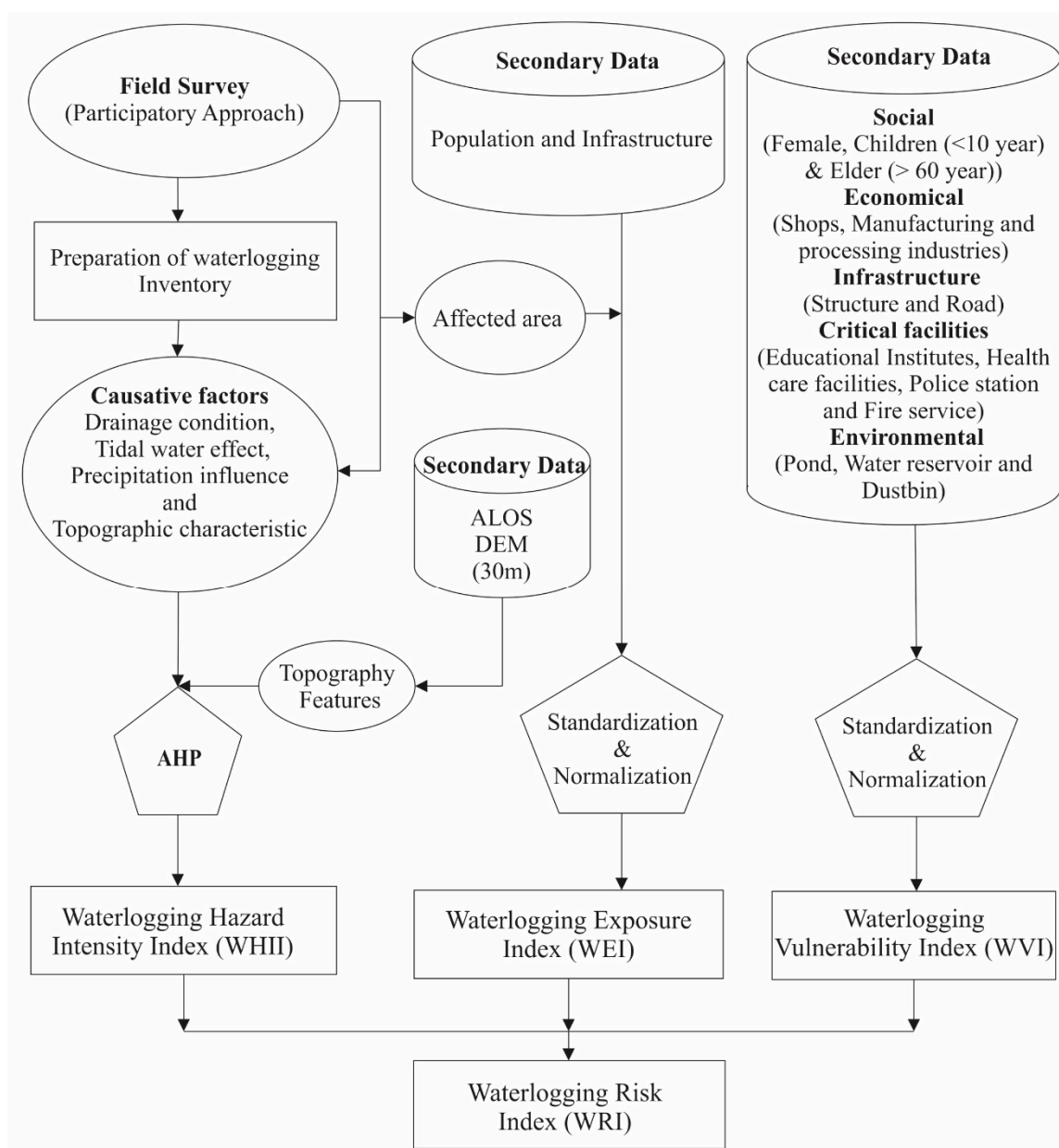
Figure 2. The adopted methodology of the study.

3.1. Preparation of Waterlogging Inventory

A waterlogging inventory map was prepared from the existing literature and field survey. At first, preliminary waterlogging locations were identified from the existing literature, such as local newspapers, research articles, and government reports [10,30–33]. An extensive participatory field survey was then conducted to confirm the exact location and extent of this hazard. The participatory survey was adopted for increasing the reliability and accuracy of the inventory data, assuming that local people had a better knowledge of the waterlogging. This field survey was first conducted in 2014 and updated in 2019. Steps followed for the preparation of the inventory map are given below:

- A team consisting of 15 members worked as facilitators. First of all, facilitators contacted the residents and formed a team of five residents from each ward to attend and share their thoughts about the survey after explaining the purpose of the study. A total of 22 wards were surveyed, and thus, 110 people (5 residents/ward × 22) participated in the survey.

- After that, some of the members were asked to identify the waterlogging locations in their respective wards and draw the boundary lines. A comprehensive base map collected from Google Earth was given to the participants to draw on, and the facilitator helped them to understand the map.
- The participants were also interviewed individually using a questionnaire (Appendix A). There were 13 questions in that questionnaire; among them, one major question was the causes of waterlogging. This questionnaire considered 40% closed and 60% open questions.
- Finally, facilitators used a hand GPS (Global Positioning System; Model: Garmin handheld GPS etrex 30×) to store the field data (waterlogging location and extent area) in a digital format and converted it into an inventory map in the GIS environment.

3.2. Preparation of the Waterlogging Hazard Intensity Index

Based on the inventory map, the waterlogging hazard intensity index (WHII) was prepared following two steps: (a) determining the major influential factors to waterlogging from the participatory survey and (b) applying the GIS-based overlying technique to combine identified factors into a single composite layer (WHII). The collected primary data and WHII were processed and represented spatially using GIS mapping, which is explained below:

3.2.1. Drainage Condition Map

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

3.2.2. Tidal Water Effect Map

Some low-lying flat areas in Chattogram City have small or no water level differences with the adjacent tidal canals and Karnaphuli River during high tide, resulting in a tidal water entrance into the city on a regular basis [22]. 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 at 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 after less than one hour of high tide without affecting the nearby built-up areas were counted as having a low influence of tidal water during waterlogging.

3.2.3. Precipitation Influence Map

To portray the importance of rain on waterlogging hazards, we asked residents to qualitatively judge the influence into three categories: intense, moderate, and light. Here, an intense (moderate) influence means light (moderate)-intensity rain was enough to create waterlogging. The areas that were susceptible to waterlogging only during heavy rainfall were considered as having a light influence.

3.2.4. Topographic Influence

During the field survey, the influence of land elevation in creating waterlogging was determined into four broad categories: very high, high, moderate, and low. The definition of each category was as follows: very high: land elevation <6 m, high: 6–10 m, moderate: 11–15 m, and low: >15 m. An elevation map prepared from the ALOS 30-m Digital

Elevation Model (DEM) [34] was given to the participants, and the facilitator helped them understand the map.

3.2.5. Analytic Hierarchy Process Analysis

GIS-based overlying technique—Multi-Criteria Decision Analysis (MCDA)—was applied to prepare the WHII map. MCDA belongs to the heuristic analysis group, including the Analytic Hierarchy Process (AHP), the Weighted Linear Combination, and the Ordered Weighted Average [35]. In this study, AHP [36] was employed to derive the weights associated with four thematic map layers identified by local people: drainage condition (A_1), precipitation (A_2), topographical characteristics (A_3), and tidal water effect (A_4). AHP was chosen because it can deal with complex decision-making and be 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., [27,35,37–39]).

The AHP process requires a predefined score or weight to input [36]. 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 Equation (2):

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

Here, *WHII* is the required hazard intensity index for a specific site; W_i and R_i are the 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 hazards. Finally, the *WHII* stands for each site = weight for A_1 × ("1" for unsatisfactory drainage, "0.66" for marginally satisfactory drainage, and "0.33" for satisfactory drainage condition) + weight for A_2 × ("1" for intense, "0.66" for moderate, and "0.33" for light influence of precipitation) + weight for A_3 × ("1" for very high, "0.75" for high, "0.50" for moderate, and "0.25" for low influence of land elevation) + weight for A_4 × ("1" for high, "0.66" for moderate, "0.33" for low, and "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 [40] into five levels: very high, high, moderate, low, and very low in waterlogging hazard intensity.

3.3. Preparation of Waterlogging Exposure Index

Exposure was assessed for elements at risk within the waterlogging affected area, where a number of people and infrastructures were identified as exposed. Population and infrastructure data were collected from Bangladesh Bureau Statistics [23] and CDA [41], respectively. These data include different population information, roads, and structures (Table 1). To prepare the waterlogging exposure index (WEI), first, the elements at risk were standardized using Equation (3). The standardized values were summed up and rescaled for normalizing the score between 0 to 1 by applying Equation (4). This index value was represented visually by GIS mapping.

$$z = X - \mu\sigma \tag{3}$$

$$X_{new} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{4}$$

where Z = standardized value, X = observed value, μ = mean value, σ = standard deviation, X_{new} = normalized value, X_{min} = minimum value of the dataset, and X_{max} = maximum value of the dataset.

Table 1. Description of elements at risk considered in the exposure analysis.

Elements at Risk	Description
Population	Gender distribution, age distribution (No.) in the affected area
Infrastructure	No. of residential building, school, college, university, hospital/clinic, fire service station, police station, water reservoir, shop, bank, manufacturing, and processing industry; roads (length) in the affected area

3.4. Preparation of Waterlogging Vulnerability Index

The vulnerability assessment was focused on determining the vulnerability of key individual facilities and resources within the affected area due to waterlogging. These facilities and resources were broadly categorized into five dimensions (complex variables): (a) social, (b) infrastructure, (c) critical facilities, (d) economic, and (e) environmental. We further subdivided these complex variables into 18 different simple variables, which were determined as sensitive [42] to waterlogging. These simple variables were selected based on the available attribute information in the spatial data summarized in Table 2. 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 the WEI (Equations (3) and (4)) by combining the indices for the five complex variables.

Table 2. Description of variables used in the vulnerability analysis.

No.	Vulnerability Dimension (Complex Variables)	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

Table 2. *Cont.*

No.	Vulnerability Dimension (Complex Variables)	Simple Variables	Description
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

3.5. Preparation of Waterlogging Risk Index

The waterlogging risk index (WRI) for Chattogram City was estimated by multiplying the WHII, WEI, and WVI layers (Equation (1)). The score was standardized and normalized using Equations (3) and (4), respectively. Finally, the resulting WRI map was reclassified using the equal interval method [40] into five levels: very high, high, moderate, low, and very low risk due to waterlogging.

4. Results and Discussion

4.1. Preparation of Waterlogging Inventory Map

A total of 58 waterlogging locations were identified in Chattogram City, where 22 wards among 41 wards were found as waterlogging-affected (Figure 3a). The total size of the affected area was 13.08 sq.km (~8.42% of city area), with a mean size and standard deviation of 0.57 and 0.9 sq.km respectively. The extent of the area and affected area names respective to each waterlogging location are shown in Figure 3b and Table 3, respectively.
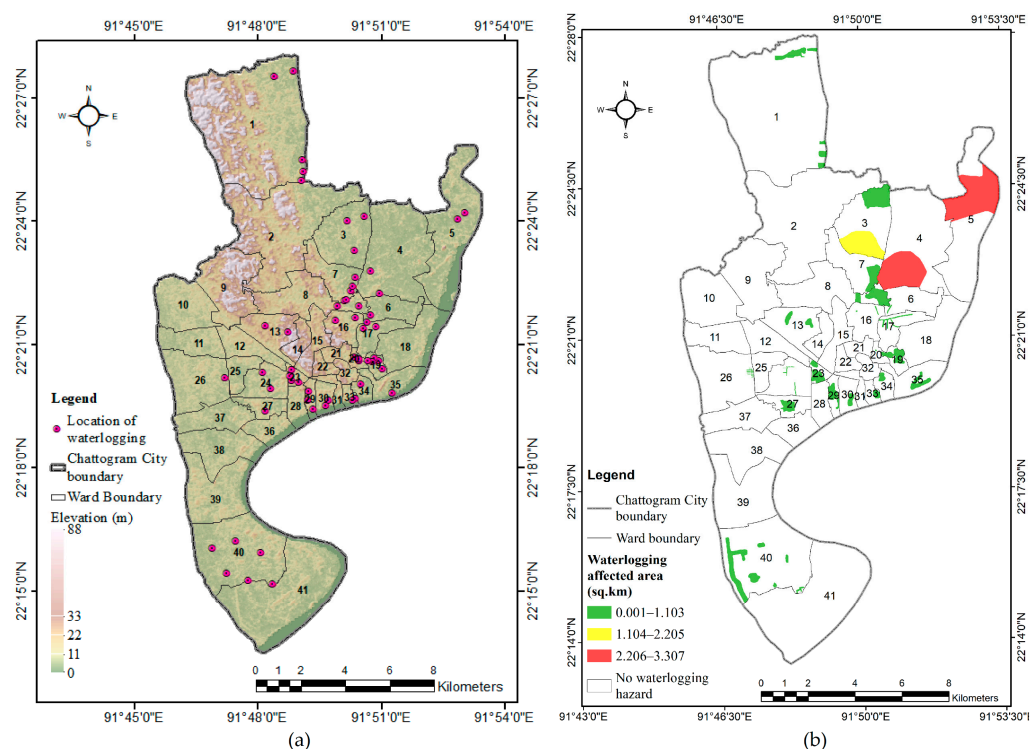

Figure 3. Ward-wise waterlogging inventory map for Chattogram City: (**a**) location (total of 58) and (**b**) extent of the area.

Table 3. Waterlogging affected area names in Chattogram City.

Ward No.	No. of Affected Areas	Affected Area Names
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		*Aluminum 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 north of stand road, Dhaka trunk road, Shuvopur*
30	2	*Hazi Bari and Maiz Para, Jele and Firingi Bazar*
33	2	*Yakub Nagar, Tekpara (Bandel canal)*
34	1	*Brickfield road*
35	1	*Chaktai Canal area and Cox's Bazar Road*
40	6	*Maizpara, Muslimabad, Dhumpara, South of T.S.P Fertilizer Factory, Hossain Ahmed Para, Colony Jama Mosque*
	Total = 58	

This study reported that some of the waterlogging points were located in the prime areas of the city, such as *Kapasgola* and *Badurtola* (ward no. 6), *Muradpur* junction area (ward no. 7), *Solokbahar* (ward no. 8), *Probartok moore, Katalgonj* (ward no. 16), CDA residential area (ward no. 27), *Firingi Bazar* (ward no. 30), and *Chaktai* canal area (ward no. 35) (Table 3). The provided inventory map is the first waterlogging inventory that covers the entire area of Chattogram City.

4.2. Causes of Waterlogging

The inventory map showed that most waterlogging points are located on the east side of the city, adjacent to Karnaphuli River, where the land elevation is between three to six m from the mean sea level (Figure 3a). It should be noted that the elevation values in Figure 3a may be higher than the actual ones because of the coarse resolution (30 m) of the ALOS DEM. During the field survey, local residents (70%) identified low elevation as a significant attributing factor to cause waterlogging.

Respondents from 13 wards (out of 22) (Figure 4a) pointed out that they were unsatisfied with the existing local drainage facilities' performances, because their places become knee-deep underwater during a heavy shower and high tides. Interestingly, there was no ward from where respondents were satisfied with their local drainage facilities,

implying that the drainage condition is the most important determinant of understanding the waterlogging severity.
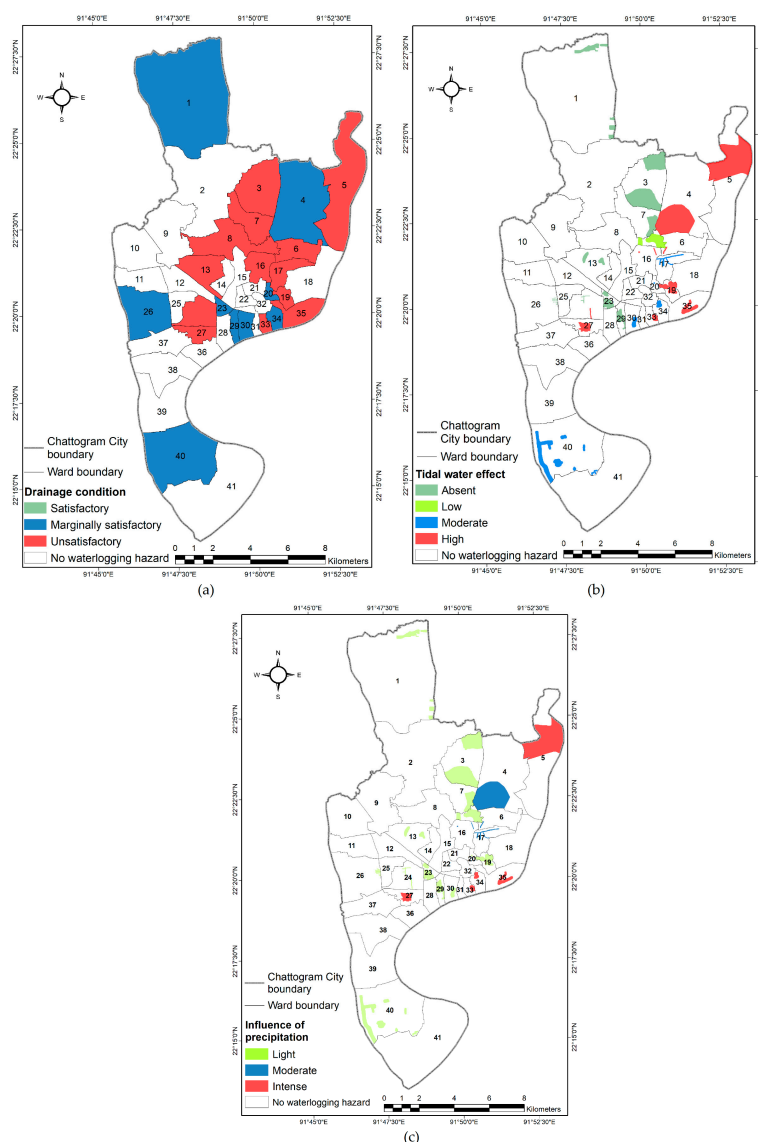

Figure 4. Ward-wise waterlogging hazard attribute layers for Chattogram City: (**a**) drainage condition map, (**b**) tidal water effect map, and (**c**) precipitation influence map.

The impact of tidal level on waterlogging is inevitable in Chattogram City (Figure A1c). It is found that 23% of waterlogging points to the experience of tidal water influence for more than two hours (indicated as a high influence in Figure 4b) when rain coincides with a high tide. The respondents (44%) claimed that improper management and a lack of sluice gates on the mouth of different canals connecting with Karnaphuli River resulted in tidal water entrances in the built-up areas, even without precipitation.

In general, heavy rainfall is accounted as the primary triggering factor to cause waterlogging (i.e., [3,17]). However, during a field survey, 32% participants reported that their living places (indicated as an intense influence in Figure 4c) were very sensitive to rainfall, since light rain is sufficient to create waterlogging. This finding is consistent with some previous literature (i.e., [43,44]). It is reasonable, because the wards (i.e., ward no. 5, 27, 33, and 35) are low-lying and, have insufficient/no sluice gates on the mouths of their tidal canals; facilitated with poor drainage structures, they can still be inundated with or without any occurrence of heavy rain.

4.3. Waterlogging Hazard Intensity Index

Table 4 shows the waterlogging attributing factor weights derived from the AHP analysis. The highest weight is assigned to the drainage condition, while the precipitation, topography, and tidal water effect are 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 [35,36].

Table 4. Weights and consistency ratio of the data layers.

Factors	Eigen Values
Drainage condition	0.5167
Precipitation	0.2406
Topography	0.1320
Tidal water effect	0.0749
Consistency ratio: 0.0829	

After applying the AHP-generated weights in Equation 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 approximately 4.17% (6.48 sq. km) of the area is classified as moderate, and the remaining 2.49 sq. km is classified as low to very low (Table 5).
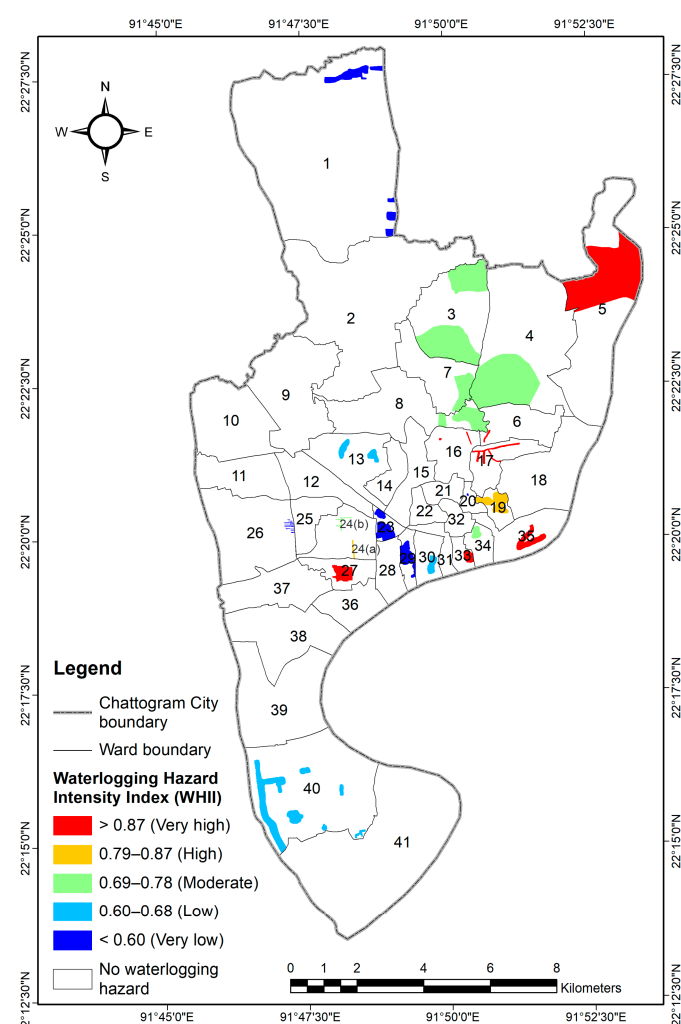

Figure 5. Ward-wise waterlogging hazard intensity index for Chattogram City.

Table 5. Distribution of areas, locations, and affected wards according to the waterlogging hazard intensity index (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

A total of 13 waterlogging points and eight wards fall within the very high and high-intensity zones. However, this does not reflect their respective waterlogging risks, which should also be greater, as will be shown in the following sections.

Next, we compared the AHP-generated WHII (Figure 5) with the field survey data, including the waterlogging frequency–depth–duration (Appendix, Figure A2). The analysis showed that the majority of the affected areas with a greater intensity (i.e., WHII > 0.78) were located in the eastern part of the city, where a greater inundation height was observed (i.e., >0.9 m, Appendix, Figure A2b), with a longer stagnant time (i.e., ≥three h, Appendix, Figure A2c). In contrast, the waterlogging frequency–depth–duration was recorded relatively less where the WHII was determined as smaller than 0.69 (i.e., ward no. 1, 13, 23, 26, 29, and 40). Overall, the AHP-generated WHII agreed well with the field survey data.

4.4. Waterlogging Exposure Index

The waterlogging exposure index for Chattogram City is illustrated in Figure 6. 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). Thirty-five percent of the total waterlogging points and six wards fall within the very high and high exposed zones (Table 6). It is clear that, except ward no. 5, most of the wards with a greater WEI (>0.6) belonging to a moderate hazard intensity zone (Figure 5). Table 6 shows that, although many waterlogging points fall within the densely populated wards (i.e., 16, 33, and 35 [23]), their respective WEI is found to be significantly low. It can be partially explained, as each of these affected area covers ~0.5 sq. km (Figure 3b). Thus, overlaying the elements at risk onto those affected areas yields a limited population and infrastructure, as exposed.

Table 6. Exposure of the area, locations, and wards as per the level of waterlogging exposure index (WEI).

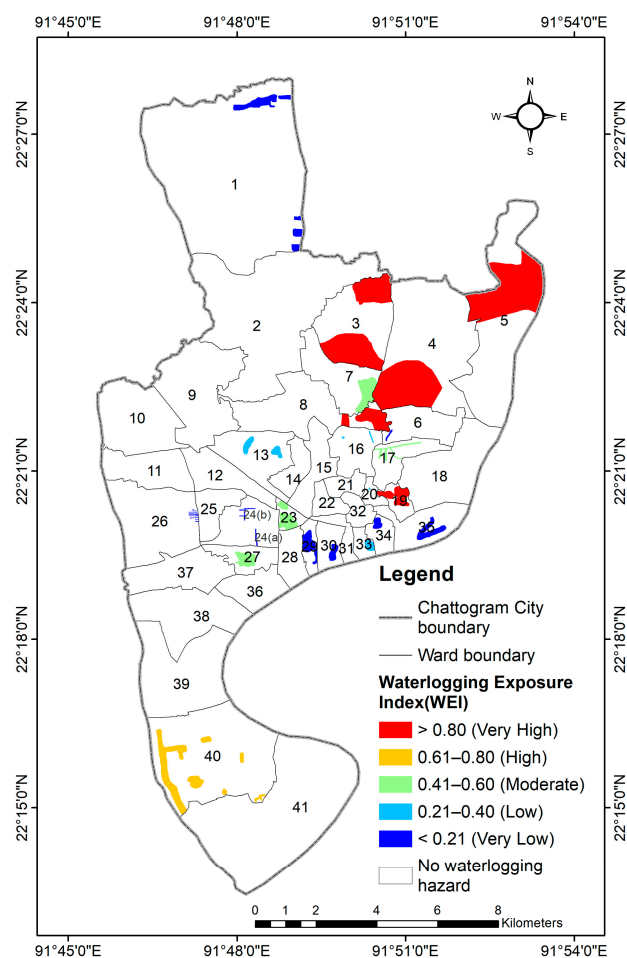| WEI	Exposure Level	Area (sq. km)	No. of Waterlogging Locations	Exposed Wards
>0.80	Very high	9.23	14	3, 4, 5, 8, 19
0.61–0.80	High	1.05	6	40
0.41–0.60	Moderate	1.11	12	7, 17, 23, 27
0.21–0.40	Low	0.31	9	13, 16, 20, 33
<0.21	Very low	1.15	17	1, 6, 26, 29, 30, 34, 35, 24(a), 24(b)

Figure 6. Ward-wise waterlogging exposure index for Chattogram City.

4.5. Waterlogging Vulnerability Index

The waterlogging vulnerability for Chattogram City is represented in Figure 7. It includes the overall WVI that combines five different vulnerability dimensions: social, infrastructure, critical facilities, economic, and environment (see Section 3.4 for the variables considered in each dimension). It is determined that more than 160,000 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) populations, respectively. The analysis illustrated that the city's outer skirts have lower social vulnerability, while it is comparatively higher in the city center, as shown in Figure 7a. Among 22 waterlogging-affected wards, ward no. 19 is ranked first in its social vulnerability. The populations in the areas with greater social vulnerability would be the most dependent on public resources (i.e., public transportation and social services) after waterlogging disaster strikes, and therefore, a social vulnerability map could indicate good investment areas for hazard mitigation activities.
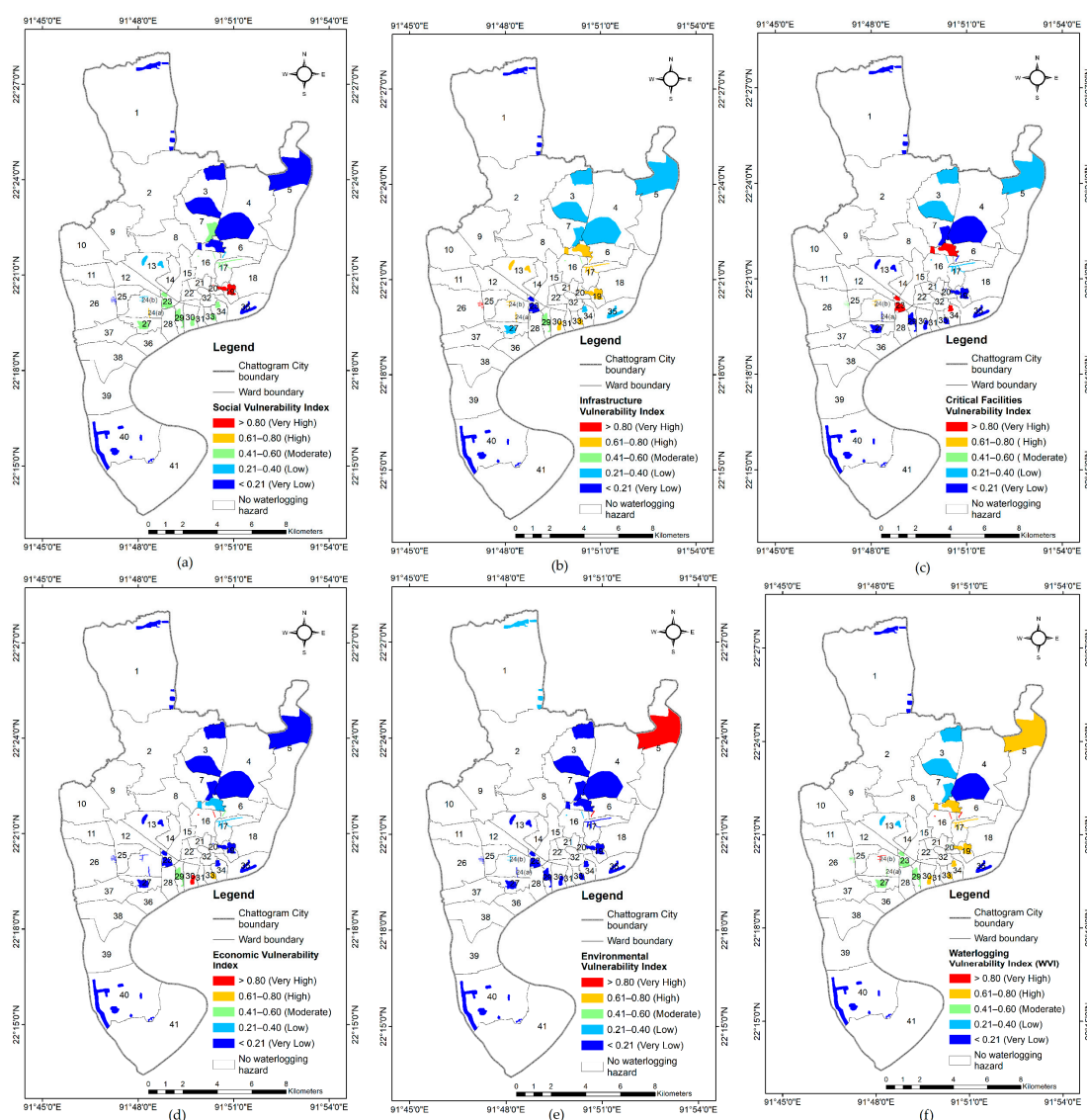
Figure 7. Ward-wise (**a**) social vulnerability index, (**b**) infrastructure vulnerability index, (**c**) critical facilities vulnerability index, (**d**) economic vulnerability index, (**e**) environmental vulnerability index, and (**f**) overall waterlogging vulnerability index for Chattogram City.

The infrastructure vulnerability is shown in Figure 7b. The results indicate that the vulnerability is comparatively higher in the city center than in the outer skirts. Among the 22 affected wards, the infrastructure vulnerability is high for ward no. 6, 17, 19, and 33, along with their greater WHII (Figure 5). It is determined that over 22,000 residential structures (~14.6% of total residential structures), including the *Chandgaon* (ward no. 4; Table 3) and CDA (ward no. 27; Table 3) residential areas, are vulnerable under five different categories of hazard intensity. The area with an infrastructural vulnerability index greater than 0.60 covers more than 1600 *kutcha* structures (see Section 3.4 for the definitions), which are essentially unable to withstand adverse impacts of waterlogging due to low structural integrity. Additionally, a large number of semi-pucka structures (more than 10,000) were found vulnerable, though not out of damage potential, as the walls and foundations were made of less sustainable building materials (i.e., bricks). In the context of Chattogram City, *pucka* structures might also be affected by waterlogging due to the corrosive effects of saline water. Such damage could increase the reconstruction costs.

Figure 7b also considered the road vulnerability in Chattogram City. The entire city is served by ~2889 km of road [41], while 361.5 km of road was identified as vulnerable to

waterlogging hazards. The present study revealed that several important roads, including *Probortok moore* (ward no. 16; Table 3) and Chattogram-Cox's Bazar connecting highway (ward no 35; Table 3), are covered by the very high hazard intensity zone (Figure 5). During the rainy season, these roads go under 0.91–1.2 m of water (Appendix, Figure A2b), resulting in a severe disruption in the major communication system of Chattogram City. It is determined that different categories of the hazard intensity zone cover a total of 133 km *semi-pucka* (brick soling) and 44.3 km *kutcha* roads (made from mud). The percentage of pucka road (paved) vulnerability is ~39% higher than the *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.

Critical facility vulnerabilities in Chattogram City are not negligible, as shown in Figure 7c. Ward no. 8, 23, and 34 are ranked highest in their critical facility vulnerabilities. Unlike the greater WHII score (>0.87, Figure 5), ward no 5, 6, 17, 27, 33, and 35 are found less vulnerable in terms of critical resources. The analysis suggests that several hospitals, police stations, and more than 250 educational institutes (~17.7% of total educational institutes in the city) fall within the different vulnerable zones. Thus, academic activities are hampered, because students might not attend classes when their places get inundated. It is important to protect critical facilities (i.e., through relocating and elevating) to confirm that service interruption is reduced, as these facilities play a key role in emergency response and recovery.

Figure 7d exhibits an economic vulnerability to waterlogging by identifying major commercial sectors: shops and manufacturing and processing industries in Chattogram City. Some major economic centers, including *Katalganj* (ward no. 16; Table 3) and *Firingi bazar* (ward no 30; Table 3), are ranked as the highest vulnerable, which might threaten a 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 serves 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 steps to prevent or minimize such losses.

The spatial distribution of environmental vulnerability is illustrated in Figure 7e. While ward no. 5 and 6 both are ranked highest (>0.81) for their environmental vulnerabilities, most of the affected wards show very low vulnerability (<0.21). Several secondary risk sites, including ponds (more than 750), waste collection sites, and water reservoirs, have been identified that can trigger further disastrous conditions if waterlogging occurs. Waterlogging can result in contamination, whereby wastes, pesticides, raw sewage, chemicals, and hazardous materials are transported through neighborhoods, sensitive habitats, and businesses. Waterborne diseases like diarrhea and 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.

Combining the five different vulnerability dimensions (8a–e) yields the overall WVI (Figure 7f) for Chattogram City. The variations in the WVI scores are significantly different from the individual vulnerability dimension scores at the ward level. For instance, ward no. 5 and 34 fall within the high vulnerable zone (>0.60, Figure 7f), while their social (Figure 7a), infrastructural (Figure 7b), and economic (Figure 7d) vulnerability scores show comparatively less (<0.41). The WVI map also suggests that the wards at the eastern side of the city show greater vulnerability than the others. The waterlogging-affected areas that have WVI scores >0.60 cover ~3.03% (4.71 sq.km) of Chattogram City, followed by moderate (0.71%), low (1.98%), and very low (2.86%), as shown in Table 7. A comparison between the WVI and WHII (Figure 5) reveals that ward no. 5, 6, 16, 17, and 33 scored higher (>0.60) in both than the other affected wards. It also needs to be noted that, although

some wards (i.e., ward no. 35) showed greater hazard intensity scores (i.e., >0.87), the overall vulnerability score was found to be low (i.e., <0.41).

Table 7. Vulnerable areas, locations, and wards as per the level of waterlogging vulnerability index (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

4.6. Waterlogging Risk Index

To address the risk potential under waterlogging condition in Chattogram City, the WHII (Figure 5), WEI (Figure 6), and WVI (Figure 7f) scores were multiplied using Equation (1). The resulting WRI is spatially presented in Figure 8. The study area (~2.71%) is at very high risk, followed by moderate (0.15%), low (3.89%), and very low (1.67%). The area, number of waterlogging points, and wards in each risk level are summarized in Table 8. The risk score is highest for ward no. 5, 18, and 19, while the most affected wards fall under the low-very low category of risk. The comparisons among the WHII (Figure 5), WEI (Figure 6), WVI (Figure 7f), and WRI (Figure 8) revealed that ward no. 5 scored the highest in all the indices presented in this study, followed by ward no. 8, 19, 17, and 33. It is interesting to note that, although the hazard intensity and vulnerability scores were greater (>0.79) for ward no. 6 and 16, their associated exposure levels were found low (<0.41) and, thus, resulted in low risks (<0.21) due to waterlogging.
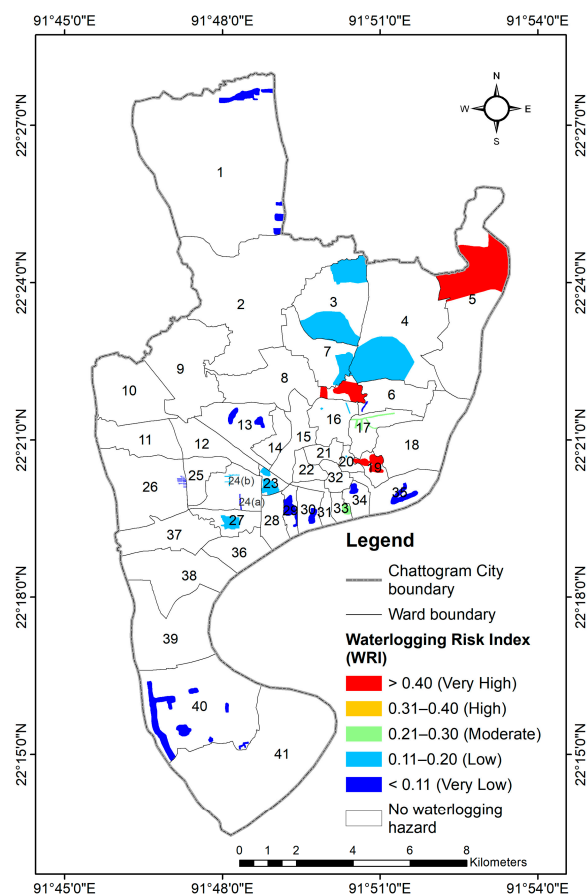

Figure 8. Ward-wise waterlogging risk index for Chattogram City.

Table 8. Risk area, locations, and wards as per the level of the waterlogging risk index (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)

5. Summary and Conclusions

The analyses presented here aimed to prepare a waterlogging inventory map and assess the waterlogging risk in Chattogram City, Bangladesh. In this regard, a 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, the WEI, WVI, and WRI were prepared. A total of 58 locations in 22 wards were identified as waterlogging-affected, covering ~8.42% of the city area. Local people addressed four factors: drainage condition, topography, rain, and tidal water effects as the primary attributes that cause waterlogging. The WHII map illustrated that most of the affected areas with greater intensity (i.e., WHII > 0.78) were located in the eastern part of the city, where the inundation height was also observed as higher ($\geq$0.9 m) than the other places. It needs to be noted that the waterlogging-affected area shown in this study did not confirm a complete accuracy, because the adopted participatory survey approach was subjective to the local residents' perceptions. In addition, the AHP method utilized in the present study was based on weighting the factor maps and overlaying those layers into a single composite layer. Any incorrect perceptions of the different criteria roles can be easily conveyed, from the expert's opinion, into the weight assignment [45]. 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 were both found to be comparatively higher in the city center than the outer skirts. The obtained WVI map suggested that ward no. 5, 6, 16, 17, and 33 were more vulnerable to waterlogging than the other locations in Chattogram City.

The waterlogging risks determined herein combined the hazard intensity, exposure, and vulnerability indices. It suggested that ~2.71% of the study area was at very high risk, followed by moderate (0.15%), low (3.89%), and very low (1.67%). The comparisons among the WHII, WEI, WVI, and WRI showed that ward no. 5 scored the highest in all the index formats, followed by ward no. 8, 19, 17, and 33. This risk assessment did not constitute a hydrodynamic or hydrological model to confirm the overall waterlogging risks 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, the 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 the waterlogging risks in Chattogram City.

Appendix A

Questionnaire (local respondent)
1. Name:
2. Age:
3. Area of living in Chattogram City:
4. Duration of living:
5. Do you face any waterlogging in your area of living?
(a) Yes (b) No
If Yes, when (period/season)?
6. What is the drainage condition to avoid waterlogging in your area of living?
(a) Unsatisfactory: Poor operational and maintenance performance, low gravity and capacity of the drainage structure, insufficient and inactive natural water bodies, and natural drainage encroachment.
(b) Marginally satisfactory: better conditions than the criteria mentioned above.
(c) Satisfactory: all type of drainage facilities are working well.
7. Whether there is backwater flow/flooding from tidal canals/rivers in your area during tide.
(a) Yes (b) No
If Yes, what is the influence of tidal water in the waterlogging situation in your area of living?
(a) High: tidal water stands for more than 2 h
(b) Moderate: tidal water stands for 1 to 2 h
(c) Low: tidal water stands for less than 1 h
8. Whether waterlogging in your area only occurs due to heavy rainfall.
(a) Yes (b) No
If No, what is the minimum rainfall intensity to cause waterlogging?
(a) Light-intensity rainfall. (b) Moderate-intensity rainfall
9. Whether waterlogging in your area occurs due to a low terrain profile.
(a) Yes (b) No
If Yes, identify the waterlogging area on the elevation map.
10. How many times per year waterlogging takes place in your area:
11. Which depth of water you usually face during waterlogging:
12. How long water remains stagnant during waterlogging in your area:
13. In your opinion, what is the main cause of waterlogging in your area?

Figure A1. Waterlogging-affected areas in Chattogram City: (**a**) low-lying area in ward no. 34, (**b**) poor drainage conditions in ward no. 7, (**c**) tidal water entrance in the slum area of ward no. 40, and (**d**) inundated open space and houses due to light rain in ward no. 19. (Source: Field survey 2014 and 2019).
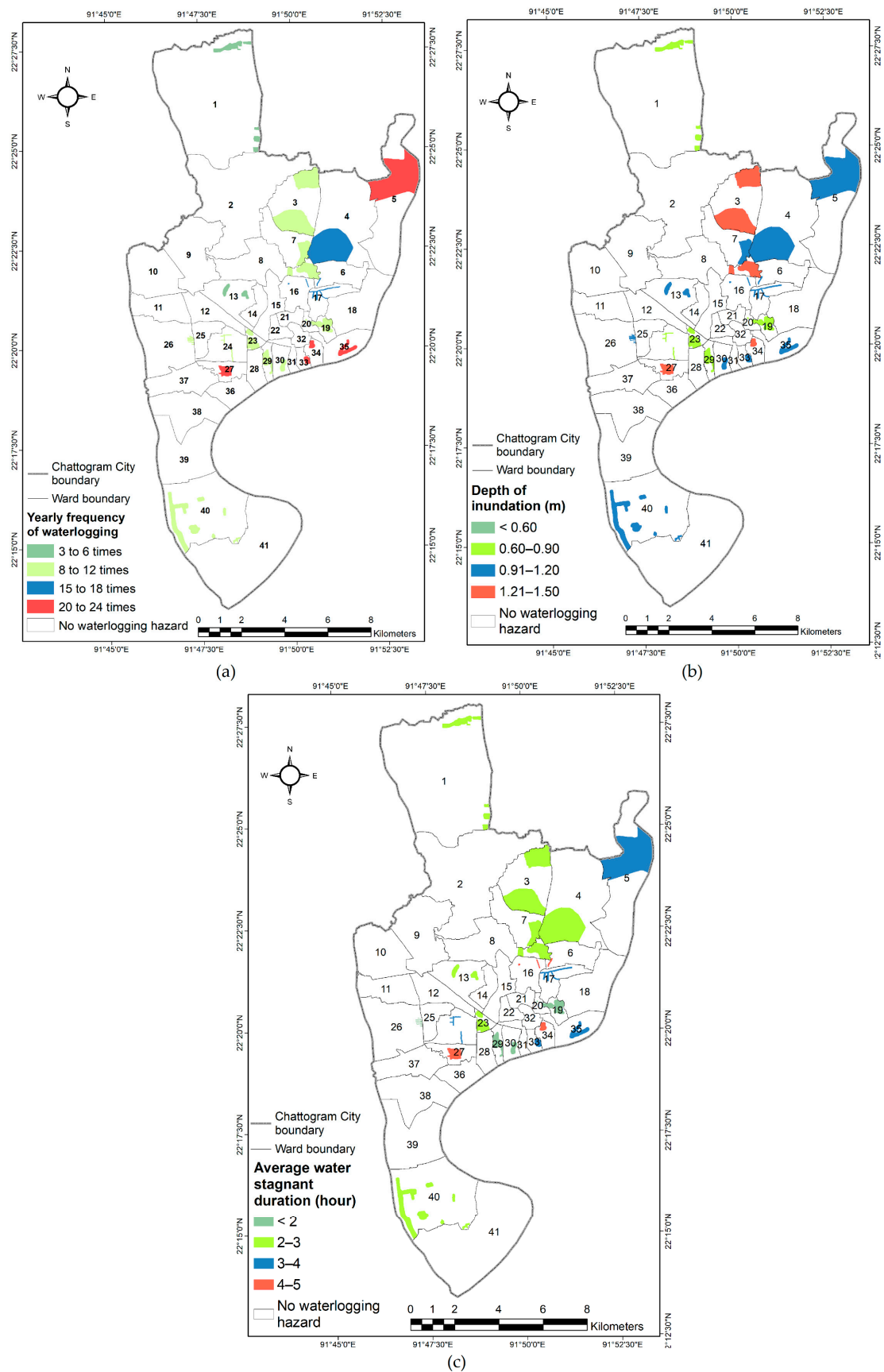
Figure A2. Ward-wise (**a**) yearly frequency of waterlogging, (**b**) depth of inundation, and (**c**) water stagnant duration (average) due to waterlogging in Chattogram City.

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