Identifying Waterlogging Risk Zones in an Urban Area of Bangladesh Using AHP-Fuzzy Rule Based Approach

M. A. Azad, S. K. Adhikary, and M. M. Rana

Abstract Waterlogging is a very common problem during the rainy season in Bangladesh, which often causes physical, social, and economic losses in both urban and rural areas. The problem is more severe, particularly in the urban areas of the country. Khulna City Corporation (KCC), being the third-largest city of the country, is located on a low-lying area on the west bank of the Rupsha River. The city has been suffering from water logging problems due to the rapid growth of the city and urbanization, the disruption of natural drainage system, high-intensity rainfall, increased population, an unplanned urban drainage system, the siltation of nearby river beds, etc. and so on. Therefore, the aim of the current study is to explore the waterlogging situation and identify waterlogging risk zones in the KCC. At first, social, economic, and hydrological data were collected from the Bangladesh Meteorological Department (BMD), the Bangladesh Bureau of Statistics (BBS), and KCC data sources. Various hydrological data such as inundation depth, drainage density, slope, etc. have been processed from the digital elevation model (DEM) through spatial analysis in the geographic information system (GIS) platform. After data collection and processing, several indicators are identified, and a criteria weight for each indicator is obtained by the analytical hierarchy process (AHP) technique. Then a fuzzy inference system (FIS) was developed in the MATLAB platform to determine the vulnerability index of three factors, such as social, economic, and hydrological. After determining the vulnerability index of three factors, a final water logging vulnerability index was determined. Finally, the waterlogging risk zones were delineated based on the index, which was interpreted by the GIS mapping. From the analysis, it is found that about 20% of the KCC area lies in the high water logging risk zone, about 42% of the

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KCC area is in the medium water logging risk zone, and the remaining areas cover the low water logging risk zones. Overall, this study demonstrates that the integrated AHP-fuzzy rule based approach can be effectively used for identifying waterlogging risk zones.

Keywords Water logging · AHP · Fuzzy rule · Vulnerability index · GIS · Khulna City Corporation

1 Introduction

Bangladesh is located on the extensive floodplains of the Ganges–Brahmaputra-Meghna (GBM) basin, where flooding is a natural part of life. Floods and waterlogging problems are a very common incidence in Bangladesh due to its geographical location in the lower downstream part of the GBM basin. The country is affected by flooding with either small or large ranges almost every year [1]. Due to the meltwater from the Himalayas, approximately 18% of the country is inundated annually, which results in the death of over 5,000 people and the damage of over seven million dwellings [2]. In addition to flood problems, the country has been dealing with a number of environmental concerns, including waterlogging, solid waste disposal, black smoke emissions from industries and vehicles, air and noise pollution, and water body contamination by the discharge of industrial effluents, and so on.

Bangladesh is a country of heavy rainfall and receives upstream river flows over which it has little or no control. Thus, waterlogging in urban areas is a frequent occurrence in the country, particularly during the rainy season, which has been a vital concern to city authorities. This is now a part of the life of city dwellers, and the frequency of this problem is increasing day by day. Most of the urban areas in the country have been experiencing waterlogging problems for the last few years, and even a little rainfall causes serious waterlogging in certain areas of the urban centers [3]. When a city experiences rapid urbanization, it becomes unable to manage the changing environment. Uncontrolled development in urban areas cannot satisfy sufficient drainage of excess rainwater, which eventually results in waterlogging parts of urban areas being inundated for a few hours to several days [3, 4]. In Bangladesh, waterlogging is one of the major problems in urban areas, particularly during the rainy season. With the rapid growth of population and unplanned urbanization in the country, the drainage and sewer infrastructures in Bangladesh have not been developed accordingly [3]. In our nation, waterlogging happens most frequently as a result of insufficient drain sections, outlet closures, and inappropriate maintenance of existing drainage systems. Most of these natural drains have been either filled in or have had human activities encroach upon them during the past decades. During the monsoon period, a huge amount of stormwater runoff is generated, which increases the runoff frequency. Only a small amount of that runoff can drain out successfully, and the remaining portion often causes waterlogging in urban areas [3, 5].

In order to minimize the aforementioned problems, identification of waterlogging risk areas and vulnerability assessment are crucial for developing affordable adaptation measures. Three different methodologies have been employed to quantify vulnerability assessment: historical loss data (HLD), vulnerability curve (VC), and vulnerability index (VI) [6–8]. Vulnerability indexing is the most commonly used approach. It is an effective tool that may help urban planners and policymakers prioritize waterlogging mitigation methods and raise public awareness by giving information and emphasizing hot locations for the flood risk, communities vulnerable to water congestion, and so on. Vulnerability can be analyzed in many ways [6–8]. However, the fuzzy rule-based approach [9] is one of the best tools among others and has been extensively evaluated by researchers in flood and waterlogging vulnerability studies [10]. Therefore, the fuzzy logic based approach has been selected in the current study for the waterlogging vulnerability study and identifying the waterlogging risk zones.

Urban flooding and waterlogging are very common occurrences in Khulna City, particularly during the monsoon season. In the recent years, the city has experienced a number of extreme rainfall events, which has resulted in waterlogging in some areas of Khulna City Corporation (KCC). For example, such as Royal Mohr, Dak Bangla Mohr, KD Ghosh Road, Gollamari, and Sonadanga frequently experience urban water logging problems almost every year [5, 11]. In addition to this, the city is currently in the development stage, which causes substantial changes in the land use and land cover. The combined effect of heavy rainfall in the monsoon season and urbanization induced land cover changes results in intense urban flooding in the city. Furthermore, the impact of climate change can exacerbate the situation and make the city more vulnerable to waterlogging [11]. Therefore, the objective of the current study is to study the waterlogging problems in the KCC area and delineate the waterlogging risk areas.

2   Study Area Description

Khulna is the third largest metropolitan city in Bangladesh, which is located in the lower delta of the GBM basin. The urban area of Khulna is located on the western bank of the Rupsha River, one of the KCC's most effective natural drainage outlets. The approximate location of KCC is shown in Fig. 1, which covers an area of about 51 km^2. The city is divided into 31 wards and is situated between 22° 49′ north latitude and 89° 33′ east longitude. The city has around 663,342 inhabitants [12]. The land elevation in the city is flat and ranges from 1 to 5 m above mean sea level [5, 11]. The annual average rainfall of in Khulna city is 1878 mm, and two-thirds of this rainfall occurs during the monsoon period. During heavy rainfall, it is incapable of evacuating the flow of the city, which creates water logging. Because of rapid urbanization, many drains have been closed, which puts pressure on existing drains. So, the canals (locally named "khals") should be saved anyway. Existing drains should be repaired and maintained properly. It is expected that the outcome of

the current study would be supportive of the proper development and maintenance planning of drainage infrastructure in the KCC and thereby reduce the waterlogging problems.
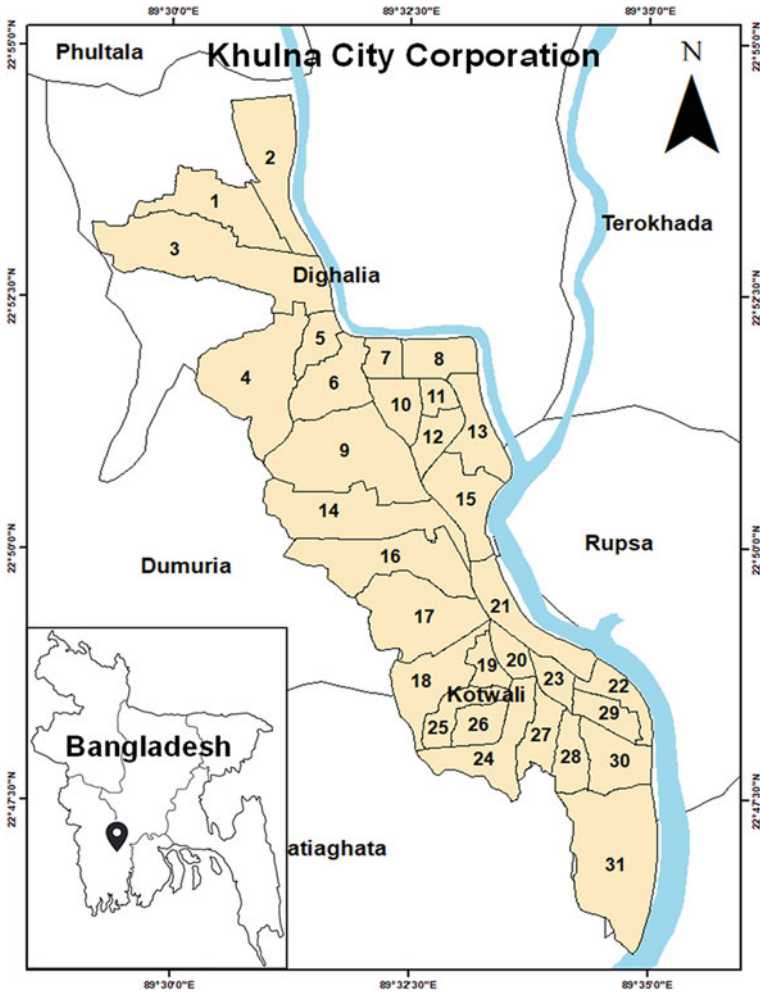

Fig. 1 The study area with different wards

3 Methodology

The methodological framework adopted in the current study is presented in Fig. 2, which is demonstrated through the use of KCC as the case study area. As can be seen from the figure, the following tasks have been undertaken in this study:

- Collection, analysis, and processing of data and selection of indicators
- Standardization of data and estimation of weighting coefficients using the analytical hierarchy process (AHP) technique
- Developing a fuzzy inference system (FIS) using the fuzzy logic toolbox in the MATLAB software platform to formulate the fuzzy logic-based water logging vulnerability index
- Identification of waterlogging risk areas in the KCC map and interpretation through spatial mapping in the ArcGIS software platform

3.1 Data Collection and Indicators Selection

In the current study, various hydrological, social, and economic data are collected, and suitable indicators have been selected for the case study. Data collected for each of the three components are provided in Table 1. In the case of hydrologic analysis, rainfall data, a digital elevation model (DEM), slope, inundation depth, drainage density, and soil permeability are gathered. Rainfall data are collected from the Bangladesh Meteorological Department (BMD). DEM has been processed from the SRTM-DEM data, which is freely available from the USGS website. By processing the DEM data on the ArcGIS platform, the slope, inundation depth, and drainage density data are obtained and organized ward-by-ward using the GIS-based raster analysis.

The soil permeability data are collected from the Bangladesh Agricultural Research Council (BARC). On the other hand, social and economic data have been collected from the Bangladesh Bureau of Statistics [12]. According to Balica et al. [8], an indicator is a trait that is inherent to a system and that estimates the condition of the system quantitatively. In this study, there are nineteen indicators selected based on the availability of data, which are presented in Table 2. The indicators are then clustered into three groups, such as exposure, susceptibility, and resilience.

Fig. 2 The flow chart of methodology adopted in the current study

Table 1 Collected data for each components

Hydrological	Social	Economic
• Rainfall	• Population density	• Kutcha and jhupri types household
• DEM	• Age	• Institutional and historical buildings
• Slope	• Disabled people	• Tenant
• Inundation depth	• Floating people	• Unemployment
• Drainage density	• Low income people	• Electricity connection
• Soil permeability	• In house population	• Sanitation facility

Table 2 List of the indicators and their clustered group

Components	Exposure	Susceptibility	Resilience
Hydrological	Flooded area ratio Annual maximum rainfall No of months heavy rainfall	Slope Soil permeability	Drainage density
Social	People of 0–9 People of 60+ Disabled people Floating people	Illiteracy rate Low income people	In house population
Economical	Kutcha and jhupri household Sanitation facility Institutional and historical buildings	Tenant Unemployment	Electricity connection

3.2 Data Standardization and Weighting Estimation by AHP

The indicators have different units and measurement scales. Hence, the indicators are converted into a standard form ranging from 0 to 1 [13]. There are different methods of standardizing data. In the current study, the data were standardized using Eq. (1).

$$S = \frac{I_n}{I_{max}} \tag{1}$$

where S is the standardized value. I_n is the value of the nth number, and I_{max} is the maximum value of each indicator obtained from all wards of KCC.

After the standardization of the data, the next step is to assign suitable weights to each of the indicators. There are several methods of weighting data, such as the Analytical Hierarchy Process (AHP), the Delphi Method, and Principal Component Analysis (PCA). In this study, the most widely used AHP method is adopted. AHP is a multi-criteria decision-making tool that is frequently used for analyzing complex decision-related problems in different fields. This is a pairwise comparison method for determining the preferred factors [14, 15]. The steps for undertaking AHP are shown in Fig. 4. As can be seen from the figure, there are a few steps to follow for the successful completion of AHP. The first step is the selection of indicators, which have been indicated earlier. The next step is to take an expert opinion survey. A scale
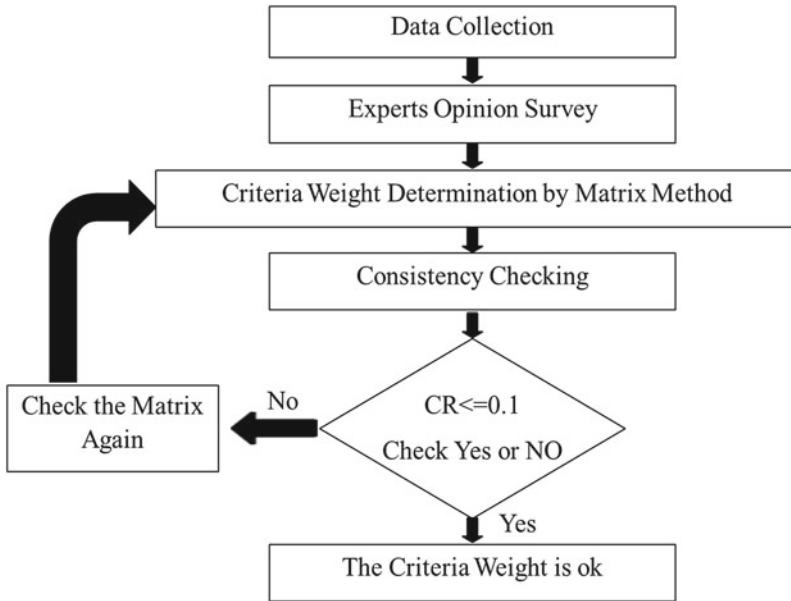
Fig. 4 Process involved in the AHP analysis technique

is used to mark the pairwise indicators. This scaling is accomplished by conducting a survey of experts in the relevant field. After the survey, a pairwise comparison matrix is formed to determine criteria weights. The final step is to check the consistency of the criteria's weight. If the consistency ratio is less than or equal to 0.10, the survey is considered consistent, and the evaluations do not require further repetitions [16]. If the consistency ratio exceeds 0.10, the decision-maker should repeat or change the analysis to improve consistency.

3.3 Development of Fuzzy Rule Based Model

In the current study, the waterlogging vulnerability index is calculated using fuzzy logic. A fuzzy rule-based model was explored by Zadeh in 1965 [6, 9]. The fuzzy method had been developed for analyzing uncertainties. In the case of the hydrological events, a model that can organize human knowledge and connect it to other data sources, such as linguistic information, is required [17, 18]. There are two types of fuzzy models, such as Mamdani FIS and Sugeno FIS. The Mamdani FIS has been selected in this study for the calculation of the waterlogging vulnerability index due to its worldwide use and acceptance. Moreover, it is simpler to comprehend than the Sugeno FIS [17]. The steps involved in the Mamdani FIS are defining fuzzy sets,
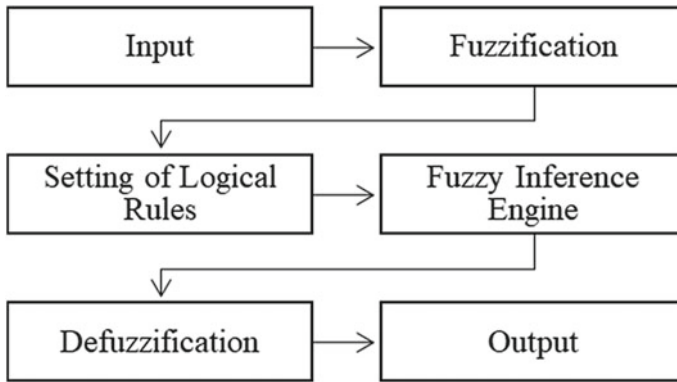
Fig. 5 Process involved with the Mamdani FIS

selecting membership functions, fuzzification logical rule setting (if–then), fuzzy inference systems, and de-fuzzification, which are shown in Fig. 5.

Fuzzy sets are sets that have degrees of membership. It indicates that the set in Boolean logic can only be defined as either 0 or 1, but in the case of fuzzy logic, the set can be any value between 0 and 1. In this study, triangular and trapezoidal membership functions are used to generate three fuzzy sets, such as low, medium, and high. This particular membership function is chosen because it gives more accurate and error-free results than other functions. In fuzzification steps, crisp input is assigned to fuzzy input according to membership functions. Since we have used if-else rules, we are familiar with Boolean logic. However, fuzzy logic follows an if–then style for its rules. For this study, it can be stated as follows: "If the inundation level is high, then the vulnerability is high." Then output is given based on rules generated by the inference engine. As indicated earlier, the data that we collected were clustered into three groups, such as exposure, susceptibility, and resilience. Three different fuzzy models were developed for these three different groups. Then a final fuzzy model is developed to determine the final water logging vulnerability index, taking the three fuzzy models into consideration, which is represented in Fig. 6.

Finally, in the defuzzification steps presented in Fig. 7, a unique value of output is shown considering all the outputs from the inference engine. The collected data have been clustered into three groups: exposure, susceptibility, and resilience. Three different fuzzy models are developed for these three indicators. As illustrated in Fig. 7, a final fuzzy model has been developed at the end to determine the water logging vulnerability index, taking the three fuzzy models into consideration.
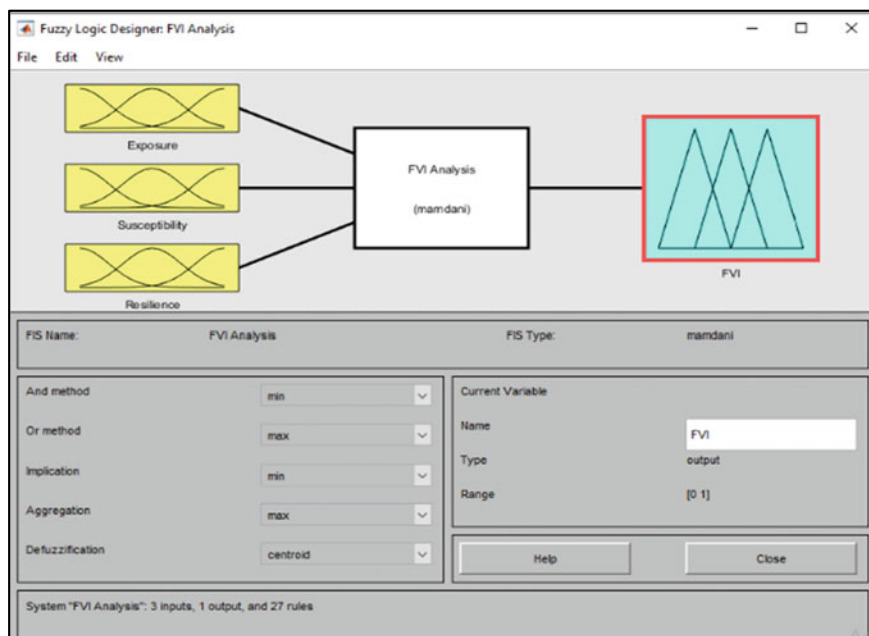
Fig. 6 Final fuzzy model considering exposure, susceptibility and resilience

4 Results and Discussion

Based on the AHP analysis, a definite weight for the criteria of the indicators has been determined. The consistency of the criteria is an important factor. We have used the pairwise comparison matrix method to determine the criteria weight. The consistency ratio of the matrix must be less than or equal to 0.1. We determined individual criteria weights for an individual expert's opinion survey. Then consistency has been checked through the matrix. Those opinions were taken into consideration, and their consistency ratio has been found to be per rules. After that, the average criteria weight of each indicator has been determined. The average maximum eigenvalue for hydrological analysis has been found to be 6.68, and the criteria weights of indicators such as the flooded area ratio, annual rainfall, number of months having heavy rainfall, slope, permeable ratio, and drainage density are 0.18, 0.15, 0.19, 0.14, 0.15, and 0.20, respectively. Likewise, for social and economic analysis, the average maximum eigenvalues are found to be 7.85, and 6.60, respectively.

The criteria weights of social indicators such as people from 0–9, people from 60+, disabled people, floating people, illiterate people, and low-income people are 0.089, 0.093, 0.266, 0.236, 0.088, and 0.177. The criteria weights of economic indicators such as kutcha and jhupri households, sanitation facilities, institutional and other households, unemployed people, non-established people, and electricity connections are found to be 0.298, 0.293, 0.112, 0.087, 0.128, and 0.083, respectively. After
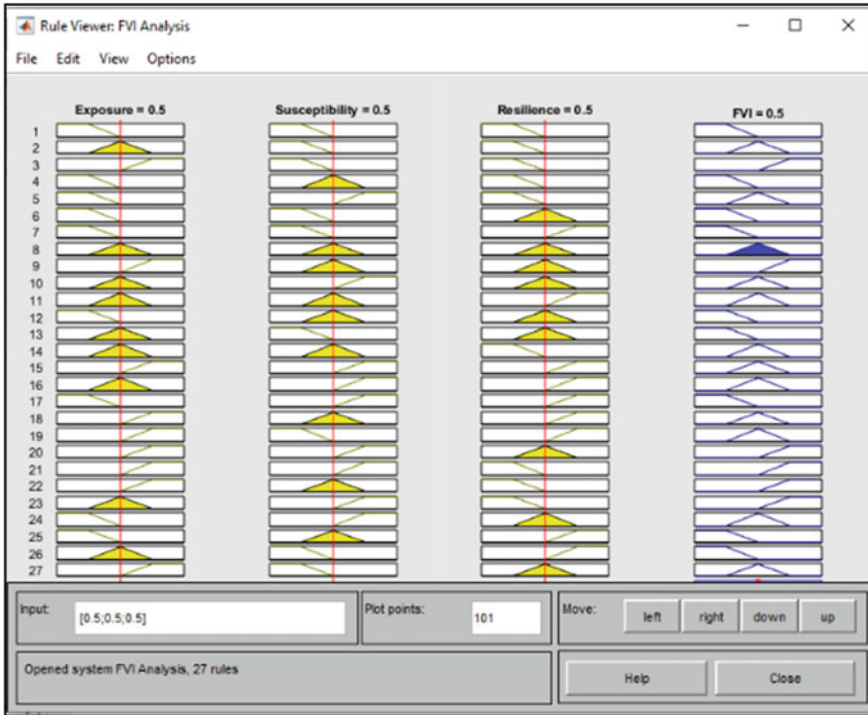
Fig. 7 Estimating water logging vulnerability index (WVI) by de-fuzzification

weighting, all the data were given as input to the fuzzy inference system, which was developed using the fuzzy toolbox in the MATLAB platform. After the calculation through fuzzy logic, all types of vulnerability indices, including SVI, EVI, and HVI, are aggregated using the arithmetic mean method in order to determine the final water logging vulnerability index. The result of the vulnerability index is then further classified into three categories, such as 'high', 'medium', and 'low'. The result is then interpreted by the spatial GIS mapping in the ArcGIS platform. The result of the analysis is presented in Fig. 8.

In the case of social vulnerability analysis, it has been found that nearly 20% of total areas are in highly vulnerable classes. On the other hand, in cases of economic vulnerability, the results range from low to medium. From hydrological analysis, 20% of total areas of the KCC have been identified as high-risk areas. Then, aggregating all the vulnerability indexes, the final vulnerability shows that 20% are in the high-water logging risk areas, 42% areas lie in the medium vulnerable class, and the remaining parts are in the low categories. Flat slopes and drainage congestion are the main factors that make them highly vulnerable to waterlogging according to hydrologic analysis. In the case of social analysis, floating people, the elderly population, and low-income people are the main reasons for vulnerability.
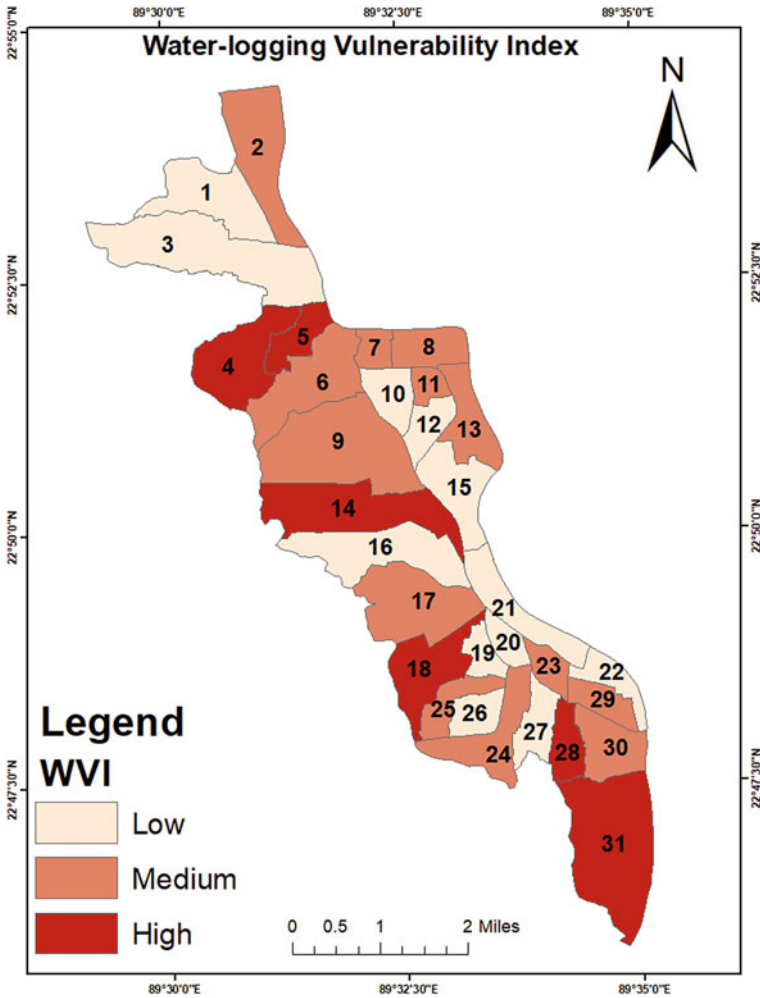
Fig. 8 Ward-wise delineation of water logging risk zones in the study area

5   Conclusions

An index-based approach is chosen in this study for exploring the water-logging vulnerability in an urban area such as the Khulna City Corporation (KCC) because it is a simple and practical tool for water management and policy makers. This study uses the AHP-fuzzy rule-based approach to assess the water logging vulnerability index (WVI) and identify the water-logging risk areas in the KCC. For the analysis, various hydrological, social, and economic data are employed. The fuzzy logic toolbox in the MATLAB platform is used to create the fuzzy model, and then the vulnerability index of each component is determined for each ward of the KCC, taking

exposure, susceptibility, and resilience into account. It is found from the analysis that 6 wards, including ward nos. 4, 5, 14, 18, 28, and 31, are located in high-risk zones both socially and hydrologically. It is also found from the study that approximately 38% of the KCC area is identified as being in the low vulnerable class, and about 42% of the KCC area falls in the medium vulnerable class. Based on the findings obtained in the current study, it can be recommended that the relevant government authorities, such as KCC, Khulna Development Authority (KDA), and Bangladesh Water Development Board (BWDB), along with different national and international non-government organizations (NGO) such as WaterAID, Nobolok, and Practical Action, should undertake necessary actions and appropriate measures to maintain the undisturbed natural flows in the drainage networks.

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