URBAN FLOOD HAZARD ZONATION IN BENGALURU URBAN DISTRICT, INDIA

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ABSTRACT

Flooding in urban areas is increasingly becoming a global challenge, driven by extreme rainfall events and the vulnerability or resilience of affected regions. This urban flood disaster not only threatens societal security but also hampers economic development in cities. Satellite remote sensing technology has played a crucial role in all aspects of flood disaster management, including preparedness, prevention, and relief efforts. Space systems, with their advantageous perspective, have proven their ability to provide essential information and services for effective flood management.

This study focuses on creating flood hazard maps for Bengaluru's urban district using an Analytical Hierarchy Process (AHP)-based Multi-Criterion Decision Analysis (MCDA) and Geographic Information System (GIS) techniques. Factors such as rainfall, drainage networks, land use, groundwater levels, terrain elevation, slope, and soil type are considered. The AHP method assigns weights and ranks to each factor, and a weighted linear combination approach is used to merge basic maps into the final flood vulnerability map.

Keywords: Flood vulnerability, Analytical Hierarchy Process, Multi-Criterion Decision Analysis, Geographic Information System

INTRODUCTION

Globally, floods have presented immense dangers to human lives and properties. They are responsible for around one-third of all fatalities, injuries, and damages caused by natural disasters. (Askew, 1999). Since 1900, over 10,000 lives have been lost to floods in the United States alone. China has faced some of the world's most devastating floods, often linked to the unstable Huang He (Yellow River). In Bangladesh, tragic events occurred in 1970, 1985, and 1991 when high tides and a tropical cyclone storm surge combined, causing widespread flooding in the low-lying delta of the Ganges and Brahmaputra rivers, and resulting in hundreds of thousands of fatalities. Many studies have extensively examined flood scenarios, focusing on factors such as high river levels, concentrated overland flow after heavy rainfall, limitations in drainage systems, and blockages in waterways and drainage channels. (Oriola, 1994; Folorunsho & Awosika, 2001; Ologunorisa, 2004). However, many issues can stem from a single cause, yet it's typically a blend of factors that leads to the most severe flooding (News release, 2007, www.defra.gov.uk). Studies have also documented the risks associated with flooding and have endeavored to devise solutions to mitigate this ongoing challenge. (Abams, 1995; Bogdani & Selenica, 1997; Hogue *et al*., 1997; Durotoye, 1999; Awosika *et al*., 2000; Folorunsho & Awosika, 2001). The likelihood of any physical, structural, or socio-economic element being compromised, damaged, or lost due to a natural hazard defines its vulnerability. This vulnerability isn't static; it's a dynamic process that considers changes and developments affecting the probability of loss and damage to all exposed elements. (UNCHS, 1981; Ologunorisa & Abawua, 2005). In simpler terms, vulnerability encompasses situations and processes that stem from physical, social, environmental, and economic factors. These elements collectively determine how susceptible a society is to the effects of hazards. (UN/ISDR, 2004). The assessment of vulnerability requires the ability to identify and understand the susceptibility of elements at risk, both within specific elements and in the broader context of society. This concept of vulnerability is utilized across various disciplines, leading to diverse theoretical approaches, either technical or social in origin, and resulting in various methods for qualitative or quantitative vulnerability assessment. Vulnerability analysis typically focuses on estimating the adverse impacts of floodwater, such as fatalities, disruptions to businesses, or financial losses. Often, this analysis centers on direct flood-related losses, which are estimated using damage or loss functions. These estimations can be conducted on different scales, ranging from microscale to meso-scale assessments. (Apel *et al*., 2008; Rahmati *et al*., 2014; Huang *et al*., 2008; Veerbeek & Zevenbergen, 2009; Merz *et al.*, 2010). The rapid urbanization and unplanned expansion of cities have increased the occurrence of flooding. This transformation has led to the conversion of many permeable surfaces into impermeable ones. Consequently, even short periods of rainfall can result in significant flooding, especially in low-lying urban areas. The concentration of people and valuable assets in cities means that even minor floods can cause considerable damage. In extreme cases, urban floods can disrupt urban development for extended periods, spanning years or even decades (Gupta & Nair, 2011). Urban flooding occurs predominantly in urban areas, particularly in flat and lowland terrains where there are inadequate drainage systems or poorly constructed ones that may be obstructed by accumulated municipal waste or eroded soil materials. The transformation of natural landscapes into paved and tarred roads significantly increases runoff, sometimes up to six times more than what would naturally happen (Etuonovbe, 2011; Jeyaseelan, 1999; Adeoye *et al*., 2009). Urbanization significantly diminishes the natural water absorption capacity, often reducing it by 2 to 6 times compared to natural landscapes. Accurate geographical data on hazards and vulnerable areas are essential for disaster preparedness. Remote sensing imagery and Geographic Information Systems (GIS) play a vital role in identifying flood-prone areas and managing flood events effectively. During urban flooding, streets can mimic rapid-flowing rivers, and basements can become hazardous as they fill with water. (Sowmya *et al*., 2014; Lowry *et al*., 1995; Smith, 2001). GIS facilitates hazard identification, vulnerability assessment, monitoring, and forecasting (Roy *et al*., 2001). Urban flooding is now a significant global concern and will shape the future development of cities. Global warming has altered rainfall patterns significantly, increasing flood risks in numerous urban areas (Guhathakurta *et al*., 2011).

Proper planning and comprehensive data collection on flood-prone areas are crucial in mitigating the effects of flooding. Identifying flood-vulnerable areas is essential for administrators to plan and manage activities effectively (Yalcin & Akyurek, 2004). Recognizing these vulnerable zones is vital to prevent further development in these areas and to enable swift emergency responses during different situations. (Mahyat *et al*. 2013). Traditional flood mapping methods are often slow and costly (Sinha *et al*., 2008). In contrast, Geographic Information System (GIS) technologies for flood hazard mapping utilize various thematic layers like slope, elevation, and land use. However, a significant challenge in GIS models lies in assessing and evaluating the relative importance of these input layers. To address this complexity, Multi-Criteria Decision Analysis (MCDA) methodologies and techniques provide a robust analytical framework for tackling intricate decision problems effectively (Köksalan, 2011; Paquette & Lowry, 2012). The combination of Multi-Criteria Decision Analysis (MCDA) and Geographic Information System (GIS) techniques has been demonstrated by several researchers to be highly effective in preparing flood hazard zoning maps. (Bates, 2004; Pradhan & Shafiee, 2009; Sanyal & Lu, 2009; Pradhan *et al*., 2014; Tehrany *et al*., 2014a, 2014b; Rahmati *et al*., 2015). Weightage and ranking are determined through an Analytic Hierarchy Process (AHP) pairwise comparison matrix, and these values are integrated with the basic input layers in Geographic Information System (GIS) software (Dung *et al*., 2022). The specific objectives of the current study titled "Urban Flood Hazard Zoning for Bengaluru Urban District Using GIS And Multi-Criteria Decision Analysis" are as follows:

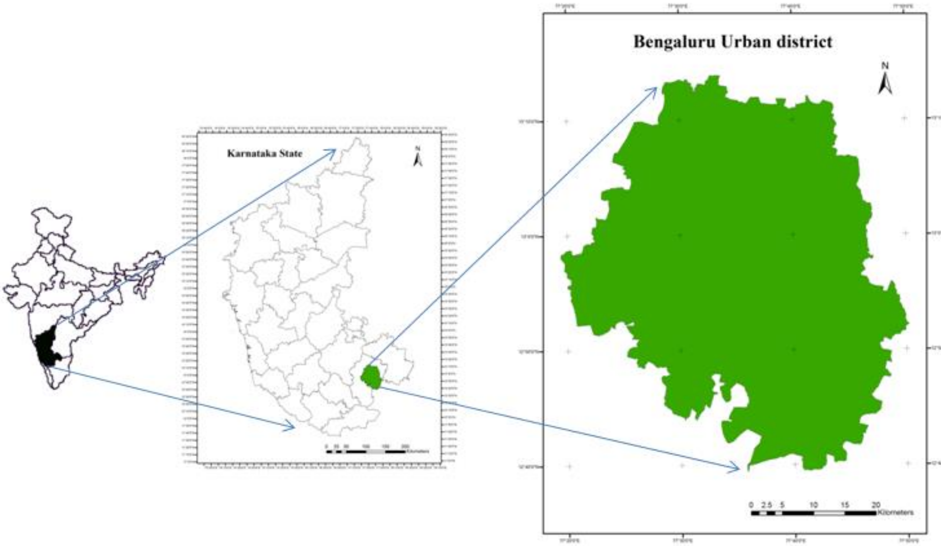
1. To spatially categorize the study area into different flood-vulnerable zones based on the severity of hazard, delineating 'Low,' 'Moderate,' and 'High' vulnerability classes using Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP).
2. To validate the obtained results by comparing them with the flood occurrence data provided by Bruhath Bangalore Mahanagara Palika (BBMP) for areas within Bengaluru city.

MATERIAL AND METHODS

Study Area

Bengaluru Urban District is situated in the southeastern part of Karnataka, covering an area of 2174 sq.km. It stretches between approximately 12˚39' 32’’ to 13˚14' 13’’ north latitude and 77˚19’44’’ to 77˚50'13’’ east longitude. The district is bordered by Bengaluru Rural District on all sides except the southeast, where it meets Dharmapuri district in Tamil Nadu (Fig. 1). Divided into four taluks—Bengaluru North, Bengaluru South, Bengaluru East, and Anekal—the district enjoys robust connectivity through airways (with its newly built international airport), railways, and roadways, linking it comprehensively within the country and globally. The district encompasses 699 villages governed by 112 gram-panchayats, along with 17 hoblies, 9 municipal corporations, and 668 villages. Key rivers in the region include Shimsa, Kanva, Arkavathi, South Pennar, and Vrishabharathi. The Shimsha and Kanva rivers from the Cauvery basin primarily drain the district, while the South Pennar River from the Ponnaiyar basin serves the Anekal taluk. The district's population stands at 95,88,910, and its average annual rainfall is recorded at 1049 mm.

Fig. 1: Location of the study area



The flowchart listing the method used in this study, has been illustrated in Fig. 2, involved several stages starting with collecting primary data and processing it within a GIS (Geographical Information System) framework along with MCDA (Multi-Criteria Decision Analysis). The selection of flood-triggering factors was based on an extensive literature review. Initially, essential criteria such as regulations and constraints were gathered through literature review. Depending on data availability, various criteria like Rainfall, distance to drainage channels, topographical features (Elevation and slope), Groundwater table depth, Urban land use, soil type, and Drainage system were identified to delineate flood hazard zones and were prepared as input map layers. The analysis utilized a methodology that integrates GIS and MCDA techniques. Specifically, the Analytic Hierarchy Process (AHP) and Pairwise comparison method was employed to calculate weights and rank each factor. AHP is a multi-objective, multi-criteria decision-making approach that uses pairwise comparisons to evaluate preferences among different alternatives. It employs a nine-point scale to express individual preferences or judgments. Psychologists have observed that utilizing a nine-point scale can effectively compare and consistently rank different options. (Pawel, 2010; Saaty & Peniwati, 2008; Dung *et al*., 2022). Pairwise judgments rely on accurate ground truth information, as well as the decision maker's knowledge and experience (Fernandez & Lutz, 2010). The integration of remote sensing and GIS techniques was employed to create new thematic data layers. All prepared coverages were organized spatially within the GIS environment, maintaining a uniform resolution and coordinate system. Thematic maps underwent reclassification and were assigned appropriate weights based on their significance in urban flood analysis. These spatial maps were cross-checked against other database layers using overlay techniques and refined iteratively for standardization. By integrating various thematic maps in GIS software using weighted index overlay analysis, the urban flood vulnerability zones were identified and classified.

Pairwise Comparison Method

The method involves pairwise comparisons to create a ratio matrix. It takes pairwise comparisons as input and produced relative weights as output.

Pairwise comparison method involves three steps:

1. Development of a pairwise comparison matrix:
   The method uses a scale with values range from 1 to 9 (Table 1).

Table 1: Scale for pairwise comparison (Saaty, 1980)

Intensity of importance	Definition
1	Equal importance
2	Equal to moderately importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

2. Computation of the weights: The computation of weights involves three steps. First step is the summation of the values in each column of the matrix. Then, each element in the matrix should be divided by its column total (the resulting matrix is referred to as the normalized pairwise comparison matrix). Then, computation of the average of the elements in each row of the normalized matrix should be made which includes dividing the sum of normalized scores for each row by the number of criteria. These averages provide an estimate of the relative weights of the criteria being compared.
3. Estimation of the consistency ratio: The aim of this is to determine if the comparisons are consistent or not.

It involves following operations:

Determine the weighted sum vector by multiplying the weight for the first criterion times the first column of the original pair wise comparison matrix, then multiply the second weight times the second column, the third criterion times the third column of the original matrix, finally sum these values over the rows,

Determine the consistency vector by dividing the weighted sum vector by the criterion weights determined previously, Compute lambda(λ) which is the average value of the consistency vector and Consistency Index (CI) which provides a measure of departure from consistency and has the formula below:

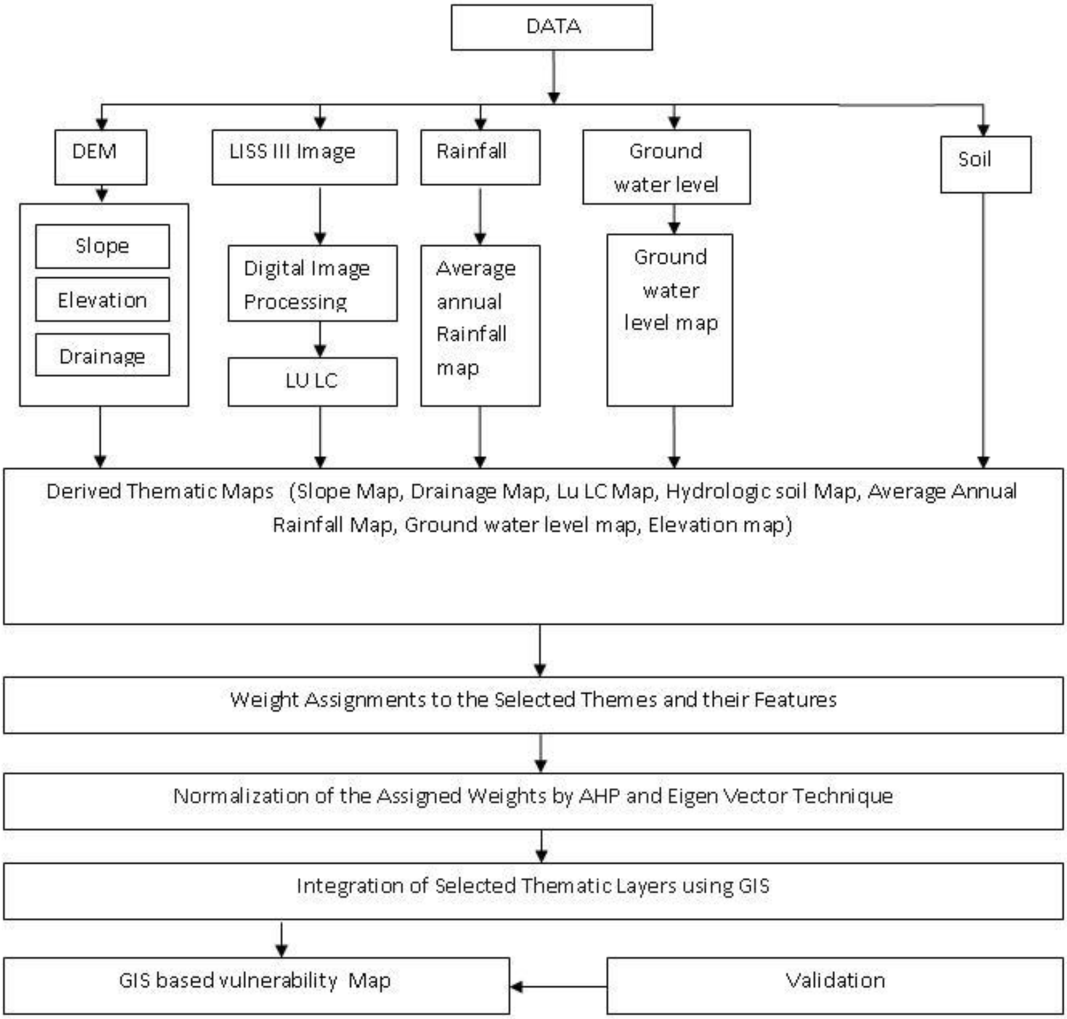
$$CI = \frac{(\lambda - n)}{(n - 1)}$$

- Calculation of the consistency ratio (CR) which is defined as follows:

$$CR = \frac{CI}{RI}$$

Where RI is the random index and depends on the number of elements being compared. If CR<0.10, the ratio indicates a reasonable level of consistency in the pairwise comparison, however, if CR ≥ 0.10, the values of the ratio indicate inconsistent judgments.

Fig. 2: Methodology of research work



RESULTS

As the urbanization is going on increasing, lots of trees are cut and pervious areas become impervious. (American Society of Civil Engineers, 1996) says that the change from previous to impervious nature result in a loss of interception and depression storage, a decrease in the potential infiltration, and a redirection of principal flow paths. Loss of vegetation and reduction of no. of trees contribute large quantity of rainfall water very rapidly to the runoff water generation even for a short and low intensity rainfall. Since the earth surface became impervious in the urban areas the runoff water cannot infiltrate and urban flood generates. There are different factors that causes flooding other than this alteration. To account for this factors that causes urban flooding seven important variables Rainfall, distance to drainage channels, topography (Elevation and slope), Ground water table depth, Urban land use, soil type and Drainage system are selected for the identification of flood vulnerable zones. These variables and its importance are described below.

Slope and elevation

Elevation and slope are critical factors in flood management. Higher elevations affect the direction and depth of water movement, leading to increased runoff, while lower elevations can result in waterlogging (Stieglitz *et al*., 1997). Areas with gentle slopes are more prone to flooding compared to steep slopes, as steeper slopes prevent water accumulation (Yashon & Tateishi, 2014). The velocity and flow of water are affected by slope gradients, resulting in flat surfaces causing reduced water flow and potential flooding (USDA, 1986). For the present study, slope and elevation data were obtained from the Digital Elevation Model (DEM) using ArcGIS 10.2 software. The CartoDEM dataset, with a resolution of 2.5 meters, was obtained from the ISRO Bhuvan website, for this purpose.

Different levels of water in the rivers significantly impact flood hazards, and this was an important parameter in determining flood risks. The study employed two methods—buffer analysis and drainage density analysis—to evaluate the influence of different river grades on flood hazards. Buffer analysis focused on main lakes and rivers, while drainage density analysis was used for other river types. Buffers were created based on the "distance to the river center" approach, as given by Wang *et al*. (2011). Proximity to drainage channels is particularly vital in urban flood mapping due to the increased risk of flooding near these channels caused by overflow (Fernández & Lutz, 2010). The study utilized DEM data and ArcGIS 10.2, to derive the drainage network of the study area. Subsequently, the Euclidean distance and reclassify tools were employed to establish various buffer zones based on distances from the center of the streams. These distance categories were set as follows: below 100 m, 100m - 500m, 500m - 700m, 700m - 1000m, and above 1000m.

Depth to groundwater table

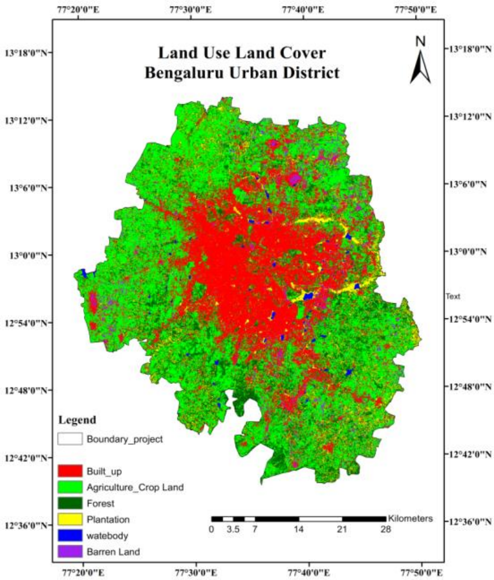
High-water tables significantly impact how well water infiltrates the ground, particularly in areas where this issue is prevalent. Such areas quickly saturate with the initial summer rains, affecting how much runoff occurs. Researchers have studied the depth of the water table as a key measure of a basin's initial storage capacity (Trosh *et al*., 1993; Yin & Li, 2001; Fernández & Lutz, 2010). For this study, data on groundwater tables was obtained from the Department of Mining and Geology in Bengaluru. The depth of the water level is measured from the surface to the highest groundwater elevation at borehole locations. To fill in missing data points, the study used the Inverse Distance Weighting (IDW) method for data interpolation.

Areas classified according to different depth classes such as 0m - 13m, 13m-17m, 23m-32m and 32m-47m.Areas comes under shallow water table (0m-13m) is more likely to be flooded than deeper water table depth (32 m – 47 m). Each class is reclassified and ranked accordingly.

Land Use Land Cover (LU LC)

LU LC is very important in flood hazard mapping.LU map gives the ideas of how much an area is vulnerable to flooding. For example, a bare soil area contributes more runoff thick vegetation areas. Concrete, paved roads and surfaces blocks the infiltration of rainfall water into the earth results in more runoff water generation. In simple terms, various land-use patterns act as protective shields, reducing water retention time while potentially amplifying flood intensity. This underscores the significant role of land use and land cover in shaping flood probabilities. (Yashon & Tateishi, 2014). Classification is done using ERDAS imagine software with Maximum likelihood classifier algorithm. Six signature classes are produced under Built up land, Agricultural crop land, Forest, Plantation, Water body and barren land. The classified LU/LC map is shown in Fig. 3.

Fig. 3: LULC Map of Bengaluru Urban district



Land use Land cover map of Bengaluru Urban district is shown in Figure 3, which reveals six LU LC classes such as Crop land, barren Land, Built Up area, Forest, plantation and Water body based on different spectral signatures of the surface features in the imagery. Figure 4a shows the LISS III Imagery of the study area. Although supervised classification served as a very good helping tool for the interpretation of land use classes, the thematic map was generated by satellite imagery and digital data. Most of the area of Bengaluru Urban district is cropland and central part concentrated with built up area.

Soil Type

Soil texture and moisture are the most important components and characteristics of soils. Soil textures have a great impact on flooding because sandy soil absorbs water soon and few runoffs occurs. On the other hand, the clay soils are less porous and hold water longer than sandy soils. This implies that areas characterized by clay soils are more affected by flooding.

The study area is classified into four different soil groups. The four hydrologic soil groups (HSGs) are described as:

Group A - These soils have a low runoff potential when fully saturated, allowing water to pass through them easily. Group A soils typically consist of less than 10 % clay and more than 90 % sand or gravel, with textures of gravel or sand. Their saturated hydraulic conductivity in all soil layers exceeds 40.0 micrometers per second (5.67 inches per hour).

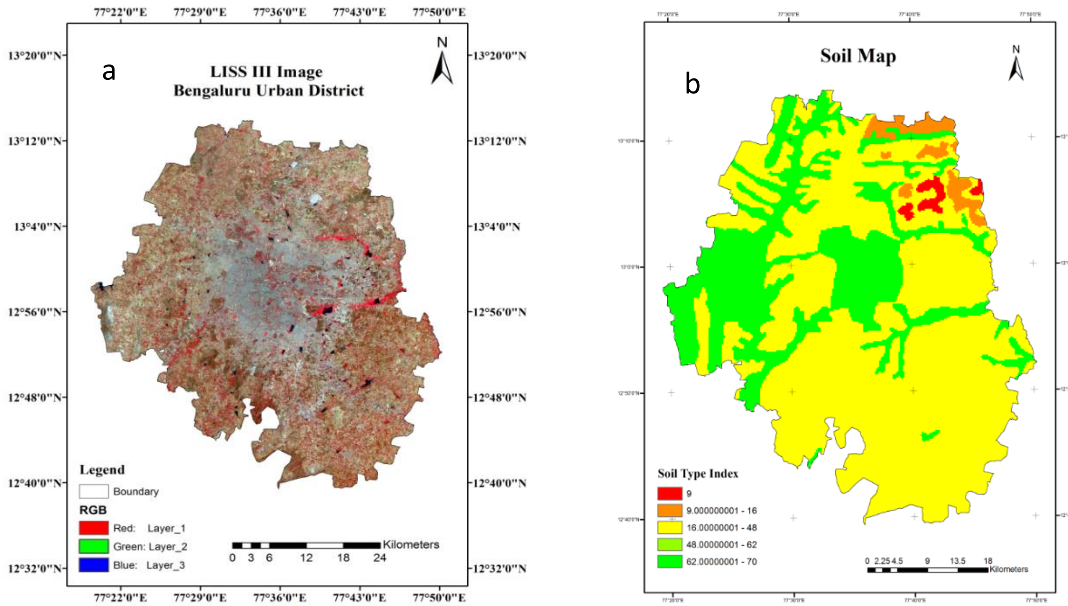
Group B - Soils in this classification demonstrate a moderate resistance to runoff when fully saturated, facilitating relatively unimpeded water transmission. Group B soils typically consist of 10 % to 20 % clay and 50 % to 90 % sand, with textures ranging from loamy sand to sandy loam. Their saturated hydraulic conductivity falls within the range of 10.0 micrometers per second (1.42 inches per hour) to 40.0 micrometers per second (5.67 inches per hour).

Group C - Group C soils have a moderately high potential for runoff when fully saturated, with somewhat restricted water transmission through the soil. These soils typically contain between 20% and 40% clay and less than 50 % sand, exhibiting textures such as loam, silt loam, sandy clay loam, clay loam, and silty clay loam. Their saturated hydraulic conductivity ranges from 1.0 micrometers per second (0.14 inches per hour) to 10.0 micrometers per second (1.42 inches per hour).Group D - Soils in this group have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted.

Group D - Soils classified in this category typically consist of over 40 % clay, less than 50 % sand, and exhibit clayey textures. The saturated hydraulic conductivity within the least permeable layer of these soils is equal to or less than 1.0 micrometers per second (0.14 inches per hour).

The Hydrologic Soil groups map of Bengaluru Urban district is obtained from NBSS Bengaluru and is shown in Figure 4b.

Fig. 4: (a) LISS III Image of Bengaluru Urban district. (b) Soil map

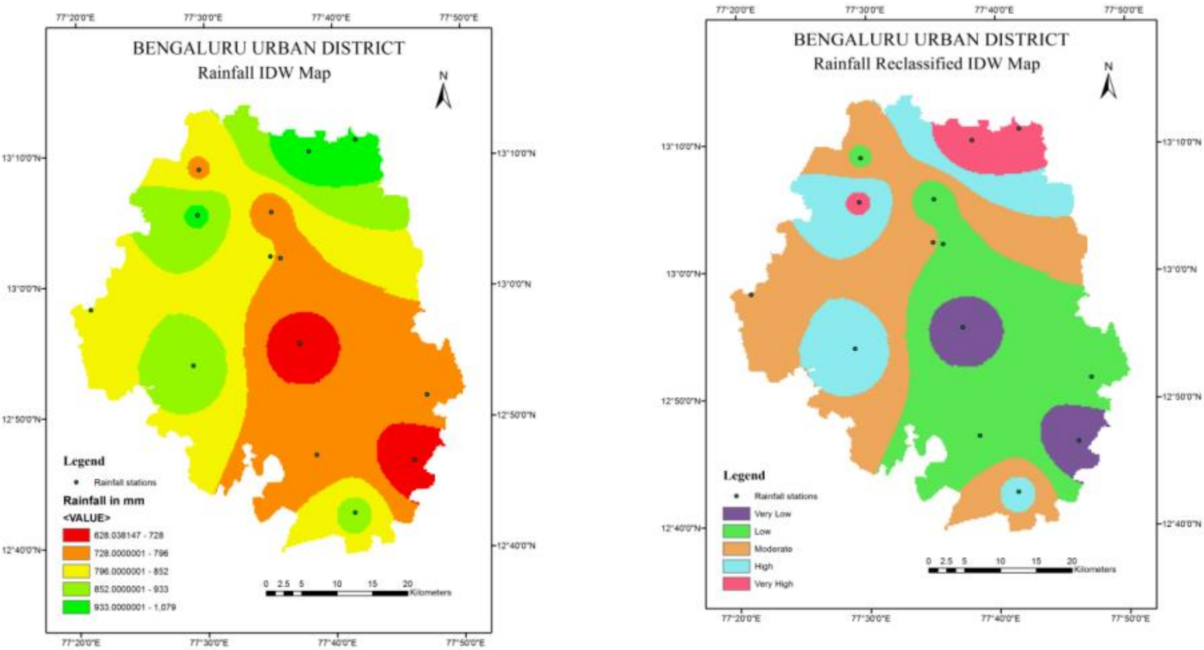


Rainfall Distribution

Intense rainfall is a key trigger for floods, especially when natural water channels can't handle the excess water. This happens when rainfall exceeds the ground's absorption capacity, leading to runoff. The volume of runoff corresponds directly to the intensity of rainfall in an area. As rain accumulates, water levels in rivers and lakes rise, potentially causing breaches in banks or dams and initiating river-based floods.

The study highlighted excessive rainfall as the primary cause of urban flooding. To assess this, data on mean annual rainfall over eleven years (1998–2013) was gathered and interpolated using Inverse Distance Weighting (IDW), creating a continuous raster of rainfall data within and around the municipal boundary. This raster layer was then categorized into five classes based on equal intervals, ranging from 1 for minimal rainfall to 5 for the highest recorded rainfall. Figure 5 depicts the results of the raster rainfall layer, IDW-interpolated data layer, and the categorized rainfall data.

Fig. 5: Rainfall map and reclassified rainfall map of Bengaluru urban district



Ranking of flood mapping criteria

AHP based MCDA is used for the ranking of selected flood causing criteria. The quality of judgement is based on available resources like field data obtained from people who residing at the study area, subject knowledge, literature review etc. All the selected criteria are arranged in a pair wise comparison matrix along column wise and row wise. Each criterion in compared with all the criteria and corresponding importance value is entered in the respective cells. The scale of the importance is based on the (Saaty, 1980). The criteria are ranked using a 1 to 5 scale with 1 representing the least important and 5 represents the most important.

To quantify the significance of each factor compared to others in the context of flood hazard determination, eigenvectors are utilized to assign weights to standardized raster layers. Table 3 outlines the results of pairwise comparisons and criterion ranking. Additionally, Table 4 illustrates the normalized matrix converted into percentage contributions, aiding in deriving the average priority vector (X) (Ouma & Tateishi, 2014). The pairwise comparison matrix and its normalized counterpart are both depicted in Table 2 and 3, for easy reference and clarity.

Table 2: Ranking of urban flood causing criteria to obtain the pairwise comparison matrix

Pairwise Comparison Matrix							
	Rainfall	Drainage	Elevation	Slope	Soil	Land-use	Ground water depth
Rainfall	1	1	2	2	1/3	1/5	3
Drainage	1	1	3	1/3	1/3	1/5	2
Elevation	1/2	1/3	1	1/3	1/3	1/5	2
Slope	1/2	3	3	1	1/3	1/3	3
Soil	3	3	3	3	1	1	4
Land-use	5	5	5	3	1	1	4
Ground water depth	1/3	1/2	1/2	1/3	1/4	1/4	1
Total	11 1/3	13 5/6	17 1/2	10	3 4/7	3 1/5	19

Table 3: Normalised pairwise comparison matrix

Normalized Pairwise Comparison Matrix									
	Rainfall	Drainage	Elevation	Slope	Soil	Land-use	Ground water depth	Priority vector (X)	Percent (%)
Rainfall	3/34	6/83	4/35	2 /10	7/75	1/16	3/19	0.099	10
Drainage	3/34	6/83	6/35	1/30	7/75	1/16	2 /19	0.081	8
Elevation	3/68	2/83	2/35	1/30	7/75	5/48	2/19	0.065	7
Slope	3/68	18/83	6/35	1/10	7/75	5/48	3 /19	0.111	11
Soil	9/34	18/83	6/35	3/10	7/25	5/16	4/19	0.275	27
Land-use	15/34	30/83	10/35	3/10	7/25	5/16	4/19	0.011	31
Ground water depth	1/34	3/83	1/35	1/30	7/100	5/64	1/19	0.058	6
Total	1	1	1	1	1	1	1	-	100

Table 4: Influencing thematic layers their classes, vulnerability score and applied weightages

Thematic Layers	Weightage (%)	Individual classes	Ranking
Rainfall (in mm)	10	628.038147-728	1
		728-796	2
		796-852	3
		852-933	4
		933-1079	5
Distance to drainage channels (in m)	8	<100	5
		100-500	4
		500-700	3
		700-1000	2
		>1000	1
Elevation (m above mean sea level)	7	609-699	5
		699-752	4
		752-792	3
		792-821	2
		821-902	1
Slope (%)	11	0-6	5
		6-14	4
		14-26	3
		26-38	2
		38-80	1
Soil (HSG)	27	Group A	1
		Group B	3
		Group C	4
		Group D	5
Land-use	31	Built-up	4
		Agri-Cropland	2
		Forest	1
		Plantation	2
		Waterbody	5
		Barren	4
Ground water depth (in m)	6	0-13	5
		13-17	4
		17-23	3
		23-32	2
		32-47	1

From the Table 3, consistency index is calculated using the formula.

$$CI = \frac{7.62 - n}{n - 1} = 0.1$$

With n = 7 decision factor. From the CI, Consistency ratio is calculated as

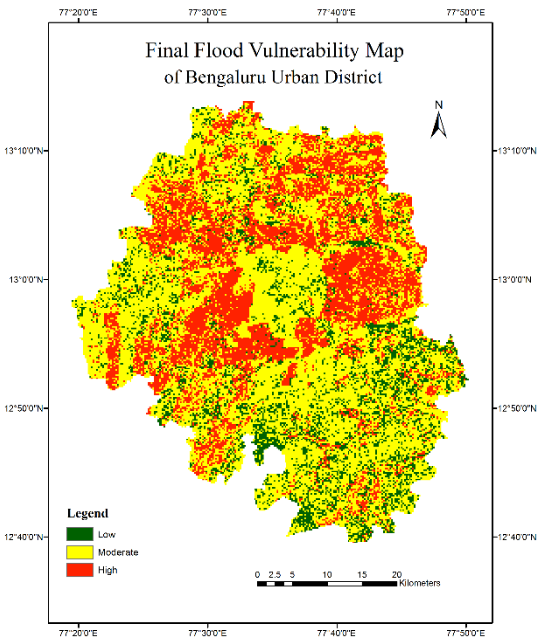
$$\begin{aligned} CR &= CI / RI \\ &= 0.10/1.32 \\ &= 0.07 \end{aligned}$$

The obtained value must be lower than 0.1, The obtained CI = 0.07 which is much lower than the specified value, Hence the comparison has high level of consistency and determined weights are acceptable. The final weights obtained after AHP analysis is used to produce final map in the weighted overlay command in Arc GIS 10.2. Table 4 gives influencing thematic layers, their classes, vulnerability score and applied weightage.

Flood vulnerability mapping for Bengaluru urban district

After calculation of weight for each factors MCDA carried out using the weight of factors and corresponding basic map to produce the final flood prediction mapping. A weighed linear combinations method is used for overlapping all the basics maps and factors to get the final output map. The result is a flood vulnerability or hazard map showing the most vulnerable areas to flooding within the urban district. The final vulnerability map is shown in Figure 6.

Fig. 6: Flood vulnerability map



The results show that 635.71 km² area (29.24 % of total study area) is prone to high flood hazard, 287.6 sq.km area comes under low vulnerable zone (13.22 %) and remaining 1250.69 km² area comes under moderate flood hazard zone (57.52 %). This indicates that more than 85 % of the study area is more vulnerable to flooding because the study area is urban and major portions of its area is paved and rainfall infiltration is very less causing more rainfall and hence leading to high flood. Around 32 % of agricultural land and 43 % of urban areas is under high flood risk. Table 5 below shows the area underlying each flood vulnerable zones.

Table 5: Areal extent of flood affected land use land cover

Class	**Flood Vulnerability zone in sq.km**		
	High	**Moderate**	**Low**
Agri-Cropland	208.68	567.52	105.48
Barren	25.6	52.64	7.32
Built-up	273.86	333.6	42.93
Forest	67.72	197.65	81.23
Plantation	31.04	68.29	21.55
Waterbody	4.07	9.51	1.29
Total	635.71	1250.69	287.6

Validation

The result map can be verified for accuracy only if high quality field data is available. Unfortunately, this kind of data is not available. However, Bruhath Bangalore Mahanagara Palika (BBMP), the administration body of Bengaluru city have identified 127 frequent flood occurring areas. These areas area cross matched with the final vulnerability zones they are comes under. It could be seen that 124 area out of a total 127 frequent flood occurring areas coming under high or moderate flood vulnerable zones. 4 locations are classified on the edges of high or low flood hazard zone cells. This indicates that the final map has a high level of accuracy.

DISCUSSION

It has proved that most of the researchers have successfully used GIS and remote sensing for preparing the flood vulnerability map. But most of them are considered only a few flood triggering factors. Literature review reveals that there is a lack of research on combination of more number of significant flood causing parameters. The entire analysis relies on assigning weights to different layers. In this study, seven thematic layers are used for weight assignment, with each layer receiving appropriate weights determined through direct or indirect relationships and AHP analysis. (Neha *et al*., 2022; Iran *et al*., 2019). This method is considered more reliable for enhancing the accuracy of flood hazard zones, as it involves a systematic allocation of weights using the AHP method and weighted overlay analysis technique within a GIS platform. The present work integrates AHP with remote sensing and GIS to create flood vulnerability zones in the Bengaluru urban district of Karnataka. The use of multi-criteria evaluation for different factors is also demonstrated to be useful in the definition of the risk areas for the flood mapping and possible prediction. In overall, the case study results show that the GIS-AHP based category model is effective in flood risk zonation. Integration of AHP based multi criterion decision analysis and GIS is a good technique for the production of flood hazard mapping. (Dung *et al*., 2022; Skilodimou *et al*., 2021; Shereif *et al*., 2018)

CONCLUSIONS

Conventional flood hazard mapping techniques use historical flood data to map floodplains. It requires detailed survey and it is expensive. Some of the data required for hazard mapping is difficult to obtain from ground measurements is time consuming. All the constraints of conventional method can be avoided using Remote sensing GIS method. For a highly accurate flood vulnerability and risk analysis demands good quality field data and subject expertise. Present paper explains an empirical approach for mapping vulnerability to flooding. In urban areas through the combination of AHP and GIS techniques. The method is useful for the decision takers authorities for making strategies for flood risk management of any administrative area. The final flood vulnerability map is validated with the available data shows higher level of accuracy (more than 95 %) and is reliable. The consistency ratio obtained is 0.07 indicates better comparison of selected physical & socioeconomic factors. The work can be improved by incorporating field data for validation. The integration of AHP based multi criterion decision analysis and GIS to produce flood hazard mapping has been successfully demonstrated.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abams, T.K.S. (1995). Floods in Niger Delta, the Case of Kaima. In: *Proceedings of the International workshop in natural Man-made Hazards in Africa* (pp. 119-130). NMGS publication.

Adeoye, N.O., Ayanlade, A., Babatimehin, O. (2009). Climate change and menace of floods in Nigerian Cities: socio-economic implications. *Adv Nat Appl Sci* 3(3): 369–377

American Society of Civil Engineers, (1996). *Hydrology handbook*, ASCE manuals and reports on engineering practice No 28, Second Edition. New York. 800 pp.

Apel, H., Merz, B., & Thieken, A.H. (2008). Quantification of uncertainties in flood risk assessments. *International Journal of River Basin Management*, 6(2): 149-162. https://doi.org/10.1080/15715124.2008.9635344

Askew, A.J. (1970). Variation in lag time for natural catchments. *Journal of the Hydraulics Division*, 96(2): 317-330. https://doi.org/10.1061/JYCEAJ.0002322

Bates, P.D. (2004). Remote sensing and flood inundation modelling. *Hydrol Process*. 18:25932597.

Dung, N.B., Long, N.Q., Goyal, R., An, D.T., & Minh, D.T. (2022). The role of factors affecting flood hazard zoning using analytical hierarchy process: A review. *Earth Systems and Environment*, 6(3): 697-713. https://doi.org/10.1007/s41748-021-00235-4

Etuonovbe, A.K. (2011). *The devastating effect of flooding in Nigeria*, FIG Working Week. http://www. fig.net/pub/fig2011/papers/ts06j/ts06j_etuonovbe_5002.p

Fernández, D.S., & Lutz, M.A. (2010). Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Engineering Geology*, 111(1-4): 90–98. doi:10.1016/j.enggeo.2009.12.006.

Folorunsho, R., & Awosika, L.F. (2001). Flood mitigation in Lagos, Nigeria through wise management of solid waste: A case of Ikoyi and Victoria Islands; Nigerian. In *UNESCOCSI workshop* (pp. 19-23), Maputo.

Guhathakurta, P., Sreejith, O.P., Menon, P.A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *J Earth Syst Sci* 120(3):359–373. https://doi.org/10.1007/s12040-011-0082-5

Gupta, A.K., & Nair, S.S. (2011). Urban floods in Bangalore and Chennai: Risk management challenges and lessons for sustainable urban ecology. *Current Science*, 100(11): 1638–1645.

Huang, X., Tan, H., Zhou, J., Yang, T., Benjamin. A., Wen, S.S., Li, S., Liu, S., Liu, A., Li, X. (2008). Flood hazard in Hunan province of China: an economic loss analysis. *Nat Hazards*. 47:6573. https://doi.org/10.1007/s11069-007-9197-z

Iran, M.S., Hossein, M., Seyed, Z.H., Ali, R.I. (2019). Assessment of food hazard mapping in urban areas using entropy weighting method: a case study in Hamadan city, *Acta Geophysica*. 67:1435–1449. https://doi.org/10.1007/s11600-019-00342-x.

Paquette, J. & J. Lowry, (2012). Flood hazard modelling and risk assessment in the Nadi River Basin, Fiji, using GIS and MCDA, *The South Pacific Journal of Natural and Applied Sciences*, 30: 33-43.

Jeyaseelan, A.T. (1999). Droughts and floods assessment and monitoring using remote sensing and GIS. In *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology* (pp 291–313). http://www. wamis.org/agm/pubs/agm8/Paper-14.pdf

Köksalan, M., Wallenius, J., and Zionts, S. (2011). *Multiple Criteria Decision Making: From Early History to the 21st Century*. World Scientific Publishing, Singapore

Lowry, J.H., Miller, H.J., Hepner, G. (1995). A GIS-based sensitivity analysis of community vulnerability to hazardous contaminants on the Mexico/US Border. *Photogrammetric Engineering & Remote Sensing*, Vol. 61, No. 11, pp. 1347-1359.

Mahyat, Sh.T., Biswajeet, P., Mustafa, N.J. (2013). Spatial prediction of flood susceptible areas using rule-based decision tree (DT) and a novel ensemble bivariate and multivariate statistical model in GIS, *Journal of Hydrology*, 504: 69–79. https://doi.org/10.1016/j.jhydrol.2013.09.034

Merz, B., Kreibich, H., Schwarze, R., Thieken, A. (2010). Assessment of economic flood damage. *Nat Hazard Earth Syst*. 10:16971724. https://doi.org/10.5194/nhess-10-1697-2010.

Bansal, N., Mukherjee, M., Gairola, A. (2022). Evaluating urban food hazard index (UFHI) of Dehradun city using GIS and multi criteria decision analysis. *Modeling Earth Systems and Environment* (2022) 8:4051–4064. https://doi.org/10.1007/s40808-021-01348-5

Ologunorisa, T.E. (2004). An assessment of flood vulnerability zones in the Niger Delta, Nigeria. *International journal of environmental studies*, 61(1): 31-38. https://doi.org/10.1080/0020723032000130061

Ologunorisa, T.E., & Abawua, M.J. (2005). Flood risk assessment: a review. *Journal of Applied Sciences and Environmental Management*, 9(1): 57-63.

Oriola, E.O. (1994). Strategies for combating urban flooding in a developing nation: A case study from Ondo, Nigeria. *Environmentalist*, 14(1): 57-62.

Pawel, C. (2010) Using the analytic hierarchy process in evaluating decision alternative. *Oper Res Decis* 20(1):5–23

Pradhan, B., Shafiee, M. (2009). Flood hazard assessment for cloud prone rainy areas in a typical tropical environment. *Disaster Adv*. 2:715.

Sinha, R., Bapalu, G.V., Singh, L.K., Rath, B. (2008). Flood Risk Analysis in the Kosi River Basin, North Bihar using Multi-Parametric Approach of Analytical Hierarchy Process (AHP), *J. Indian Soc. Remote Sens*. 36: 335–349. https://doi.org/10.1007/s12524-008-0034-y

Rahmati, O., Nazari Samani, A., Mahdavi, M., Pourghasemi, H.R., Zeinivand, H., (2014). Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. *Arab. J. Geosci*. http://dx.doi.org/10.1007/s12517-014-1668-4.

Roy, L., Leconte, R., Brissette, F., Marche, C. (2001). The impact of climate change on seasonal floods of a southern Quebec River basin. *Hydrol Processes* 15: 3167–3179 https://doi.org/10.1002/hyp.323

Saaty, T.L. (1987). The analytic hierarchy process—what it is and how it is used. Math Model. *Elsevier* 9(3–5): 161–176.

Saaty, N. P. (1980). *The Analytic Hierarchy Process*. McGraw Hill. International, New York, 1980.

Saaty, T. L., & Peniwati, K. (2013). Group decision making: drawing out and reconciling differences. RWS publications.

Sanyal, J., Lu, X.X. (2009). Ideal location for flood shelter: a geographic information system approach. *Flood Risk Manag*. 2: 262271. https://doi.org/10.1111/j.1753-318X.2009.01043.x

Shereif, H. M., Gan S.Y. (2018). Multi-criteria approach to develop flood susceptibility maps in arid regions of Middle East, *Journal of Cleaner Production*, Volume 196: 216-229, https://doi.org/10.1016/j.jclepro.2018.06.047.

Skilodimou, H.D.; Bathrellos, G.D.; Alexakis, D.E. (2021). Flood Hazard Assessment Mapping in Burned and Urban Areas. *Sustainability* 13: 4455. https://doi.org/10.3390/su13084455

Smith, K. (2001). *Environmental hazards: assessing risk and reducing hazards*. Third Edition. Routledge (Taylor & Francis Group), New York, USA

Sowmya, K., John, C. M., & Shrivasthava, N. K. (2014). Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. *Natural Hazards*. doi:10.1007/s11069-014-1372-4

Stieglitz, M., Rind, D., Famiglietti, J., Rosenzweig, C. (1997). An efficient approach to modeling the topographic control of surface hydrology for regional and global climate modeling. *Journal of Climate* 10 (1): 118–137. https://doi.org/10.1175/1520-0442

Tehrany, M.S., B, Jebur, M.N. (2014b). Spatial prediction of flood susceptible areas using rule-based decision tree (DT) and a novel ensemble bivariate and multivariate statistical model in GIS. *J Hydrol*. 504: 6979. https://doi.org/10.1016/j.jhydrol.2013.09.034

Tehrany, M.S., Lee, M.J., Pradhan, B., Jebur, M.N., Lee, S. (2014a). Flood susceptibility mapping using integrated bivariate and multivariate statistical models. *Environ Earth Sci*. 72: 40014015.

Trosh, P., De Trosh, F., Brutsaert, W. (1993). Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. *Water resources research* 29 (2): 427–434. https://doi.org/10.1029/92WR02087

UN/ISDR, (2004). *Glossary*. Basic Terms of Disaster Risk Reduction. Source http://www.unisdr.org/unisdr/eng/library/lib-terminology-eng%20home.htm 2004.

UNCHS, (1981). *Preparatory assistance for the reconstruction of human settlements in the El Asnam region*, Algeria Habitat News 3/2 August (pp18-20). United Nations Centre for Human Settlements (UNHabitat). Nairobi

USDA (1986). *Urban hydrology for small watersheds*. Technical Release 210-VI-TR-55. 160 pp.

Veerbeek, W., Zevenbergen, C. (2009). Deconstructing urban flood damages: increasing the expressiveness of flood damage models combining a high level of detail with a broad attribute set. *Journal of Flood Risk Management*, 2(1): 45-57.https://doi.org/10.1111/j.1753-318X.2009.01021.x

Wang, Y., Li, Z., Tang, Z., & Zeng, G. (2011). A GIS-Based Spatial Multi-Criteria Approach for Flood Risk Assessment in the Dongting Lake Region, Hunan, Central China. Water Resources Management, 25: 3465–3484. doi:10.1007/s11269-011-9866-2

Yalçin, G., & Akyurek, Z. (2004, July). Analysing flood vulnerable areas with multicriteria evaluation. In *20th ISPRS congress* (pp. 359-364).

Yashon, O.O., Tateishi R. (2014). Urban Flood Vulnerability and Risk Mapping Using Integrated Multi-Parametric AHP and GIS: Methodological Overview and Case Study Assessment, *Water*, 6: 1515-1545

Yin, H., Li, C. (2001). Human impacts on floods and flood disasters on the Yangtze River. *Geomorphology* 41 (2–3): 105–109. https://doi.org/10.1016/S0169-555X(01)00108-8