Review Paper:

Bay of Bengal-Induced Cyclone Shelter Susceptibility Assessment in Kolkata Municipal Corporation using GIS-Based AHP and Frequency Ratio Models

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Abstract

Kolkata remains highly vulnerable to cyclonic disturbances originating from the Bay of Bengal due to its riverine proximity and dense urban fabric. Historical cyclones such as Aila (2009) and Amphan (2020) have caused extensive socio-economic damage and infrastructure collapse across the region. Despite the frequency of such events, a comprehensive, GIS-based cyclone shelter susceptibility mapping tailored to the urban environment of the Kolkata Municipal Corporation (KMC) is lacking.

The city, governed by the KMC, plays a vital role in national trade and commerce and is home to around 4.6 million residents. The city is located at 22°30′ North latitude and 88°30′ East longitude and is approximately 120 km from the Bay of Bengal on the eastern bank of the Hooghly (Ganga) River.

The current study aims to bridge this gap by assessing cyclone shelter suitability using an integrated GIS-based Analytical Hierarchy Process (AHP) and Frequency Ratio (FR) modelling approach. Input data such as satellite imagery and DEM from USGS, rainfall from IMD and wind datasets from global sources were utilized to develop thematic layers including elevation, slope, aspect, drainage, NDVI, LULC, soil and geomorphology.

The AHP model facilitated expert-based multi-criteria decision analysis by assigning weights to the factors, while the FR model statistically evaluated their contribution based on historical cyclone occurrences.

The integrated overlay of both AHP and FR outputs within the GIS environment produced a high-resolution Cyclone Shelter Susceptibility Map, classifying the KMC region into zones of very high, high, moderate, low and very low suitability.

Keywords: Cyclone Shelter, GIS, Analytical Hierarchy Process, Frequency Ratio, Bay of Bengal Hazards.

Introduction

Kolkata, the capital city of West Bengal, is one of the most densely populated urban centers in eastern India and holds strategic importance due to its proximity to the Bay of Bengal. Located approximately 120 kilometres from the coast, the Kolkata Municipal Corporation (KMC) region spans 206.08 Sq.km and houses over 4.6 million people, making it one of the most critical zones for urban risk management in the face of natural disasters[3]. The city's coastal adjacency and low-lying topography make it highly susceptible to cyclonic events originating from the Bay of Bengal.

Historically, cyclones such as Aila in 2009 and the devastating Amphan in 2020 have wreaked havoc in the region, leading to severe damage to life, property, infrastructure and livelihoods, particularly affecting vulnerable communities[9]. Given Kolkata's socio-economic significance, including its role as a major commercial, industrial and transportation hub contributing significantly to the national GDP, protecting its population and infrastructure from cyclone-related hazards is of paramount importance[11]. Despite numerous disaster preparedness initiatives, there remains a lack of detailed, location-specific cyclone shelter suitability mapping within the urban framework of KMC, highlighting a critical research gap in the domain of spatial risk assessment[14].

To address this, the present study aims to develop a comprehensive cyclone shelter susceptibility assessment for the KMC area using Geographic Information System (GIS) tools integrated with two decision-making models: the Analytical Hierarchy Process (AHP) and the Frequency Ratio (FR) model. These models were employed to analyze multiple physical, environmental and socio-economic factors influencing cyclone vulnerability. By generating thematic layers such as elevation, slope, LULC, drainage, vegetation, geology and others and combining them through multi-criteria evaluation, a prioritized cyclone shelter suitability map was developed[1].

Study area

The present study is focused on the jurisdictional boundary of the KMC which serves as the administrative and governance unit of central Kolkata. The area spans approximately 206.08 sq.km and is subdivided into 16 boroughs and 144 municipal wards, each with distinct urban and infrastructural characteristics. The region lies on the eastern bank of the Hooghly River and is characterized by flat topography with minor elevation variations, which makes it prone to waterlogging and drainage congestion during intense rainfall events. The city's drainage system is interlaced with both natural and engineered channels, contributing to the hydrological complexity of the urban landscape. The land use in the area is predominantly built-up, interspersed with green spaces, water bodies and slum settlements, all of which influence the vulnerability and shelter accessibility during cyclone events[16].

The selection of this area for cyclone shelter suitability analysis is based on its compact urban structure, critical infrastructure and the need for micro-level spatial planning to ensure disaster resilience[23]. A detailed representation of the spatial extent and administrative boundaries of the study area is provided in figure 1, which illustrates the location map of the KMC.

Climatic and Topographical Characteristics: The KMC region lies within the tropical monsoon climate zone, experiencing hot, humid summers and substantial rainfall during the monsoon season, typically from June to September. The area records an average annual rainfall of about 1,500 to 1,800 mm, much of which is concentrated during the southwest monsoon. The topography of the region is predominantly flat and low-lying, with elevations ranging between 1.5 to 11 meters above mean sea level, which renders the city particularly vulnerable to waterlogging and urban flooding during high-intensity rainfall events[17]. The elevation and slope maps of the KMC region are shown in figure 2. The city's natural drainage system, once supported by an extensive network of wetlands and canals, has been significantly altered due to rapid urbanization, further exacerbating flood risks. The relatively gentle slope and poor drainage characteristics make the area highly susceptible to stormwater accumulation during cyclonic rainfall, thereby compounding the impacts of coastal hazards[12].

Data Sources and Acquisition: To construct a comprehensive Cyclone Shelter Susceptibility Map (CSSM) for the KMC, a wide array of datasets from multiple sources was collected and processed within a Geographic Information System (GIS) environment. These datasets cover satellite imagery, topographical elevation models and meteorological records essential for analyzing terrain, hydrology, rainfall patterns and population density, each of which plays a pivotal role in determining cyclone vulnerability. The complete data types with the sources are summarized in table 1.

Satellite and DEM Data: High-resolution satellite imagery was sourced from the United States Geological Survey (USGS), specifically Landsat 8 data, to generate thematic layers such as Land Use/Land Cover (LULC), Normalized Difference Vegetation Index (NDVI) and urban layout features. The Landsat 8 scene selected for this study was completely cloud-free (0% cloud cover) and captured during the post-monsoon period in the latter half of 2024. The temporal selection ensures minimal atmospheric interference while providing high-quality surface data[6]. A Landsat 8 composite map of the KMC was generated using ArcGIS software.

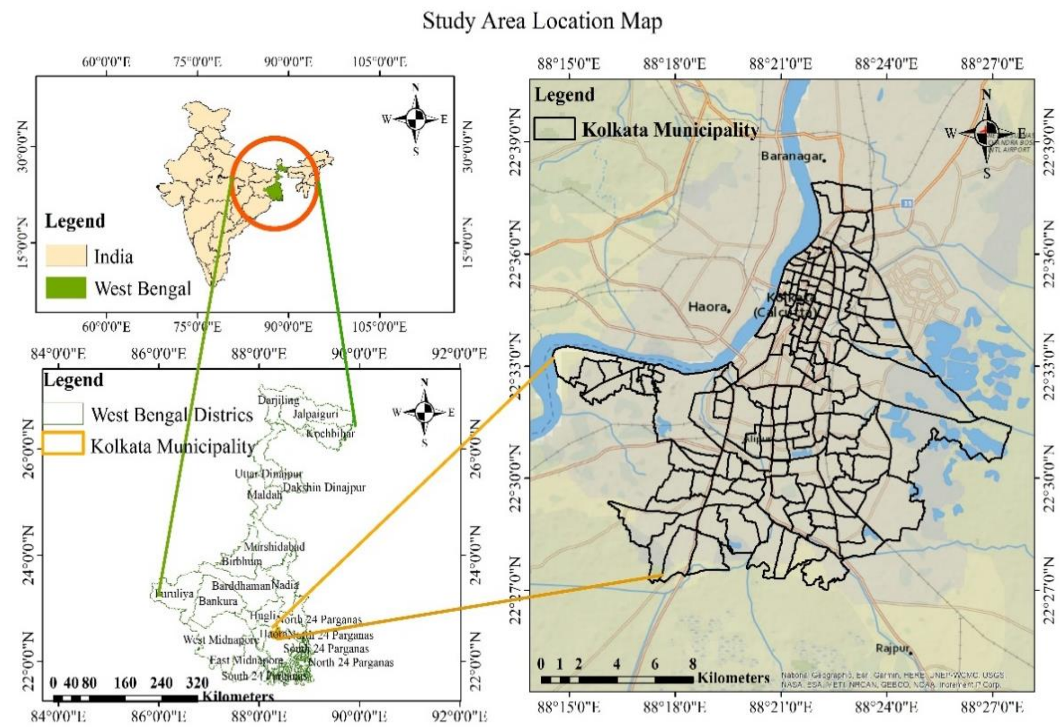


Fig. 1: Geological location map of the KMC region with ward boundaries

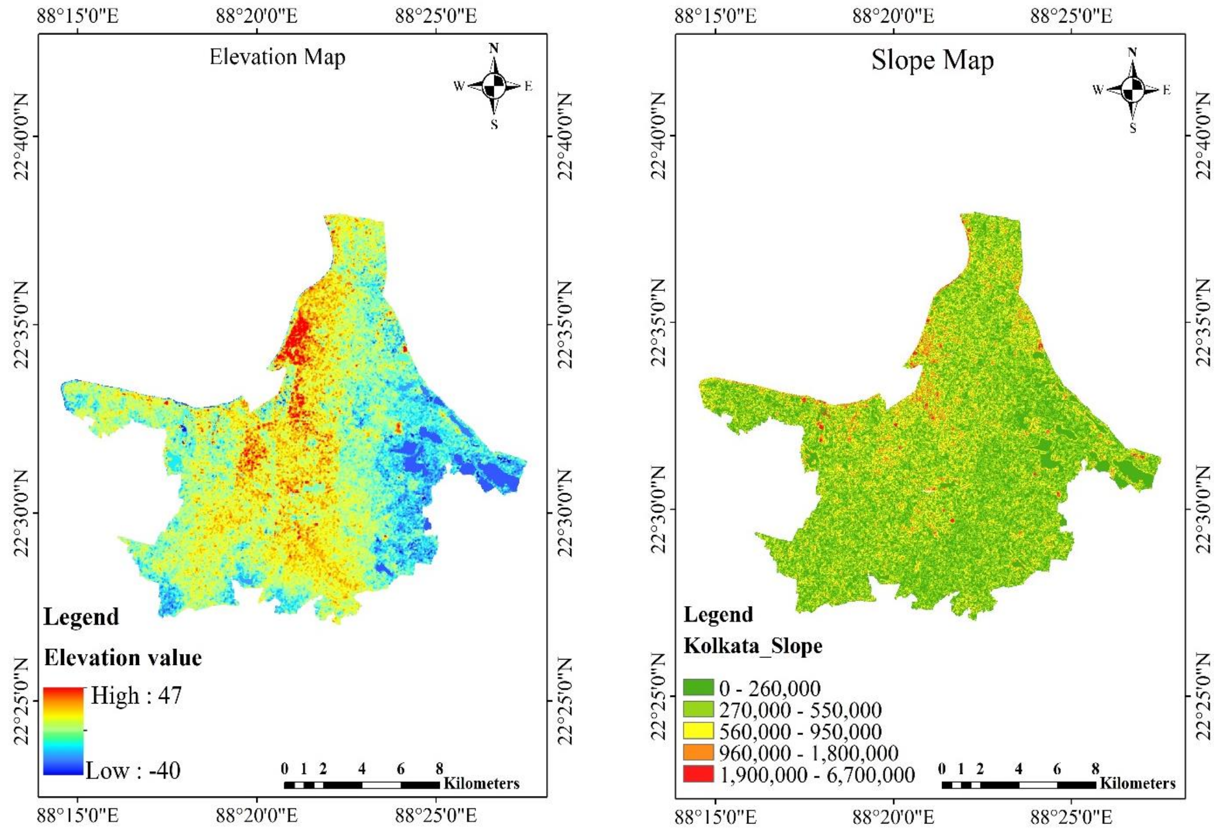


Fig. 2: Spatial variation of elevation and slope of the KMC region

Table 1
Data types and sources

Data type	Data source	Period	Resolution	Thematic layers developed
Landsat 8	USGS website	January - December 2024	30m × 30m	NIR, NDVI, LULC, distance from River
SRTM-DEM	USGS website	January - December 2024	30m × 30m	Elevation, slope, aspect, roughness, Hillshade and TWI
Rainfall	IMD	2024	NA	Rainfall map and temperature
Geological features	Bhukosh	NA	30m × 30m	Geology, Geomorphology, Lithology, water bodies, Rail and Road network

Additionally, elevation data was acquired from the USGS Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) which provides 30-meter spatial resolution elevation profiles. This data was instrumental in creating slope, aspect, flow direction, flow accumulation and watershed delineation maps, enabling the topographical modelling required for susceptibility analysis[8]. The maximum elevation is observed as 47 meters over the central and north part of the KMC. The DEM also supports hydrological modelling, which is vital for understanding flood-prone zones within cyclone-affected areas. The landsat-8 imaginary and aspect of the KMC are depicted in figure 3.

Rainfall statistics: Meteorological data was obtained from the IMD, which provided annual and monthly rainfall records for the Kolkata region. On average, Kolkata receives approximately 1400-1600 mm of rainfall annually. Notably, from June to September in the peak monsoon seasons, the average cumulative rainfall reaches approximately 158 cm, accounting for most of the city's annual precipitation. Monthly rainfall and temperature variations are illustrated in figure 4.

Windrose diagram of KMC: The windrose diagrams, illustrated in figure 5, present the wind speed and directional distribution for KMC during January-June and July-December 2024. Wind speeds are categorized into six classes: ≥11.10, 8.80-11.10, 5.70-8.80, 3.60-5.70, 2.10-3.60 and 0.50-2.10 km/h, with calm conditions accounting for 0%. The directional intensity ranges from 0.69% to 3.45% in the January-June period and 0.674% to 3.37% from July to December. These diagrams play a crucial role in analyzing wind behaviour for cyclone vulnerability assessments and shelter suitability mapping in the current study[2].

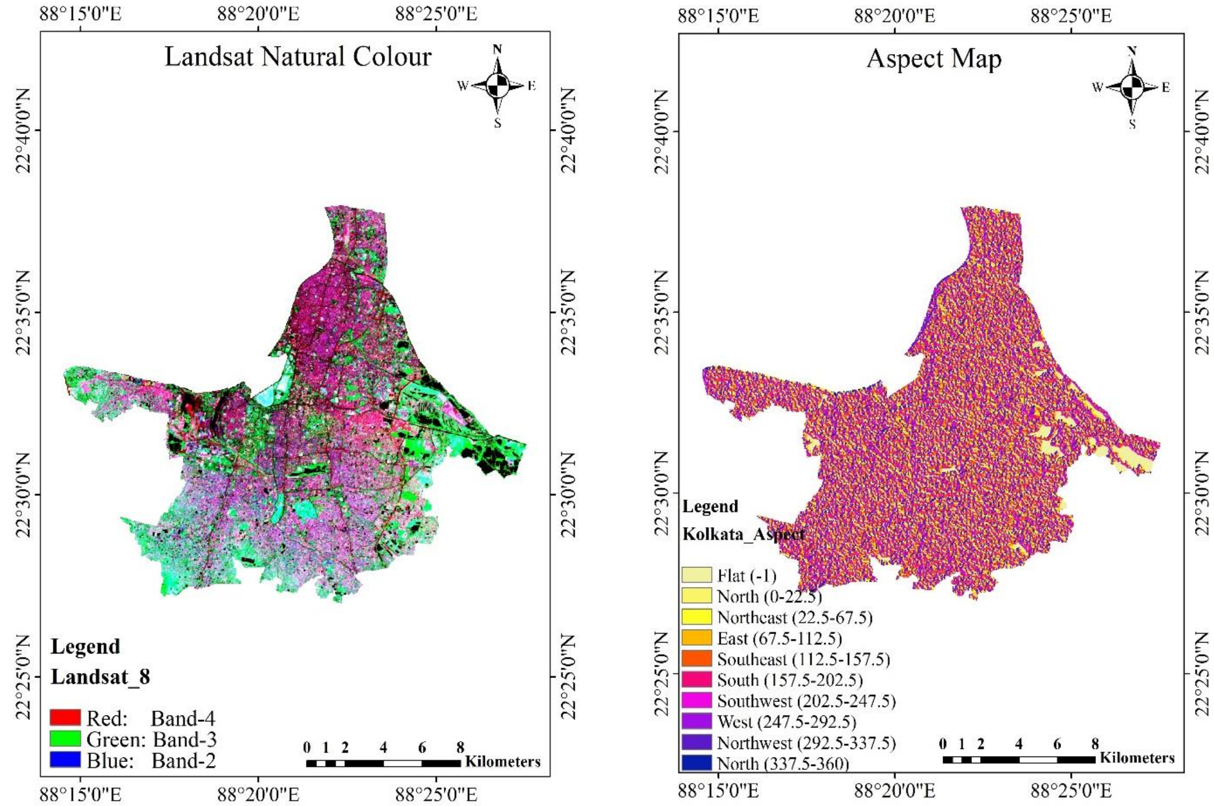


Fig. 3: Landsat8 and aspect map of the KMC region

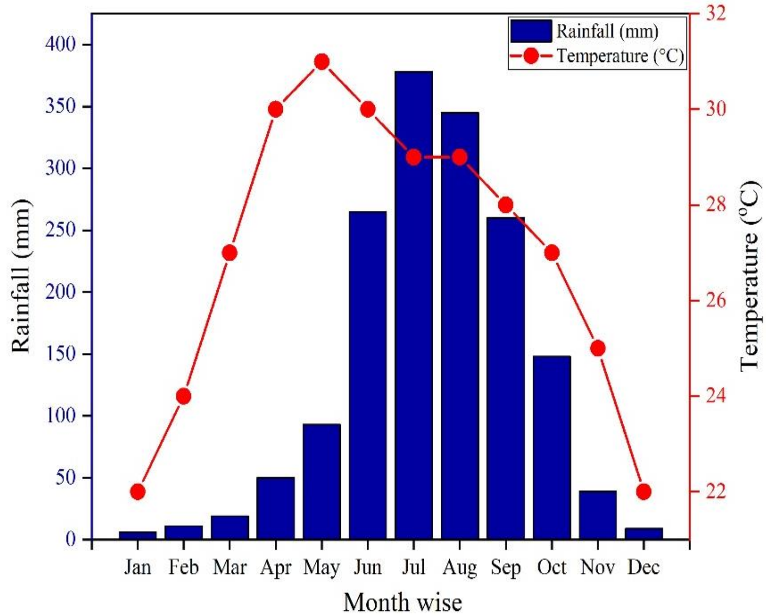


Fig. 4: Monthly variation of average rainfall and temperature in Kolkata Municipal Corporation for the year 2024

Development of various thematic layers: Roughness and Hillshade maps are crucial in understanding terrain variability and slope illumination which directly impact water runoff patterns during cyclonic events. The roughness map for KMC was developed using GIS and classified into five groups: 0.11-0.31, 0.32-0.44, 0.45-0.56, 0.57-0.68 and 0.69-0.89. Higher roughness areas can hinder emergency access and increase flood accumulation risks[13]. The hillshade map, which shows the terrain's shading effect due to elevation, highlights slope directions and aspects, with a maximum hillshade value observed at 180. These maps are presented in figure 6 and aid in selecting shelter sites with suitable topographic stability[15].

Contours and basin delineation further enhance understanding of the hydrological framework of KMC. Contour lines reflect elevation changes, influencing water flow directions, while basin mapping helps in identifying natural catchment areas susceptible to flooding[18]. The maximum basin value noted is 1493, indicating large watershed zones that may require prioritized shelter planning. These maps are depicted in figure 7, supporting shelter placement in low-flood-risk zones[7].

Vegetative and land use patterns are also key factors in cyclone vulnerability. The NDVI of KMC was developed and classified the region into water bodies, land, shrubs and healthy vegetation, helping to assess natural surface cover which can either buffer or accelerate surface runoff[21]. The NDVI theme is developed using the equations 1 and 2.

$$NDVI = \frac{(NIR-R)}{(NIR+R)} \quad (1)$$

$$\text{In Landsat 8, NDVI} = \frac{(\text{Band } 5-\text{Band } 4)}{(\text{Band } 5+\text{Band } 4)} \quad (2)$$

where NIR is near infra-red and R is red band. Simultaneously, the LULC map categorizes the region into cropland, built-up land, water bodies and permanent wetlands[10]. These layers, shown in figure 8, help in identifying impermeable surfaces and high-exposure built-up areas, which require greater shelter capacity[21].

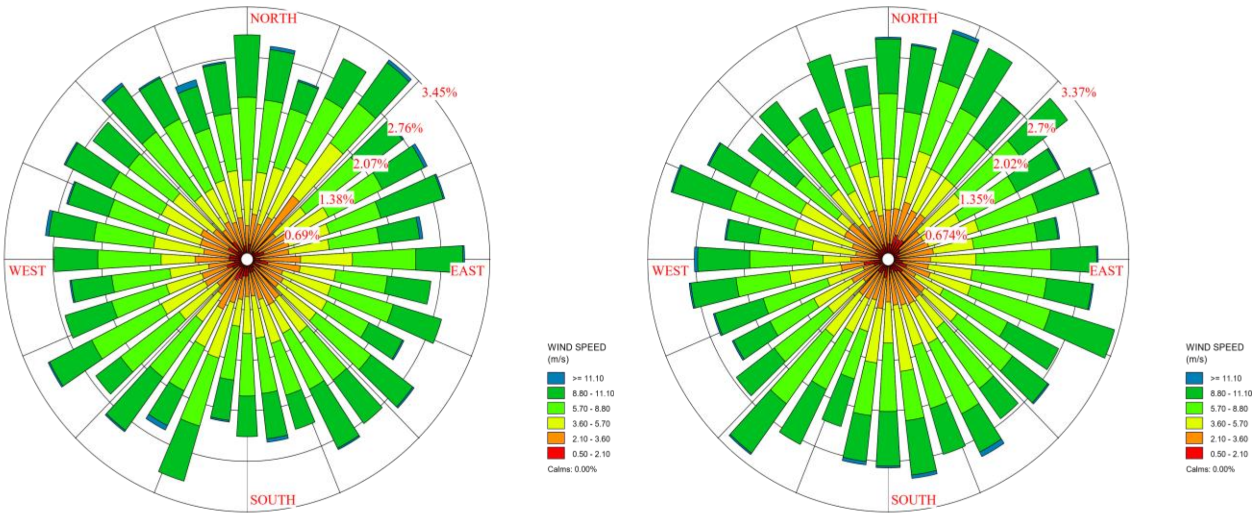


Fig. 5: Windrose diagrams showing comparative wind direction and speed distribution for Kolkata Municipal Corporation during January-June and July-December 2024.

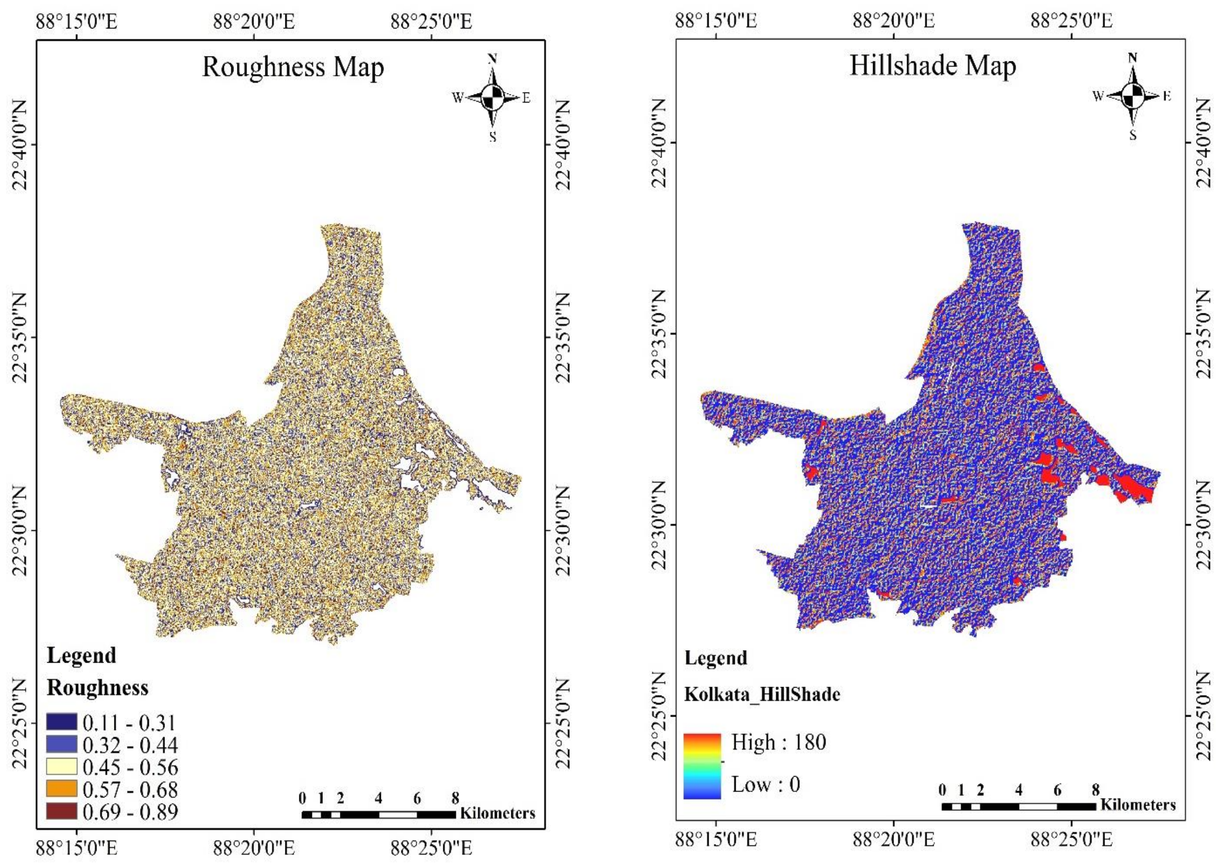


Fig. 6: Roughness and Hillshade maps of KMC showing terrain variability and slope illumination.

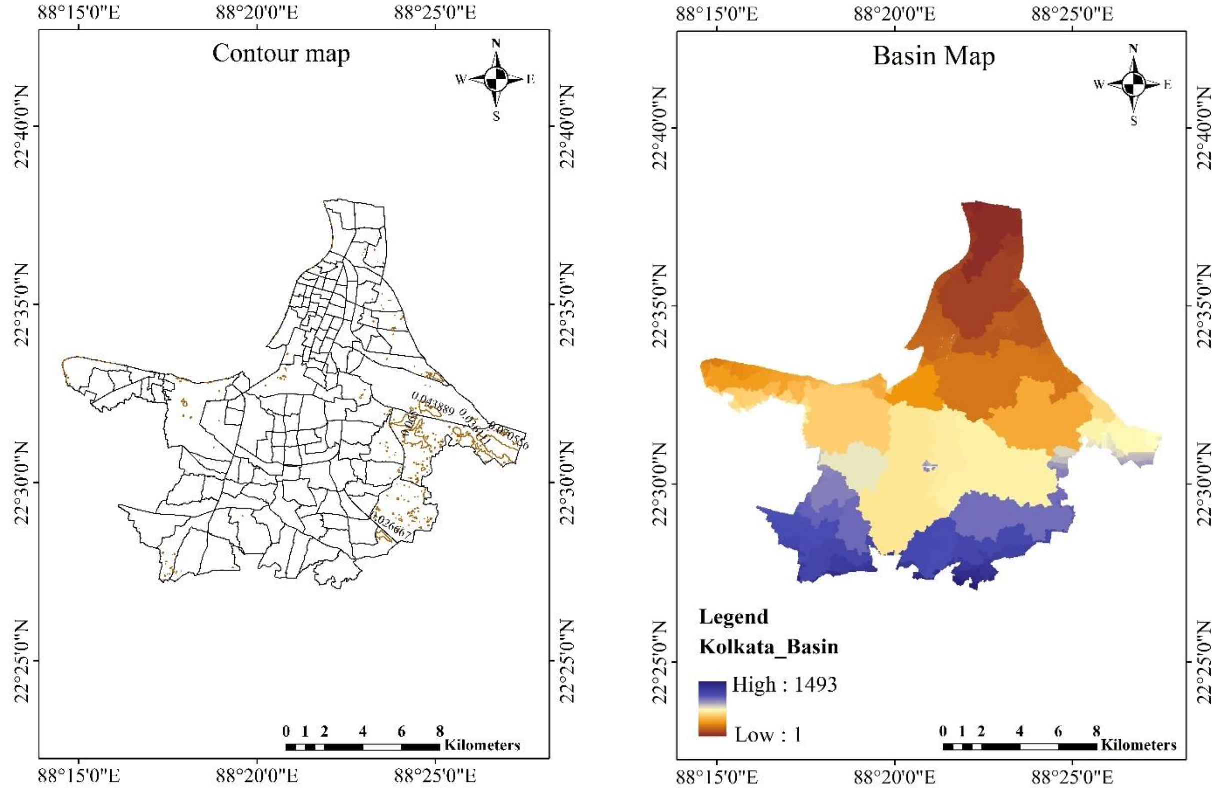


Fig. 7: Contour and basin maps of KMC illustrating elevation transitions and hydrological catchment zones.

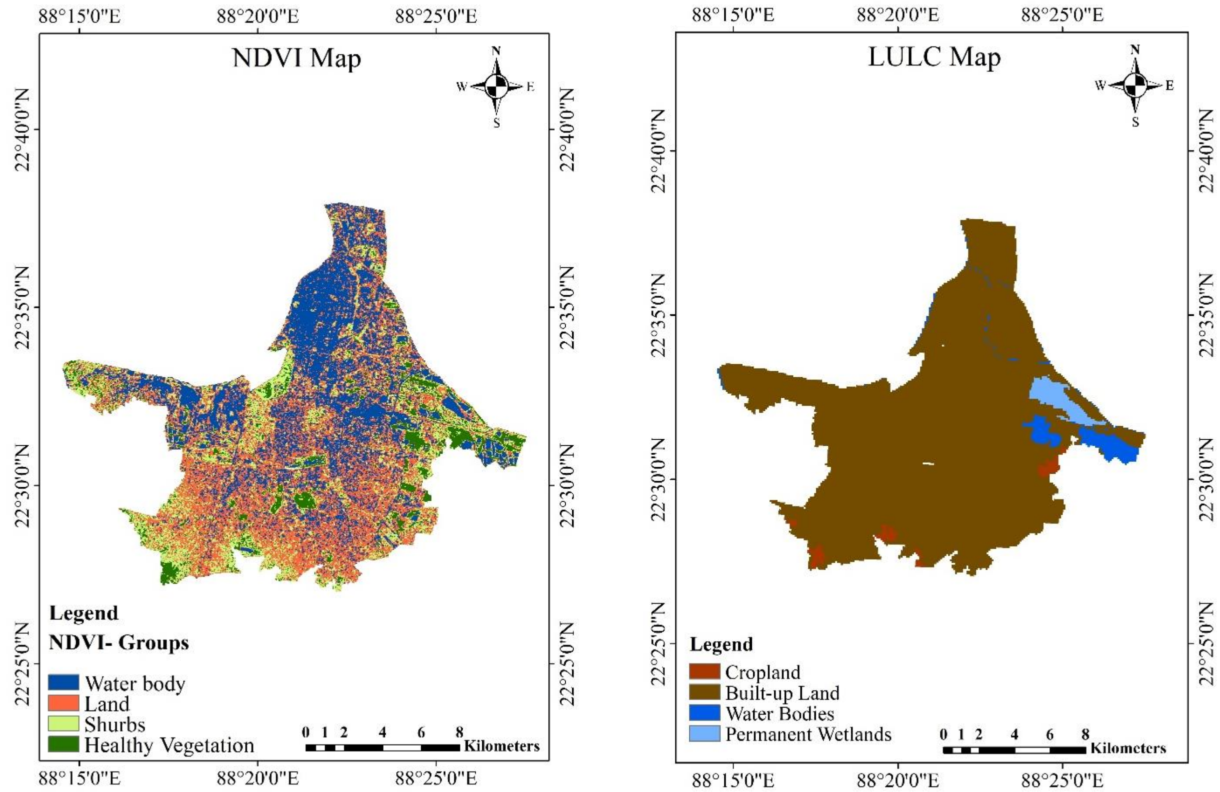


Fig. 8: NDVI and LULC maps of KMC classifying vegetation and urban land types

TWI and stream network layers serve to identify flood-prone zones with high moisture accumulation. The TWI map is classified into five intervals: -19 to -15, -14 to -12, -11 to -5, -4.9 to 2.1 and 2.2 to 8.6. Areas with higher TWI values are highly susceptible to water retention. Stream network analysis reveals the eastern and southwestern parts of KMC as more vulnerable to cyclonic flooding. These findings are presented in figure 9 and guide the strategic positioning of cyclone shelters in less flood-prone locations. Geomorphological features and infrastructure proximity are also keys in determining shelter site suitability[18]. The geomorphology of KMC is dominated by older deltaic plains, ponds and water bodies, indicating relatively low-lying terrain. Additionally, proximity to the railway network and water bodies has been analysed, with eastern and southwestern parts showing higher susceptibility to waterlogging[19]. These layers are shown in figure 10 help in assessing ground stability and accessibility during disasters.

Drainage characteristics including line density and flow direction, play a vital role in identifying surface water pathways. The line density map is classified into five categories: 0-93, 94-190, 200-280, 290-370 and 380-460 indicating variation in drainage infrastructure. The flow direction map, categorized into 1-2, 2.1-8, 8.1-32, 33-64 and 65-130, illustrates the general movement of surface water which is essential for locating shelters away from flow-converging zones[24].

Additionally, distance from river mapping helps in buffering against potential riverine flooding. These drainage-related maps (line density and flow direction) are illustrated in figure 11. Proximity to river and watershed delineation maps are illustrated in figure 12, all these layers forming a critical component of shelter planning[22].

Analytical Hierarchy Process (AHP): The AHP is a structured, multi-criteria decision-making (MCDM) approach that enables complex problems to be broken down into a hierarchy of more easily comprehended sub-problems. Each of these can then be analysed independently and systematically[20]. In the context of cyclone shelter suitability mapping for the KMC, AHP was employed to evaluate multiple spatial and physical parameters influencing site vulnerability and shelter adequacy[4].

Criteria Selection and Weight Assignment: In this study, a total of 10 thematic layers were selected based on their relevance to cyclone vulnerability and shelter planning[5]. These include TWI, elevation, wind velocity, slope, distance from river, LULC, NDVI, Drainage density, precipitation and geomorphology. The weight for each thematic layer was derived using literature support, applying a pairwise comparison method where each criterion was rated against others on a scale of relative importance ranging from 1 (equal importance) to 9 (extreme importance of one over another). These comparisons were compiled into a Pairwise Comparison Matrix (PCM), from which Eigen vectors were calculated to determine the normalized weights of each factor[26].

Pairwise Comparison Matrix and Consistency Ratio: After establishing the PCM, the Consistency Index (CI) and Consistency Ratio (CR) were computed to assess the logical consistency of the weight assignments. A CR value of less than or equal to 0.1 (10%) is considered acceptable, indicating that the judgments are reasonably consistent[25]. The AHP process mainly involved hierarchy design, pairwise comparison, weight derivation, consistency ratio and weighted overlay.

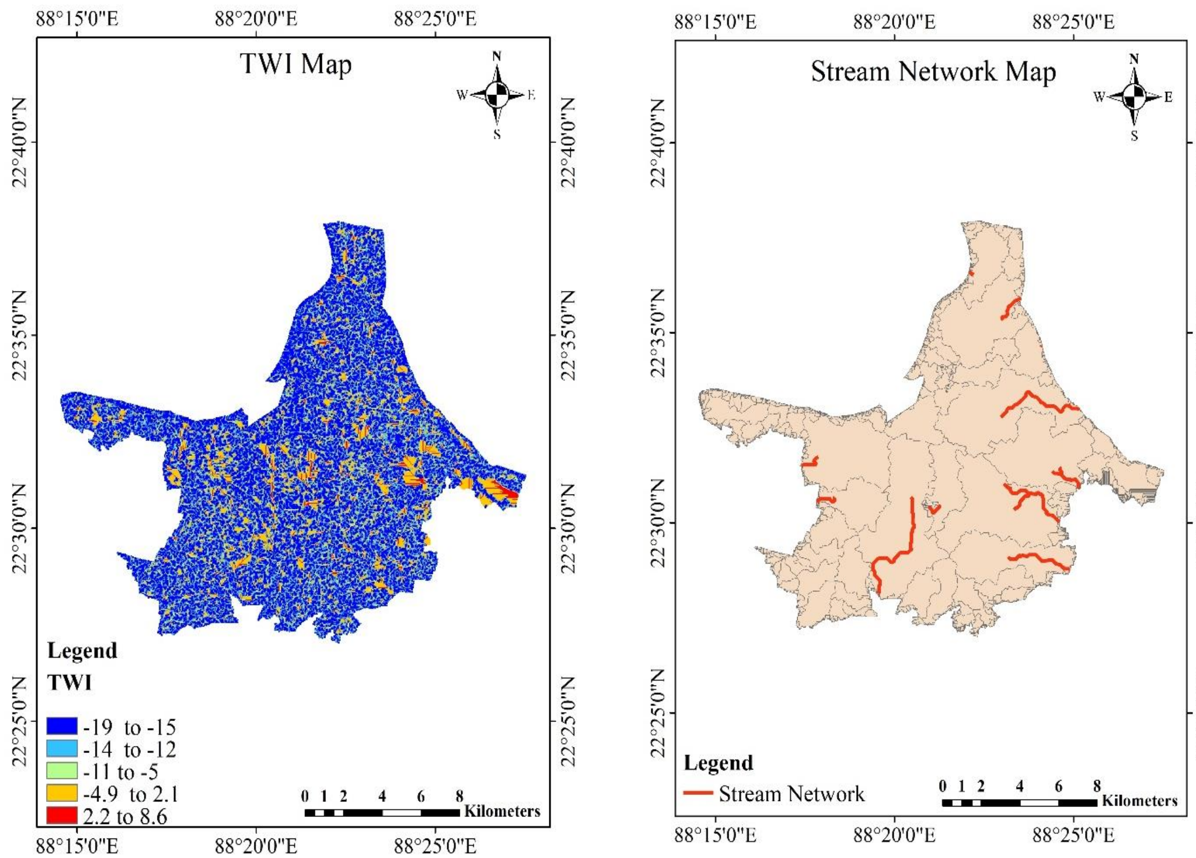


Fig. 9: Topographic Wetness Index and stream network maps showing potential flood accumulation zones

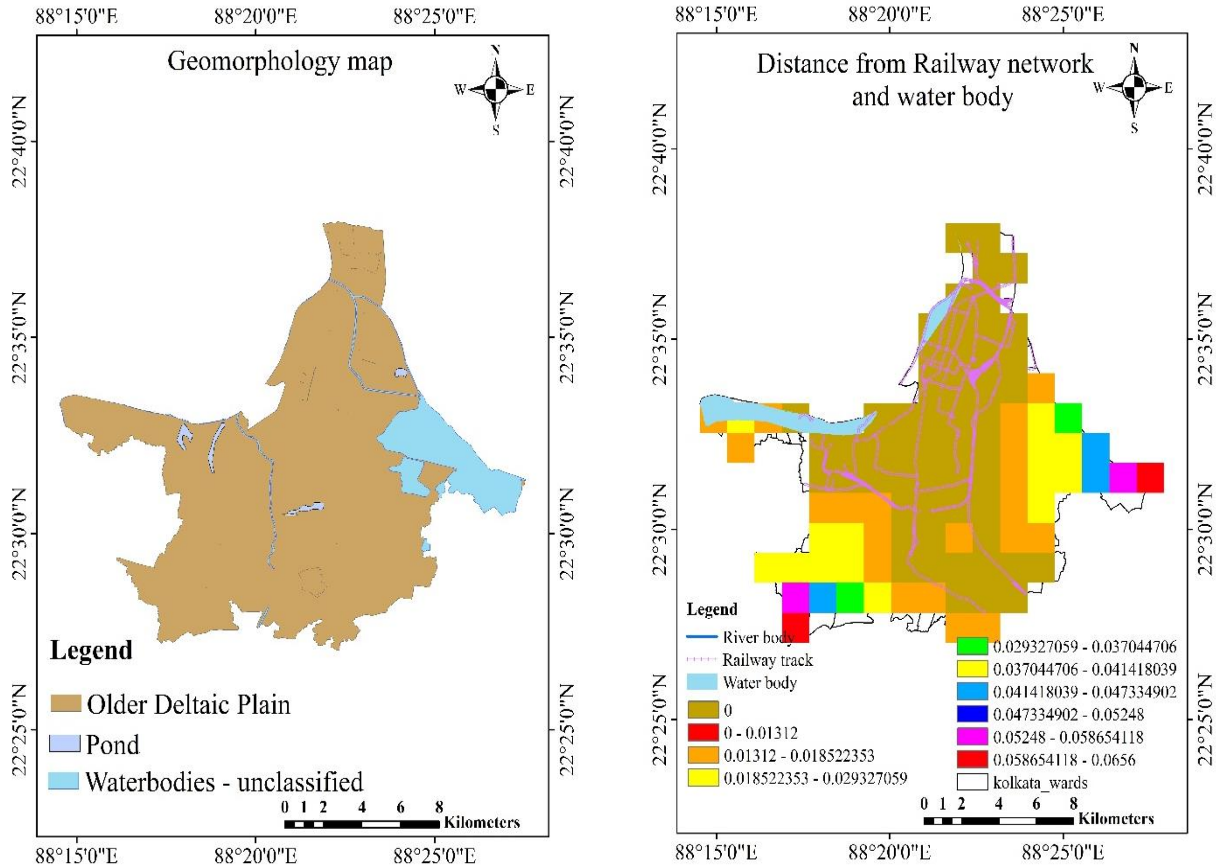


Fig. 10: Geomorphology and proximity maps highlighting terrain types and vulnerable zones near infrastructure

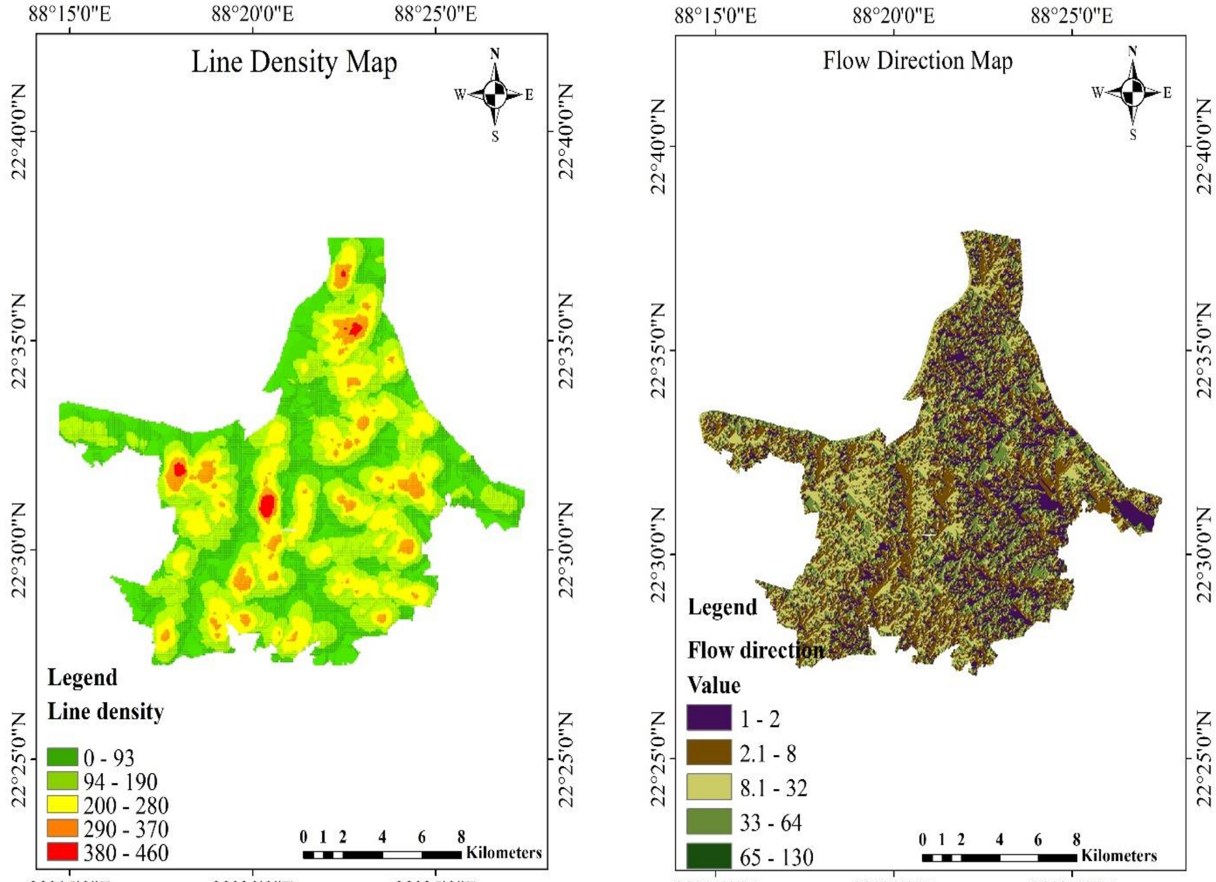
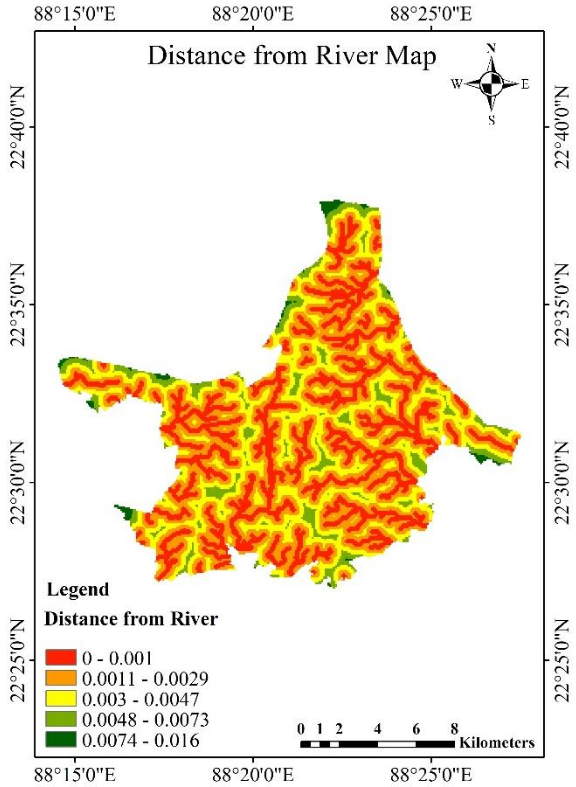


Fig. 11: Line density and flow direction maps indicating drainage density and surface runoff patterns



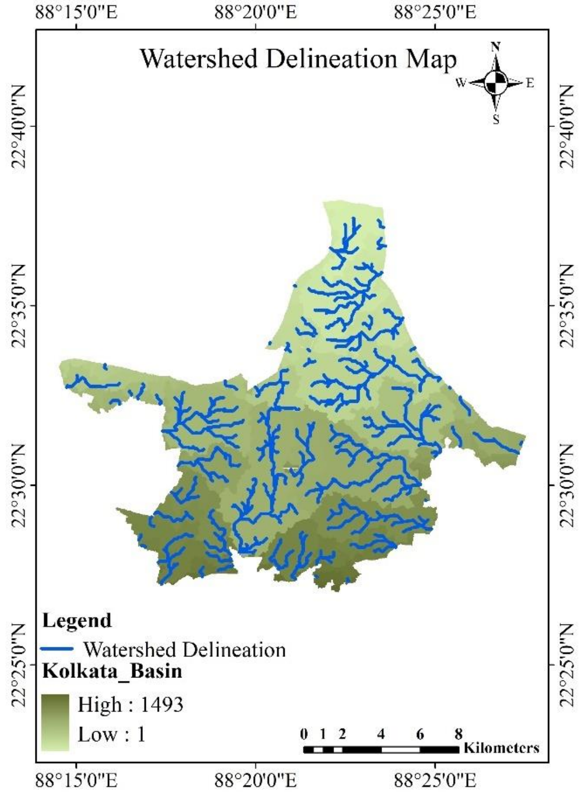


Fig. 12: Distance from river map representing proximity of urban zones to riverine flooding sources.

Table 2
Ranking criteria of AHP

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgement slightly favor one element over another.
5	Strong importance	Experience and judgement slightly strong one element over another.
7	Very strong importance	One element favored very strongly over another.
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation.
2, 4, 6 and 8 are used to express intermediate values		

Weighting the criteria using AHP: The AHP framework was employed to derive the relative weights of selected criteria by evaluating their comparative significance[27]. This process involves constructing a PCM and utilizing mathematical algorithms to quantify the relative importance of each criterion[8]. As outlined by Hussain et al[8], the methodology comprises of three primary steps: the formation of the comparison matrix, normalization of the pairwise comparisons and the calculation of the CI using equation (3), followed by the computation of the CR as shown in equation (4).

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

In this context, λ_{max} is derived from the multiplication of the average weights from the normalized matrix with the sum of columns in the original matrix while n indicates the matrix order. The term RI represents the Random Index, a predefined value corresponding to the number of criteria, which assist in determining acceptable consistency.

For this analysis, the AHP model was executed using the Microsoft Excel-based AHP template developed by Goepel[7], providing an efficient tool for automated calculation and consistency verification. Each criterion was comparatively ranked against all others, with intensities of preference assigned based on a fundamental scale proposed by Saaty[23] ranging from 1 to 9, as detailed in table 2 and the PMC corresponding to each considered layer is summarised in table 4. Table 3 deals with various parameters and their characteristics.

FR Model: The Frequency Ratio (FR) model is a widely recognized bivariate statistical method utilized to assess an area's susceptibility to natural hazards, particularly floods[1]. This model evaluates the correlation between independent flood-contributing factors and the observed flood-prone areas (dependent variable).

Table 3
Various parameters and their characteristics

Parameter	Suitability class	Ratings	% weight
Elevation	Not suitable	5	14.81
	Less suitable	4	
	Moderately suitable	3	
	suitable	2	
	Not suitable	1	
Drainage Density	Not suitable	5	13.71
	Less suitable	4	
	Moderately suitable	3	
	suitable	2	
	Not suitable	1	
Slope	Less suitable	2	12.95
	Highly suitable	5	
	suitable	4	
	Moderately suitable	3	
	Not suitable	1	
Distance from the River	Not suitable	1	15.21
	Less suitable	2	
	Moderately suitable	3	
	suitable	4	
	High suitable	5	
TWI	Highly suitable	1	12.18
	suitable	2	
	Moderately suitable	3	
	Less suitable	4	
	Not suitable	5	
Wind velocity	Not suitable	1	7.68
	Less suitable	2	
	Moderately suitable	3	
	suitable	4	
	High suitable	5	
Precipitation	Highly suitable	1	9.33
	suitable	2	
	Moderately suitable	3	
	Less suitable	4	
	Not suitable	5	
Land Use Land Cover	Moderately suitable	3	7.06
	suitable	2	
	Highly suitable	5	
	Less suitable	4	
	Not suitable	1	
NDVI	Moderately suitable	3	4.56
	suitable	2	
	Highly suitable	5	
	Less suitable	4	
	Not suitable	1	
Geomorphology	Very high	5	3.05
	High	4	
	Moderate	3	
	Low	2	
	Very Low	1	

The FR values were calculated using equations (5-7) as introduced by Rahman et al[15]:

$$FR = \frac{FP/_P}{FA/_A} \quad (5)$$

$$RF = \frac{FR\ of\ factor\ class}{\varepsilon\ FR\ of\ factor\ classes} \quad (6)$$

$$PR = \frac{(RF_{max} - RF_{min})}{(RF_{max} - RF_{min})\ Min} \quad (7)$$

In these equations, FP denotes the number of flood points in a specific factor class, P is the total number of flood points, FA indicates the area of the factor class and A is the overall area of the study region. To standardize the FR into a probability scale ranging from 0 to 1, the relative frequency (RF) was derived through normalization. Subsequently, the PR was calculated using another equation to quantify the correlation between the actual flood inventory (used as training data) and the various influencing criteria. In this study, 120 randomly selected flood points were used for model training while 60 points were reserved for validation to ensure robust performance evaluation.

Table 4
PMC of Thematic Layers Used in AHP for CSSM of KMC

Factor	TWI	Elevation	Wind velocity	Slope	Distance from River	LULC	NDVI	Drainage density	Precipitation	Geomorphology	Normalized Principal Eigenvector (%)
TWI	1	0.5	3	1.3	0.5	4	1.2	2.5	0.75	1.42	12.18
Elevation	2	1	1.16	2	1.2	1.83	0.83	0.87	1.88	4.14	14.81
Wind velocity	0.33	0.85	1	0.2	0.37	0.2	1	0.25	1.14	0.5	7.68
Slope	0.75	0.5	3.5	1	1.16	5	1	0.83	0.75	2	12.95
Distance from river	2.10	0.83	2.7	0.	1	3	0.33	0.75	0.6	2.2	15.21
LULC	0.4	0.54	5.9	0.4	0.3	1	3.25	1.33	1	1.5	7.06
NDVI	0.25	1.2	1	1	3	0.30	1	0.22	1.11	0.87	4.56
Drainage density	0.4	1.1429	4	1.2	1.33	0.75	4.5	1	1.1	1.2	13.17
Precipitation	1.33	0.52	0.87	1.3	1.66	1	0.9	0.90	1	1	9.33
Geomorphology	0.5	0.24	2	0.5	0.45	0.66	1.14	0.83	0.4	1	3.05

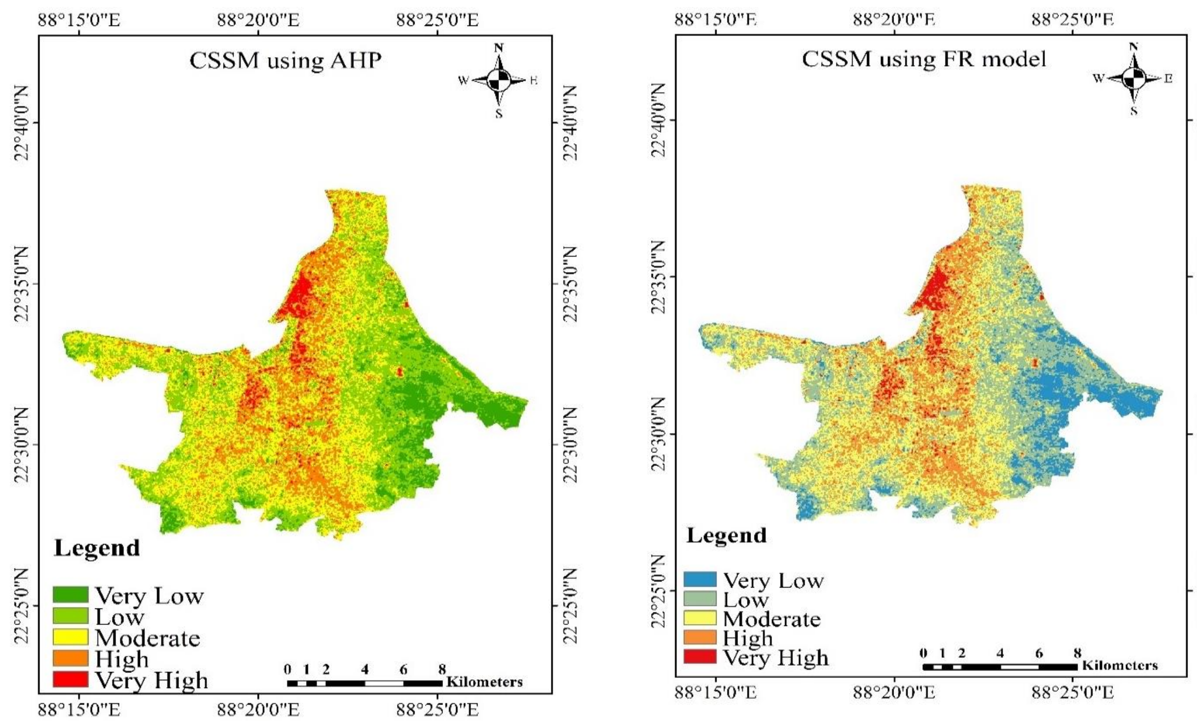


Fig. 13: CSSM of KMC using AHP and FR approach

Conclusion

This study employed a GIS-based multi-criteria decision-making approach to assess cyclone shelter susceptibility in the cyclone-prone region of the KMC. By integrating the AHP and FR models with thematic geospatial datasets, the research identified and prioritized regions within KMC that were vulnerable to cyclonic impacts originating from the Bay of Bengal. A total of 10 geospatial criteria were used for the AHP analysis including elevation, slope, TWI, NDVI, LULC, drainage density, precipitation, wind velocity, distance from rivers and geomorphology. Each factor was assigned a weight based on its relative importance to cyclone vulnerability, as determined through the AHP: PMC.

The final normalized weights from the principal eigenvector were elevation (14.81%), drainage density (13.17%), lope (12.95%), distance from River (15.21%), TWI (12.18%), wind velocity (7.68%), precipitation (9.33%), LULC (7.06%), NDVI (4.56%) and geomorphology (3.05%). These weights underscore the critical influence of topography and hydrological behaviour in identifying cyclone shelter sites, with elevation and proximity to water features being the most influential.

The maximum elevation recorded in the study area was 1493 meters, significantly affecting flood susceptibility and shelter suitability. The TWI, a key hydrological parameter, ranged from -19 to 8.6, influencing surface runoff accumulation and low-lying area identification. Drainage density and slope also played pivotal roles in determining runoff pathways and water stagnation zones. Land use and vegetation cover, represented through NDVI and LULC layers, helped to assess impermeable surfaces and open areas feasible for shelter construction.

Windrose diagrams, developed using temporal wind data for January-June and July-December 2024, revealed the seasonal shifts in wind direction and intensity, contributing to a better understanding of cyclone trajectory patterns. While the model proved effective, it is not without limitations. The accuracy of AHP depends heavily on expert judgment, which introduces subjectivity, though consistency checks were applied.

Additionally, socio-economic and infrastructural variables like shelter accessibility, crowd capacity, or real-time transport availability were not incorporated due to data unavailability. Future work could integrate machine learning models, citizen-reported flood data and high-resolution socio-demographic layers to enhance accuracy and on-ground applicability. Despite these limitations, the study provides a crucial foundation for cyclone preparedness planning and spatial disaster resilience in the urban context of KMC region.

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