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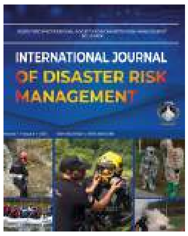

Article

COSI-SAFE: A GIS-Based Multi-Criteria Framework for Evaluating Urban Open Space Suitability for Post-Earthquake Emergency Sheltering

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ABSTRACT

Emergency response preparedness is a critical component of comprehensive earthquake risk management. The selection of suitable sites for post-disaster emergency sheltering during the response phase is central to effective contingency planning in densely populated urban areas. However, conventional planning often relies on ad-hoc methods that fail to systematically balance competing suitability factors. We propose COSI-SAFE, a Comprehensive Open Space Suitability Index (COSI)-based Suitability Assessment for Emergency-sheltering (SAFE) framework that evaluates the suitability of open spaces for temporary shelter establishment in the immediate aftermath of an earthquake in a densely populated urban area (Mirpur area in Dhaka City, Bangladesh), utilizing a GIS-based multi-criteria decision-making (MCDM) approach. The evaluation framework defines suitability based on three key dimensions — quality, capacity, and accessibility. Quality indicators were derived from field surveys and secondary data sources. Capacity and accessibility assessments were conducted using spatial analysis tools, including network and proximity analysis in the ArcGIS platform. The Analytic Hierarchy Process (AHP) was applied to combine the three criteria and derive the COSI for the identified open spaces. The results indicate that most open spaces are either moderately or poorly suited for use as emergency shelters, with only a small fraction deemed highly favorable in a post-earthquake context. Specifically, 1.2% of the open spaces were found to be completely unsuitable, 23.5% had low suitability, 56.8% were moderately suitable, and only 18.5% were fairly suitable for temporary shelter establishment. When weighted by total open-space area rather than site counts, the distribution was: unsuitable 0.8%, low 18.0%, moderate 59.5%, and fair 21.7%, indicating that a limited number of large open spaces contribute disproportionately to the total available shelter area. The findings highlight the inadequacy of existing open spaces to accommodate potential sheltering demand, emphasizing the need for proactive planning in the studied region. Assuming a deterministic Mw 7.5 event and displacement rates of 80% for partially damaged and 100% for extensively damaged buildings, we estimate a shelter-seeking population of 576,678, of whom 242,381 (42.0%) could be accommodated within a 700 m walking radius at 1.7 m^2/person. The developed methodology offers a replicable planning tool for policymakers, emergency managers, and responders to strengthen earthquake response preparedness and inform post-disaster response strategies in high-density, earthquake-prone urban areas.

KEYWORDS

Earthquake response; contingency planning; emergency shelter; open space suitability; Analytic Hierarchy Process (AHP); Geographic Information System (GIS).

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1. Introduction

In response to escalating environmental risks worldwide, particularly in urban settings, the global disaster policy landscape has increasingly shifted emphasis towards pre-disaster preparedness and strategic planning. The Sendai Framework for Disaster Risk Reduction 2015–2030 highlights "Strengthening disaster preparedness for effective response" as a central priority (UNISDR, 2013). One of the prime strategies in improving disaster response preparedness in the pre-disaster context is the identification of suitable emergency shelter sites before the disaster occurs (Chandler, 2007; Tai et al., 2010). Emergency shelters provide essential refuge for displaced populations in the immediate aftermath of a disaster, and proactive planning for such facilities is widely endorsed. In the context of earthquake emergencies, where events unfold rapidly with little to no warning, preparedness measures such as the pre-identification of emergency shelter sites are especially critical (Wright & Johnston, 2010).

Post disaster emergency sheltering planning and preparation is an important component of earthquake contingency planning in high density urban context. Globally, scholars have underscored the importance of integrating site suitability assessments into emergency shelter planning. Studies highlight that the appropriateness of open spaces for emergency sheltering must be evaluated based on a combination of factors such as spatial quality, site accessibility, and sheltering capacity. While disaster planners tend to prioritize technical aspects like safety, resource access, and logistics, affected populations often emphasize proximity, access routes, and basic amenities (Da Silva, 2007; Tai et al., 2010). Bridging these perspectives is vital to developing effective and context-sensitive post disaster sheltering strategies.

Recent work underscores the same planning priorities we address in this study. For Bangladesh, studies highlight systemic preparedness needs and institutional roles in evacuation planning and shelter coordination, including police-led route planning, shelter placement, and prioritization of vulnerable groups (Islam, 2023). Other research has called for stronger, evidence-based approaches across hazard domains, including earthquakes and floods (Hossen et al., 2022; Podder et al., 2022). Complementary programmatic evidence from Bangladesh and the Philippines further shows that targeted, risk-informed mechanisms for shelter support, such as cash and voucher programs, can speed up post-disaster accommodation when site readiness is clear, linking preparedness analytics with actionable response pathways (Cañete et al., 2025).

The lack of a systematic and replicable methodology for evaluating potential emergency shelter sites in densely populated, disaster-prone urban areas present a critical vulnerability in global disaster preparedness. Historically, the selection of such sites could be an ad-hoc process, often relying on identifying available open spaces like parks and schools without a rigorous, multi-faceted analysis of their true suitability in a crisis (Ma et al., 2019). This non-systematic approach is fraught with peril because it fails to adequately address the immense complexity and uncertainty inherent in a post-disaster environment (Bakhshi et al., 2023). A truly effective evaluation must simultaneously consider a wide array of competing criteria, such as the physical favorability of the terrain, the availability of critical infrastructure like electricity and sanitation, the accessibility of the site when transport networks are disrupted, the total capacity of the shelter, and its proximity to affected populations. The primary criteria for selecting emergency shelter sites (Soltani et al., 2014) as suggested by existing literature, are as follows:

- Size and Location: This category emphasizes that shelters should be of a suitable size for the affected population and easily accessible. Proximity to the homes of those affected is a critical factor, mentioned in all reviewed studies. Other considerations include the condition of existing infrastructure, land drainage, and soil permeability.
- Disaster Risk Reduction: To prevent further harm, shelter sites must be located a safe distance from various hazards. This includes avoiding areas with geological risks like landslides or active seismic faults, as well as steering clear of hazardous materials, high-voltage lines, and structurally unsound buildings. A low land slope is also a frequently cited criterion to minimize the risk of geological hazards.

- Relief and Rescue Facilities: The availability of essential services is crucial. This includes proximity to medical centers and sources of relief services that can provide food, water, and other necessities. A reliable water supply for drinking, domestic use, and fire safety is a key consideration.
- Feasibility: This category addresses the practical aspects of site selection. Security and protection for the sheltered population are paramount. Economic factors, such as the cost of establishment and maintenance, must be justifiable. Additionally, land ownership and any necessary usage rights should be predetermined.
- Environmental Aspects: The chosen site should take environmental factors into account. This includes considering seasonal variations, potential environmental hazards, and the presence of vegetation, which can offer shade and reduce erosion. Sites should not be located in ecologically fragile or protected areas.
- Social Aspects: The cultural and social needs of the displaced population must be respected to ensure the shelter is functional and sustainable. Consulting with the local population and considering public opinion can help prevent conflict and ensure the chosen site is well-received.

Simple qualitative assessments or single-criterion decision-making cannot effectively balance these diverse factors, which often have conflicting priorities; for example, a large-capacity site may be poorly accessible, or a highly accessible site may be in a high-risk flood zone. Advanced systematic methodologies, such as the Best-Worst Method (BWM) and Large Group Decision-Making (LGDM), are designed specifically to overcome this challenge by providing a structured framework for weighing numerous criteria based on expert consensus, thereby producing a more robust and defensible selection (Jiao et al., 2024). Furthermore, a significant flaw in non-systematic planning is its failure to account for the dynamic nature of a disaster and the diverse perspectives of stakeholders. Shelter demand is not a static number; it fluctuates over time as building damage is assessed and essential services are gradually restored, a complexity that requires forecasting models rather than simple population counts. A systematic approach integrates these time-varying demand calculations to ensure shelters are planned for peak need without excessive overbuilding (Celik, 2024). Additionally, the process of weighing criteria is highly subjective if left to a small group of planners. Systematic methods like Large Group Decision-Making (LGDM) are crucial because they incorporate the collective intelligence of a large and diverse group of experts, from civil engineers and urban planners to geologists and rescue managers, thereby minimizing individual bias and ensuring a more holistic and resilient outcome (Zhao et al., 2017). This necessitates the development of a replicable framework. Unlike a one-off plan, a systematic methodology offers a transferable, step-by-step process that can be adapted and applied to countless other cities facing similar threats, ensuring that lessons learned and best practices in one region can be used to bolster urban resilience on a global scale.

Another critical challenge in urban disaster planning for cities like Dhaka is the unquantified gap between the supply of potential emergency shelters and the immense demand from a displaced population. This knowledge deficit obscures the true scale of a city's vulnerability, creating significant difficulty for emergency planners (Albris et al., 2020). Without a clear, data-driven understanding of this supply-demand mismatch, authorities cannot efficiently prioritize limited resources, preposition life-saving supplies, or design effective evacuation routes. The absence of a systematic, ranked assessment of potential shelter locations forces decision-making to be less strategic, hindering proactive efforts to enhance urban resilience.

This study aims at contributing to addressing these gaps by proposing an integrated methodological framework for assessing the suitability of open spaces for temporary emergency shelters in seven wards of the Mirpur area of Dhaka, Bangladesh. The evaluation combines both qualitative and quantitative criteria, including spatial quality, service capacity, and accessibility, to produce a ranked index of shelter suitability. The findings aim to support proactive disaster preparedness and contribute to enhancing Dhaka's overall earthquake resilience. Additionally, the study proposes a replicable model that can be applied to assess open space suitability in other high-density urban areas facing similar disaster risks. The contribution of this paper is three-fold:

- The study contributes a globally applicable framework for systematically evaluating emergency shelter suitability in any disaster-prone, high-density urban area. Recent advances in GIS–MCDM shelter siting combine AHP/fuzzy-AHP and large-group weighting with spatial optimization, and increasingly pair suitability with accessibility analyses (e.g., location–allocation, equity metrics). Representative studies include Ma (2022) on integrating multi-criteria evaluation with location–allocation for earthquake shelters, Bakhshi Lomer et al. (2023) on risk-driven LGDM/OWA for earthquake shelter suitability, Zhou et al. (2024) on spatial equity of emergency shelters, and Wang et al. (2024) introducing a graph-learning model (VGAE-RF) for shelter prediction. Unlike these, COSI-SAFE emphasizes a decomposable, AHP-weighted index of open-space micro-suitability (quality, capacity, accessibility) and reports area-weighted coverage with explicit sensitivity tests on weights, radius/capacity, and displacement assumptions. By integrating qualitative and quantitative measures of quality, capacity, and accessibility into a single COSI using the AHP, it provides a scalable and adaptable model for urban cities worldwide, particularly those in the Global South facing challenges of rapid urbanization and limited resources.
- The research demonstrates the framework's effectiveness through a real-world application in Dhaka, a representative example of a rapidly urbanizing and vulnerable city. The findings, which reveal a critical gap between shelter capacity and demand, significant accessibility constraints, and deficiencies in essential services like water, serve as a proof-of-concept, illustrating the kinds of critical planning gaps the methodology can uncover in similar urban environments globally.
- The study also provides an actionable blueprint for translating complex spatial analysis into concrete policy and planning tools for any municipality. By generating a prioritized ranking of potential sites and identifying "crisis hotspots", the research offers a model for how local authorities anywhere can develop tiered sheltering strategies, optimize the pre-positioning of logistical support, and inform more effective evacuation planning.

2. Study Area

This study was conducted across seven wards (local administrative divisions) in the northeastern part of the Mirpur area in Dhaka, Bangladesh. Bangladesh is considered among the world's most disaster-prone countries, experiencing frequent floods, cyclones, droughts, and earthquakes. The Asia Pacific Disaster Report (2015) ranks Bangladesh 10th globally in exposure and 5th in overall disaster risk threats (ESCAP, 2015). Positioned at the convergence of the Eurasian, Indian, and Burmese tectonic plates, the country is particularly vulnerable to seismic activity. More than 250 earthquakes have been recorded since 1971 in the country, several exceeding magnitudes 6.0 (Apu & Das, 2021; Zaman et al., 2018). Dhaka, the capital and economic center of Bangladesh, faces heightened earthquake risk due to its rapid and unplanned urbanization over the past several decades. High population density, substandard construction practices, and insufficient infrastructure have significantly undermined the city's seismic resilience. The risk is further compounded by weak institutional capacity for emergency response (Islam et al., 2010; Podder et al., 2022). Despite facing significant risks, Dhaka continues to face a gap in systematic planning tailored to the city's unique seismic vulnerabilities.

Administratively managed by the Dhaka North City Corporation (DNCC), Mirpur is one of the most densely populated and rapidly urbanizing regions within the capital. The area is characterized by unplanned urban growth, narrow roads, and a high density of residential and commercial structures, many of which are not built to seismic safety standards (Nowsheen et al., 2021). Geographically, the study area lies between 23°49'20.46'' N and 90°21'55.50'' E and falls under DNCC Zones 2 and 4. Among the selected wards, Wards 6, 7, and 8 belong to Zone 2, while Wards 9, 10, 11, and 12 are part of Zone 4. The study considered all existing open spaces in these wards, regardless of their type, function, or ownership status. A total of 81 open spaces (Figure 1) were identified using freely available satellite imagery from Google Earth (2022-23), that were subsequently verified through ground truthing. These spaces were preliminarily screened as potential emergency shelter sites to be used in the aftermath of a disaster. Standard suitability parameters were then applied to these sites, resulting in a comprehensive evaluation of their potential to serve as temporary emergency shelters.

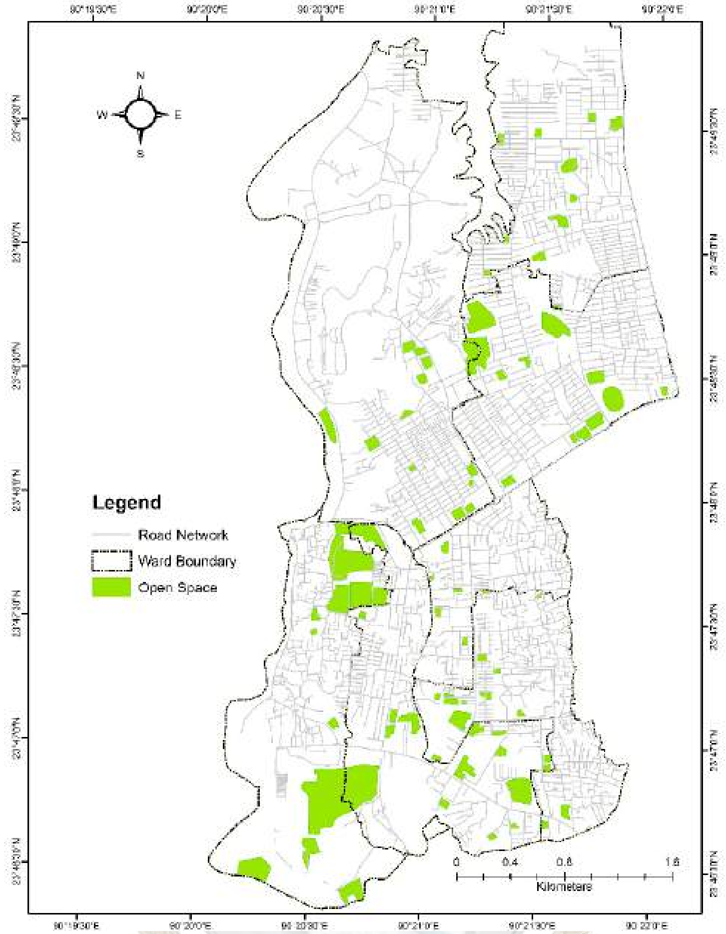

Figure 1. Map showing the distribution of the 81 open spaces in the study area [Sources: Google Earth imagery (2021–2022; digitized by author), Bangladesh Comprehensive Disaster Management Program (CDMP), 2009; CRS: EPSG:4326 (WGS84) and EPSG:32646 (UTM Zone 46N)]

3. Methodology and Methods

This study followed a GIS-based MCDM approach to evaluate the suitability of open spaces for establishing temporary emergency shelters in a post-earthquake scenario. Suitability of open spaces has been conceptualized as a function of three core dimensions: the capacity of a space to accommodate displaced populations, the availability of essential services, and the accessibility of the space within a disrupted urban context. Accordingly, the methodological framework incorporates three interrelated measures: capacity measurement, accessibility analysis, and quality evaluation. Capacity and accessibility analysis has been predominantly performed using GIS whereas, quality evaluation was primarily conducted through field survey and secondary data exploration. Finally, the AHP was adopted to generate a comprehensive suitability index for potential emergency sheltering sites.

3.1. Capacity Measurement

Capacity measurement evaluates the relative ability of an open space to serve displaced populations in the immediate aftermath of an earthquake. The parameter has been defined on the basis of two quantitative indicators, Capacitated Accessibility and Facilitation Efficiency. Capacitated Accessibility Value is defined as the ratio of the population that can potentially be served at a given open space (service) to the shelter-seeking population in the immediate surroundings (demand) of that space, as shown in equation (1), where CAV is Capacitated Accessibility Value, P_S is Population Potentially Facilitated (Service), and P_D is Shelter-Seeking Population in Immediate Area (Demand).

$$CAV = {P_S}/{P_D} \quad (1)$$

Again, potential utilization of a particular sheltering space's absolute or entire capacity also influences its suitability to be used for emergency sheltering purposes. Considering this, facilitation efficiency measures relative service provision (supply) by individual open spaces in relation to its actual sheltering capacity in view of potential network impedance and surrounding population distribution. Facilitation Efficiency, thus, represents the ratio of the population that can be served at a candidate open space (service) to the space's actual sheltering capacity (capacity) as shown in Equation (2), where FEV is Facilitation Efficiency Value, P_S is Population Potentially Facilitated (Service), and C is Actual Facilitation Capacity of the Space (Capacity).

$$FEV = {P_S}/{C} \quad (2)$$

Data inputs for these calculations include site or space specific sheltering need (Demand), sheltering service (supply), and actual capacity of a space to accommodate sheltering.

3.1.1. Sheltering Need (Demand) Calculation

This study adopts the deterministic magnitude (Mw) 7.5 design-earthquake scenario used by the CDMP Dhaka Earthquake Risk Assessment (2009). We rely on the building-damage outputs provided by CDMP, which report counts of buildings by damage state for each ward based on a HAZUS-compatible vulnerability approach. For consistency with our demand model, we aggregate the building damage states into two groups: Extensively Damaged (ED) ≈ *extensive* + *complete*; and Partially Damaged (PD) ≈ *slight* + *moderate*. Casualty estimates from CDMP are used as Cn in Eq. (3) to avoid double counting. Ward-level population totals [Bangladesh Bureau of Statistics (BBS), 2022; projected] are disaggregated evenly to buildings (equal weights) due to the absence of building-level occupancy data.

Following FEMA's HAZUS methodology, a modified two-step approach was applied to estimate sheltering demand (FEMA, 2003). First, the number of shelter-seeking individuals was calculated at the administrative (Ward) level. Second, this demand was spatially disaggregated to individual buildings to assign specific weights to each demand point. Under the Mw 7.5 scenario, all residents in extensively damaged buildings were assumed to require relocation. Additionally, extended disruptions to lifeline services, such as water supply and electricity, could force even those in moderately or slightly damaged, or even undamaged buildings to seek temporary shelter. For example, major pipeline damage following an earthquake could disrupt water supply for up to 80% of urban users (SYNER-G Project, 2013). Based on this rationale, 80% of residents in partially damaged buildings were assumed to require shelter. The total potentially displaced population at the Ward level is given by:

$$TDP_n = \sum ED_{Pop} + 0.8 \sum PD_{Pop} - \sum C_n \quad (3)$$

Where, TDP_n is the total number of potentially displaced population in ward n, ED_{Pop} is the population in extensively damaged buildings, PD_{Pop} is the population in partially damaged buildings, and C_n is the number of casualties in ward n. To reflect uncertainty in translating building damage into displacement, we tested three interpretations of the CDMP damage data: Low - only residents in ED buildings are displaced; Medium (baseline) - residents in ED + PD buildings are displaced, with the 0.8 factor applied to PD as in Eq. (3); and High - all residents of damaged buildings (ED + PD) are displaced, representing a conservative assumption of widespread lifeline disruption and safety concerns. These scenarios provide a plausible range of post-event displacement for coverage analysis. After displacement demand was defined, the number of shelter-seeking populations within the 700 meters service area of each candidate open space was calculated to represent immediate sheltering demand. The 700 meters threshold was selected in consultation with local experts, reflecting the maximum distance distressed populations are likely to walk in the immediate aftermath of an earthquake to reach safe shelter while minimizing exposure to aftershocks.

3.1.2. Sheltering Capacity measurement

To determine individual space's absolute sheltering capacity, it is essential to consider the minimum required living area per displaced person. According to the Sphere Handbook (2011), the recommended minimum covered floor area per person in emergency shelter situations is 3.5 square meters. However, in the immediate aftermath of a catastrophic event, providing less than the standard 3.5 square meters per person may be acceptable, particularly in high-density urban contexts, to accommodate the largest number of people while still ensuring life-saving protection (Sphere Project, 2011). Given the high population density and space limitations in Dhaka City, this study adopts a more pragmatic standard, 1.7 square meters (approximately 18 square feet) of living space per person, as the minimum requirement for emergency shelter. Using this benchmark, the absolute sheltering capacity of each open space has been calculated accordingly.

3.1.3. Sheltering Service (Supply) Calculation

In determining sheltering-service (supply) by individual open spaces, the number of distressed populations potentially facilitated at each open space has been computed. The principles of location-allocation analysis of ArcGIS's Network Analyst extension have been utilized in this regard. The analysis provides estimation on the maximum coverage of each sheltering space taking into consideration absolute sheltering capacity of individual sites, network impedance and distribution of shelter-seeking population in immediate areas.

3.2. Accessibility Measurement

In this study, accessibility to a particular open space has been evaluated based on 3 parameters – Access Road condition, Distance from major roads or primary access routes and Road blockage potential in nearby areas to each open space.

3.2.1. Access Road Condition

Shelters should be accessible by convenient routes so that earthquake victims can enter, exit and receive relief services quickly (Soltani et al., 2015). Areas accessible with sufficient number of well-spaced primary/secondary roads ensure ease of access by vulnerable population as well as shelter supply vehicles during emergency situations. On the contrary, areas accessible only by local level narrow tertiary roads may not be fairly suitable for emergency sheltering purposes as it hampers or impedes convenient access for people and vehicles. Based on this assumption, appropriate preference scores have been assigned to individual sheltering spaces to reflect their suitability in consideration of ease of access. For example, open spaces accessible only via single tertiary or local level road were considered less suitable and assigned a suitability score of 0.3 (in a scale of 1) whereas spaces accessed by multiple primary/secondary roads were deemed highly preferable and given the highest suitability score of 1.

3.2.2. Distance from Major (Primary) Roads

Sheltering areas should be proximal to major roads (primary roads) to ensure the immediate and uninterrupted delivery of essential logistics and services required for the functioning of temporary shelters (Unal & Uslu, 2016). Sites that are located farther from primary routes may face delays in receiving critical services such as emergency healthcare, food supply, and rescue support, thereby limiting their usability as effective sheltering spaces, especially during the critical early stages of disaster response. In this study, relative suitability scoring for each open space was assigned based on its distance from major roads: sites located more than 1000 meters (1 km) away were considered comparatively less preferable and scored 0.3; those situated between 300 and 1000 meters received a moderate score of 0.7; and sites within 300 meters were deemed highly preferable, receiving the highest suitability score of 1.

3.2.3. Road Blockage Potential in Close Proximity

The functionality of an emergency shelter significantly depends on unimpeded access via surrounding roads. In the aftermath of a major earthquake, road networks can experience substantial disruption due to damaged infrastructure, including collapsed buildings and bridges. Debris from multistoried buildings may occupy portions of the road, narrowing or completely blocking access and hindering emergency response operations (Duan et al., 2016). To assess this risk, the study evaluates the road blockage potential in the vicinity of each candidate open space using a probabilistic approach based on two key assumptions: 1) All multistoried buildings within the study area are considered vulnerable to collapse in a high-magnitude earthquake scenario and 2) A collapsed building is assumed to affect only the nearest adjacent road segment. Using GIS-based topological analysis, the nearest road segment for each multistoried building was identified. The ratio W/H was explicitly defined as the adjacent road carriageway width (W) divided by the building height (H), both expressed in meters and treated as a dimensionless index. Building height was estimated based on the number of floors multiplied by an average storey height of 3.0 m, following standard urban design assumptions for Dhaka. Road carriageway width was extracted from the centerline of the road network dataset using buffered right-of-way polygons and verified through visual interpretation of satellite imagery. All spatial distance and area calculations were conducted in the Bangladesh Transverse Mercator (BTM) projection (EPSG: 3106) to ensure metric consistency.

The Road Blockage Index (RBI), quantifies the likelihood of a building obstructing nearby roads and was calculated using this W/H ratio. Following the criteria developed by Mansouri et al. (2008), buildings were classified into four blockage categories, as shown in Table 1, where lower W/H values indicate higher blockage potential.

Table 1. RBI (Road Blockage Index) of Buildings based on Building Height (H)-Adjacent Road width (W) ratio[1]

Criteria	RBI
$W/H<0.5$	4
$0.5\leq W/H<1$	3
$1\leq W/H\leq 2$	2
$W/H> 2$	1

[1](Source: Mansouri et al., 2008)

Each building was assigned an RBI value based on this classification. For every open space, the nearby road blockage potential was then calculated as the proportion of high-blockage potential buildings (those with RBI ≥ 3) to the total number of buildings within a 700-meter service area. The following equation (4) was used to compute the Road Blockage Potential Value for each open space:

$$\text{Road Blockage Potential Value of individual open space} = \text{No. of Buildings with High RBI (RBI} \geq 3) / \text{Total no. of buildings within 700 meters service area} \quad (4)$$

The resultant value from equation (4) reflects the likelihood of road obstruction near a particular open space, which directly affects its accessibility and functional suitability for emergency sheltering. A higher value indicates a greater probability of nearby roads being blocked or narrowed, which could significantly hinder emergency access and logistical support. Open spaces were therefore assigned suitability scores inversely proportional to this potential. Spaces with higher road blockage potential were considered less suitable and were assigned lower suitability scores.

3.3. Qualitative Suitability Measurement

The quality evaluation of individual open spaces, specifically in terms of basic service availability, was conducted in three major steps: (1) identifying appropriate quality evaluation criteria and corresponding indicators (2) collecting data on the indicators for the identified open spaces and (3) assigning quantitative suitability scores to the data through expert consultation. Quality assessment of each open space, in terms of use in emergency sheltering purpose, was conducted through a structured assessment of three overarching criteria: Land use suitability, Hazard and environmental risk exposure, and Critical infrastructure and basic services access.

Land use suitability factors focus primarily on the type and ownership of each open space. Publicly owned spaces such as city parks and playgrounds were considered more suitable due to ease of access and minimal legal barriers to use for emergency sheltering. In contrast, lands with private ownership or those used for dumping or agriculture were considered less feasible for emergency shelter use, as they present complications in rapid mobilization and pose potential environmental or health hazards. Hazard and environmental risk exposure, on the other hand, address the likelihood of secondary hazards and pollution risks. Open spaces vulnerable to flooding, fire hazards, or the collapse of adjacent tall buildings are deemed less suitable for emergency sheltering. Additionally, the presence of pollution, whether from nearby industrial pollution sources, air contaminants, or water pollution, further diminishes a site's potential for use as an emergency shelter. Spaces free from these risks are preferred for their safety and health viability. Besides, Critical infrastructure and basic services availability is another crucial determinant of an open space's quality as a sheltering site. Considered indicators in this category include the availability of electricity, water supply, and proximity to medical services. Lack of these services significantly undermines a site's readiness to support displaced populations. Hence, sites equipped with reliable electrical infrastructure or alternative energy sources, clean water access (such as tap water, tube wells, or nearby natural water bodies) and nearby medical facilities are considered highly suitable to facilitate emergency shelters in post disaster situations (Soltani et al., 2014; Anhorn & Khazai, 2015).

A combination of primary and secondary data collection methods was employed to ensure a comprehensive assessment of the identified indicators. Field surveys and spatial analysis were complemented by policy documents, urban planning records, and hazard risk maps collected from local administration. Additionally, scoring of the data was guided by the insights of 15 domain experts, who participated in interviews and provided judgments through pairwise comparisons. The specific criteria, indicators and corresponding scores used for the qualitative suitability evaluation of open spaces are summarized in Table 2.

Table 2. Qualitative Suitability Evaluation Criteria, Indicators and Suitability Scores

Criteria	Indicator	Type / Condition	Suitability Score (in a scale of 1)
Land Use Suitability	Open Space Type	Park, Playground	1.0
		Educational Facility Grounds (School/College/University)	0.9
		Religious Facility Grounds (e.g., Mosque/Temple Courtyards)	0.8
		Institutional Premises	0.7
		Active Agricultural or Cultivated Land	0.5
		Dumping Site/hazardous land	0.2
	Ownership of Space	Public (Government, City Corporation)	1.0
		Community-Owned	0.8
		Individually Owned	0.6
		Private Company-Owned	0.5
Hazard and Environmental Risk Exposure	**Secondary Hazard Potential**	No Potential Hazard	1.0
		Water Logging / Flooding	0.7
		Fire / Chemical Explosion	0.5
		Tall Building Collapse	0.4
		Water Logging & Fire/Chemical Explosion	0.3
		Water Logging & Tall Building Collapse	0.2
		Fire & Tall Building Collapse	0.2
		All Three Hazards	0.1
	Pollution Potential	No Pollution	1.0
		Air Pollution	0.8
		Water Pollution	0.6
		Industrial Waste Pollution	0.4
		Air & Water Pollution	0.5
		Air & Industrial Waste Pollution	0.3
		Water & Industrial Waste Pollution	0.2
		All Three Pollution Types	0.1
Critical infrastructure and basic services access	Power/Electricity Supply	Distribution Line & Generator/Alternative Power Source	1.0
		Alternative Power Source / Generator	0.7
		Nearby Distribution Line	0.6
		No Electricity Supply	0.1
	Water Availability	Tap Water, Tubewell & Natural Source	1.0
		Any Two Among Tap, Tubewell, Natural Source	0.8
		Tap Water Only	0.6
		Natural Source (e.g., Pond, River)	0.5
		Tube Well Only (Deep or Shallow)	0.4
		No Water Supply	0.1
	Medical Service Availability	On-Site Medical Service	1.0
		Within 500 meters	0.8
		Within 500 to 1000 meters	0.7
		More than 1000 meters	0.4
		Unknown Distance	0.1

Note: All scores are on a 0–1 scale (1 = most suitable). Distance and threshold bands (e.g., 500 m, 1000 m) are aligned with the 700 m service radius used in the accessibility analysis. Thresholds are based on recommended emergency walking distances in post-disaster shelter studies. All units are standardized to meters (m).

3.4. Comprehensive Open space Suitability Index (COSI) Calculation using Analytic Hierarchy Process (AHP)

In this study, the AHP serves as the core technique of the MCDM framework, enabling systematic weighting and integration of multiple indicators for spatial decision-making. To derive a final composite value for the suitability of each open space, the three major criteria, quality, capacity, and accessibility, were integrated using the AHP. This is a widely adopted multicriteria decision-making approach. The process involves establishing a hierarchical structure of all relevant indicators, followed by expert-driven pairwise comparisons to determine the relative importance of each criterion (Saaty 1980; Vaidya & Kumar 2006).

Expert judgement played a central role in the AHP process. After data collection, a group of domain experts of about 15 people provided input through structured pairwise comparisons, following Saaty's 9-point scale of relative importance (Saaty, 1980). These comparisons helped construct a comparison matrix, which was then normalized. The average of each row yielded the local weights for each indicator. The global weight for each sub-criterion was calculated by multiplying its local weight with the weight of the corresponding main criterion. A consistency check was performed to ensure the reliability of expert assessments, with all consistency ratios falling below the acceptable threshold of 10%. The weights of the suitability criteria and sub-criteria are mentioned in Table 3.

3.4.1. AHP weighting and consistency

To conduct the AHP process, four AHP matrices were constructed: a 3×3 matrix for the main criteria (Quality, Capacity, Accessibility) and sub-criteria matrices for Quality (7×7), Capacity (2×2), and Accessibility (3×3). Expert judgements (Saaty 1–9 scale) were aggregated to local weights; global weights were obtained by multiplying local weights by the corresponding main-criterion weight. We report pairwise matrices, principal eigenvalues (λ_{max}), Consistency Index (CI), and Consistency Ratio (CR), with Random Index (RI) values from Saaty (n = 3→0.58; 4→0.90; 7→1.32; etc.). The standard AHP Formulas were applied: $CI=(\lambda_{max}-n)/(n-1)$, $CR=CI/RI$. For transparency and reproducibility, weights are reported to three decimals and sum to 1.000 (main level) and 1.000 within each criterion at the sub-criterion level. Complete matrices and weights appear in Supplementary Tables S1–S4.

Table 3. Weights of open space suitability criteria and indicators

Aggregated criteria weight	Main Criteria		Sub-Criteria/ Indicators	Weights
0.194	Quality Measurement	Land Use Suitability	Type of the open space	0.051
			Ownership	0.020
		Hazard and Environmental Risk Exposure	Secondary hazard	0.031
			Pollution	0.010
		Critical infrastructure and basic services access	Water availability	0.031
			Medical service	0.041
			Power/Electricity supply	0.010
0.561	Capacity Measurement		Capacitated accessibility	0.418
			Facilitation efficiency	0.143
0.245	Accessibility Measurement		Access road type	0.112
			Proximal road blockage potential	0.092
			Distance from major road	0.041
Total				1.000

[*Note:* All values represent global weights, normalized to sum to 1.000. Global weights were obtained by multiplying each sub-criterion's local weight by the corresponding main-criterion weight derived from the AHP pairwise comparison matrices.]

Table 3 summarizes the aggregated weights of criteria and sub-criteria used in computing the COSI. These weights reflect the relative importance of each indicator in evaluating the overall suitability of open spaces for emergency sheltering, with higher-weighted indicators exerting a greater influence on the final COSI value. These global weights were used to compute a composite score for each open space by calculating the weighted sum of the scores it received across all indicators. This resulted in a final index, the COSI, for each site. The COSI values served as the basis for ranking the identified open spaces in the study area, offering a rational and systematic tool for prioritizing emergency shelter locations. The overall methodological framework illustrating the sequential steps and integrated approach in determining the COSI value of individual open spaces is illustrated in Figure 2.

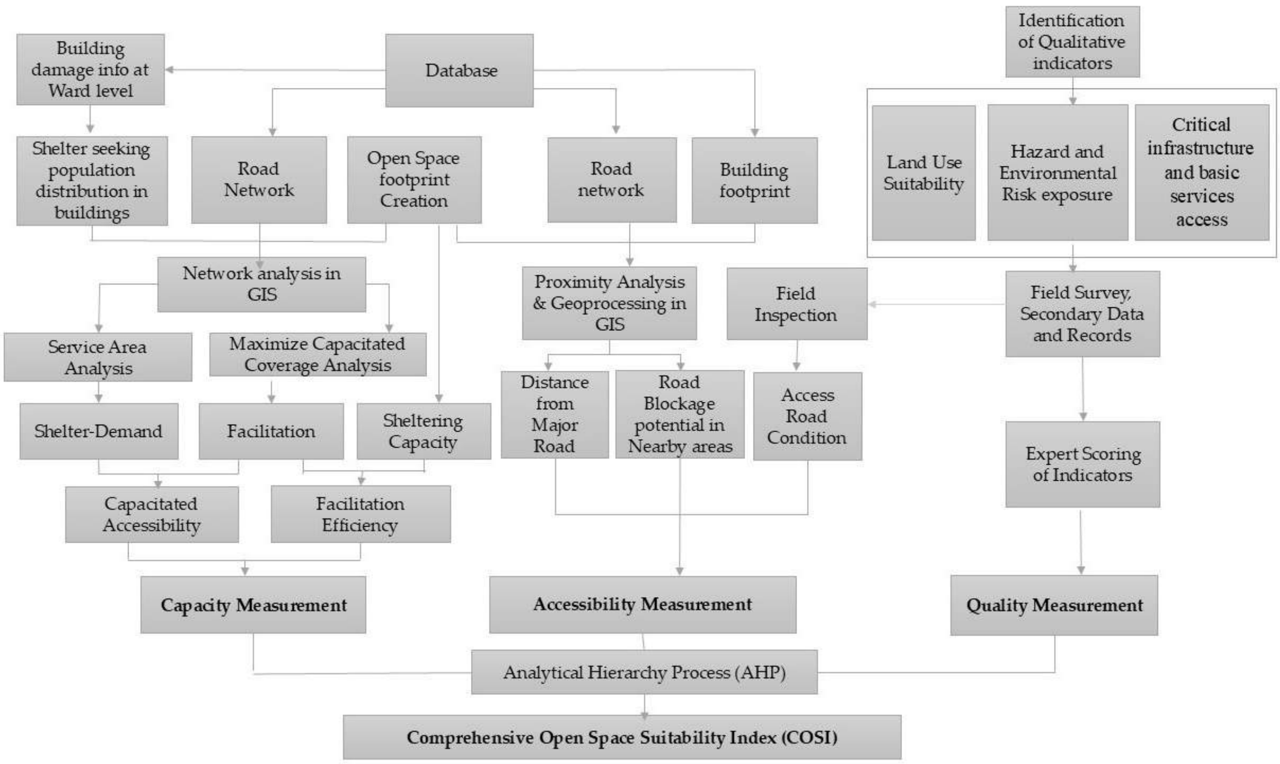

Figure 2. Methodological Framework for COSI development

3.5. Sensitivity Analysis

To test the robustness of the AHP-derived results, sensitivity analysis tests have been conducted in two steps. First, the main-criteria weights have been verified (Quality, Capacity, Accessibility) by ±10% and ±20% of their baseline values while proportionally adjusting the remaining criteria. Then the COSI values were recalculated and suitability class distributions and top-10 rankings for the open spaces were reexamined. Second, the classification outcomes were compared using two approaches: the equal-interval method applied in the baseline analysis and Jenks natural breaks optimization. The objective was to determine whether modest variations in weights or classification schemes substantially altered the suitability categories or rankings of priority sites.

In addition to varying weights and classification schemes, we also tested the robustness of shelter suitability outcomes against different assumptions of capacity and service radius. For capacity, we compared the Sphere minimum standard of 1.7 square meters per person with an expanded requirement of 3.5 square meters per person, recalculating effective shelter capacities accordingly. For service radius, we examined thresholds of 500 meters, 700 meters (baseline), and 1000 meters to capture differences in walkable access. Coverage and suitability scores were recomputed for each combination, allowing us to evaluate how sensitive accessibility and site rankings were to these assumptions.

3.6. Expert Validation:

Finally, to complement the sensitivity tests and ensure that modeled results reflect practical realities, an expert validation was performed. Preliminary site suitability maps and rankings were shared with a panel of three domain experts, including an urban planner, a structural engineer, and a disaster management practitioner. Experts were asked to review whether the identified top sites were consistent with their experience of local emergency response capacity, accessibility, and safety. Their feedback confirmed that the highest-ranked sites were generally aligned with expectations, particularly in terms of accessibility and open-space availability, while also highlighting the need to consider contextual factors such as land-use conflicts and community familiarity in future work.

4. Results

4.1. Capacity Indicators

The capacity measurement segment of the research has generated information on relative serviceability of the candidate open spaces in the study area based on two quantitative parameters- capacitated accessibility and facilitation efficiency.

Capacitated accessibility indicates how well an open space can meet local demand, with higher values signifying better facilitation. The analysis revealed that a majority of the candidate sites (70%) scored low (<0.5) in this indicator, suggesting that in many cases, local shelter demand exceeds available site capacities. These low scores also highlight a high potential for overcrowding during emergencies in the majority of the open spaces (Figure 3), posing a critical risk for effective disaster response.

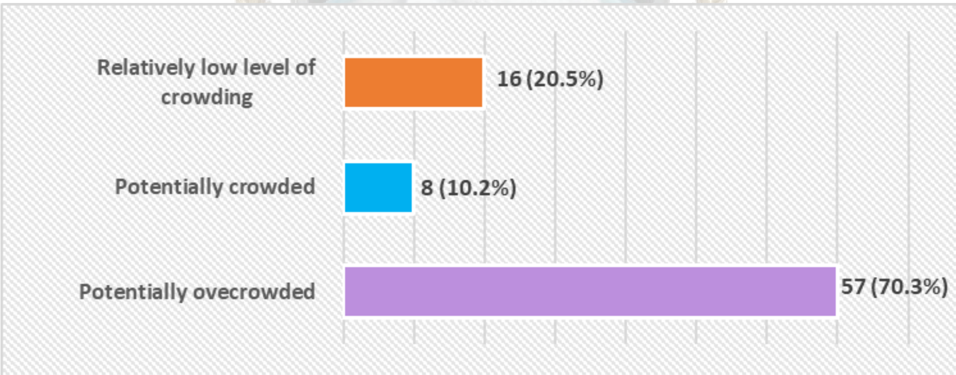

Figure 3: Crowd potential of open spaces under emergency conditions (Chart shows both counts and percentages). Category thresholds are defined by capacitated accessibility value (CAV): CAV ≥ 0.65 = Relatively low crowding; 0.50 ≤ CAV < 0.65 = Potentially crowded; CAV < 0.50 = Potentially overcrowded.

Facilitation efficiency, on the other hand, measures the utilization of a site's actual capacity. Sites with higher values indicate more effective use of space. An area with considerably large capacity and potentially lower demand in immediate surroundings may have higher capacitated accessibility value signifying adequate supply in meeting the immediate demand. But it may not provide maximized service with respect to its actual capacity owing to different reasons related to network impedances and population distribution dynamics such as - locating at a farther distance from areas with high demand, having lower population density in immediate surroundings etc. The study found that 73% of open spaces exhibited efficiency values greater than 0.65, and 55 sites reached the maximum efficiency score of 1.0 (Figure 4). This suggests that despite capacity-demand mismatches, many sites are optimally located in areas with consistent population distribution and good network connectivity. However, spaces with lower efficiency may face access-related limitations or localized population imbalances.

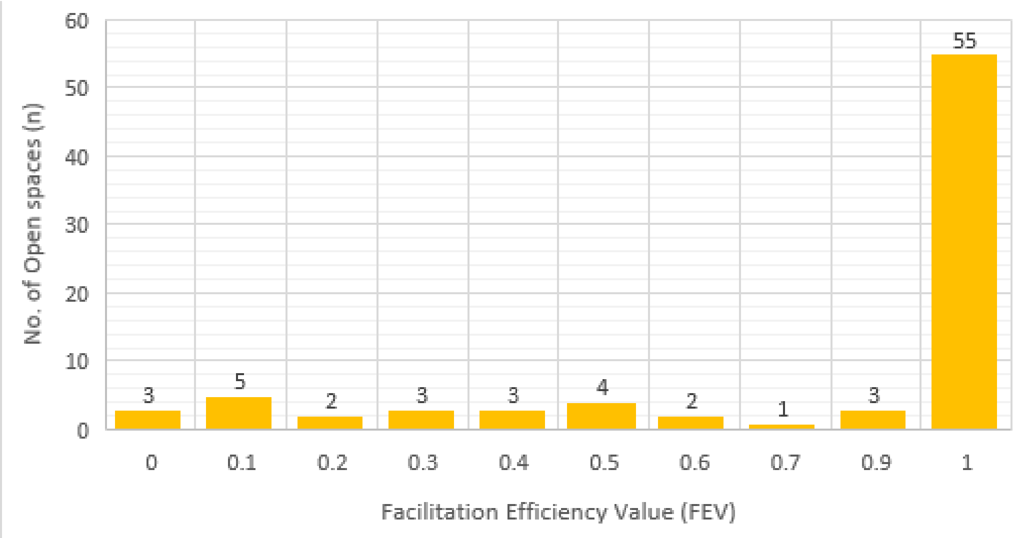

Figure 4. Histogram showing the number of open spaces (n) by Facilitation Efficiency Value (FEV). Bin width = 0.1

Aggregating the two indicators produced a site-specific capacity score. The results indicate that 60.5% of the open spaces are less suitable, 21% highly suitable, and 18.5% moderately suitable from a capacity standpoint. High proportion of open spaces with lower capacity measurement value may predominantly be attributed to lower service-demand ratio for most of the open spaces. This is an indication towards an inadequate supply of sheltering facilities compared to high population density in the study area. Analysis of the capacity parameters also suggests that, around 42% of the shelter seeking population in the entire study area will potentially be accommodated in case all the considered open spaces are turned into temporary shelter establishment sites in the immediate aftermath of earthquake (Table 4). It implies an inadequate supply of sheltering facilities compared to immediate sheltering needs in the study area.

Table 4. Emergency Sheltering Coverage Summary for the study area

Metric	Value	Percentage
Total shelter-seeking population	576,678	—
Population potentially served	242,381	42.03%
Buildings served	12,584 out of 25,916	48.56%

4.2. Accessibility Indicators

Accessibility of individual open spaces has been assessed based on three key indicators: access road condition, distance from major (primary) roads, and road blockage probability in the vicinity of each open space.

Field surveys and secondary data reveal that 68% of the open spaces are accessible only via a single narrow tertiary road, which makes them less suitable for facilitating emergency logistics and evacuation support. In terms of proximity to major roads, 55.6% of the open spaces are located within 300 meters, providing a logistical advantage for the rapid deployment of emergency services. Meanwhile, 34.6% lie between 300 and 1000 meters, and 9.9% are situated more than 1000 meters away, making them less favorable for prompt emergency response. The third accessibility indicator, proximal road blockage potential, ranges from 0.01 to 0.29, indicating a moderate likelihood of road obstruction across the study area. This relatively low blockage probability can be attributed to the limited number of multistoried buildings in the area, since the RBI is largely influenced by building height.

When combining all three indicators, the comprehensive accessibility scores for most open spaces range between 0.41 and 0.65. Suitability categories (e.g., low, moderate, fair, high) were defined by experts based on the aggregated indicator values (see Table 5). Approximately 67.9% of the open spaces fell into the moderately suitable category, while the remainder are classified as either low or fairly suitable in terms of accessibility (Figure 5). The findings suggest that targeted infrastructure improvements—such as widening access roads and mitigating blockage risks could significantly enhance the usability of these spaces during emergencies.

Table 5. Suitability categories based on aggregated criteria values for accessibility

Value Range	Suitability status
0.00 - 0.19	Unsuitable
0.20 - 0.40	Low suitability
0.41 - 0.65	Moderately suitable
0.66 - 0.80	Fairly suitable
0.81 - 1.00	Highly suitable

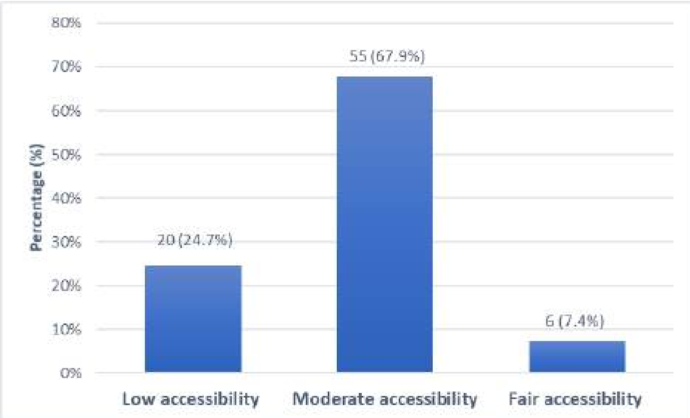

Figure 5. Distribution of open spaces by accessibility category.
Bars show the number and percentage of open spaces (n, %) in each category (n=81)

4.3. Quality Indicators

The quality assessment component of the study evaluated the overall fitness of the open spaces to function effectively as emergency shelter sites, using a range of qualitative indicators. These indicators provide critical insights for emergency responders in assessing site readiness and potential constraints. Over 70% of the open spaces are situated on government-owned land, which facilitates rapid acquisition and deployment in crisis situations. However, approximately 38% of the sites are exposed to hazards associated with the potential collapse of adjacent tall building blocks, indicating a heightened risk of on-site obstruction. A particularly notable finding concerns the availability of essential services: 44% of the open spaces lack adequate water supply, which could severely limit their functionality as emergency shelters. This underscores the need for contingency planning to ensure swift provisioning of water resources. On a more positive note, the majority of sites are located within 1 kilometer of medical facilities, significantly enhancing their value for emergency shelter use. When all seven qualitative indicators are aggregated, the resulting quality scores show that 58% of the open spaces fall into the moderately suitable category (score range: 0.41–0.65). About 30% are deemed highly suitable, with scores exceeding 0.66, while the remaining 16.05% are categorized as less suitable for immediate sheltering purposes.

4.4. Comprehensive Opens Space Suitability Index (COSI) Score

Based on the aggregated scores from all three major suitability criteria, quality, capacity, and accessibility, the COSI value was calculated for each open space using the Analytical Hierarchy Process. To facilitate interpretation and prioritization, the resulting COSI values were classified into five distinct categories:

- Highly Suitable (COSI > 0.80)
- Fairly Suitable (0.66 ≤ COSI ≤ 0.80)
- Moderately Suitable (0.41 ≤ COSI < 0.66)
- Low Suitability (0.20 ≤ COSI < 0.41)
- Unsuitable (COSI < 0.20)

The COSI-based Suitability Assessment for Emergency-sheltering (SAFE) reveals that none of the evaluated open spaces fall within the highly suitable category. However, a notable 18.5% of sites demonstrate fair suitability, making them promising candidates for emergency shelter establishment. The majority of open spaces (56.8%) fall into the moderately suitable range, indicating potential usability with limited intervention. The remaining 23.5% of open spaces, falling within the low suitability and unsuitable categories, are the least favorable for emergency shelter use without substantial improvements (Table 6). Figure 6 shows the COSI value distribution of the identified 81 open spaces.

Table 6. Comprehensive suitability status of the studied open spaces (n=81)

COSI value range	Number of open spaces	Percent	Suitability status
0.00 - 0.19	1	1.2%	Unsuitable
0.20 - 0 .40	19	23.5%	Low suitability
0.41 - 0 .65	46	56.8%	Moderately suitable
0.66 - 0.80	15	18.5%	Fairly suitable
0.81- 1.00	0	0	High suitability
Total	81	100	

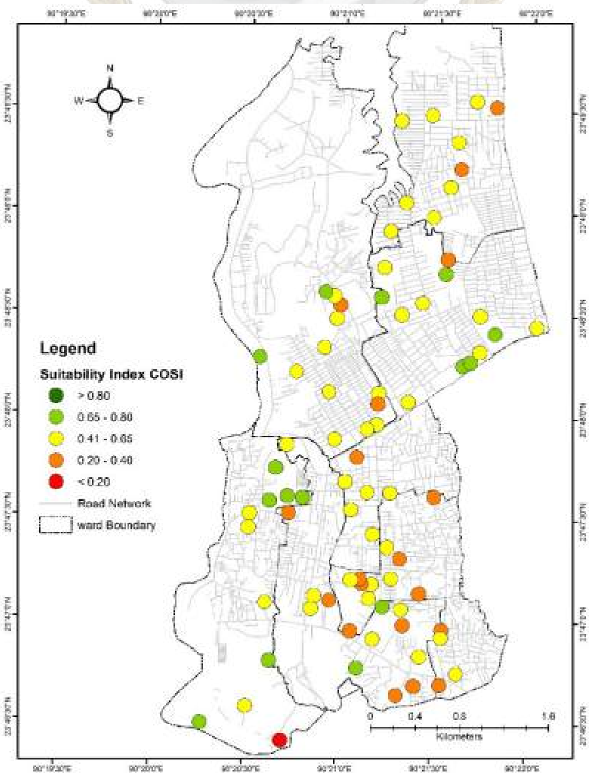

Figure 6. Map Showing COSI value distribution of the Open spaces [Source: CDMP (2009), Google Earth imagery (2021–2022; digitized by author); CRS: EPSG:4326 (WGS84) and EPSG:32646 (UTM Zone 46N)]

4.5. Ranking of the Open Spaces

To assist in emergency planning, all studied open spaces were ranked based on their COSI, which integrates quality, capacity, and accessibility scores. In instances of equal COSI values, sites with higher capacity scores, the most critical parameter, were prioritized. Table 7 lists the Top-10 open spaces most suitable for immediate post-earthquake sheltering in the study area. These sites consistently performed well across all criteria, particularly in capacity, indicating a higher potential to serve affected populations efficiently. In Table 7, the quality, capacity, and accessibility values represent the weighted contributions of each criterion, which together sum to the final COSI score for each site. All top-ranked sites fall into the 'Fairly Suitable' category and should be prioritized in shelter planning and resource allocation.

Table 7. Weighted contributions of quality, capacity, and accessibility to the Comprehensive Open Space Suitability Index (COSI) for the Top 10 ranked sites

Rank	Name of the Space/Place	Open Space ID	**Qualitative value**	**Capacity Value**	**Accessibility Value**	**COSI value**
1	Mirpur College Field	40	0.15	0.47	0.18	0.80
2	Mirpur Stadium	43	0.13	0.46	0.19	0.79
3	Golartek playground	33	0.14	0.50	0.13	0.77
4	BCIC staff quarter 2	47	0.09	0.52	0.14	0.75
5	Buddhijibi Shahid Minar Area 2	35	0.13	0.44	0.18	0.74
6	Kolyanpur housing	65	0.11	0.49	0.13	0.73
7	Mirpur govt primary school	41	0.14	0.43	0.15	0.72
8	TCC hostel	68	0.16	0.39	0.17	0.72
9	BCIC college	51	0.13	0.46	0.12	0.71
10	Buddhijibi Shahid Minar Area 1	12	0.13	0.40	0.18	0.71

4.6. Sensitivity Analysis Results

The sensitivity tests for AHP confirmed the stability of the framework. When main-criteria weights were varied by ±10–20%, fewer than 3% of sites shifted between suitability categories. Importantly, the Top-10 ranked sites remained unchanged in membership across all scenarios, with only minor positional changes observed in two cases. Similarly, reclassification using Jenks natural breaks produced nearly identical results to the equal-interval method, with one site moving between the "moderate" and "fair" categories. These findings suggest that the model is robust to reasonable variations in weight assignments and classification methods.

The capacity and radius sensitivity tests showed predictable but meaningful variations. Under the stricter 3.5 square meters per person assumption, overall effective coverage decreased by about 40–45% compared to the 1.7 square meters baseline, with several larger sites reaching capacity limits almost immediately. Changing the service radius also influenced coverage outcomes. At 500 meters, total coverage fell by approximately 25% compared to the 700 meters baseline. Expanding radius to 1000 meters increased coverage by roughly 20%, though with reduced spatial precision in linking demand to nearby populations. Even though the absolute values changed, the ranking of the top sites stayed mostly the same, with 8 of the original Top-10 sites appearing across all scenarios. This shows that the framework's site prioritization is robust to these variations.

Population displacement assumptions also influenced demand estimates. Under the low scenario (ED only), overall displaced population was smaller and few capacity shortfalls occurred. The medium scenario (ED + PD, baseline) produced moderate demand consistent with Eq. (3). The high scenario (all damaged buildings) substantially increased demand, exceeding capacity at several sites and reducing effective coverage by approximately 10–15% compared to baseline. Despite these differences, site prioritization remained stable, with 7–9 of the original Top-10 sites consistently retained. Overall, these combined sensitivity analyses demonstrate that while absolute suitability and coverage metrics fluctuate under different assumptions, the relative ranking and spatial prioritization of sites remain highly consistent, confirming the robustness and reliability of the proposed framework for practical emergency shelter planning.

4.7. Expert validation results

Expert reviewers confirmed that the model's top-ranked sites were broadly consistent with locations they would expect to perform well during an emergency. The experts agreed that accessibility and capacity considerations were appropriately captured, though they noted that social familiarity and informal community practices could further influence actual site usage. This feedback supports the plausibility of the framework outputs and highlights avenues for incorporating community-level knowledge in future applications.

5. Discussion:

This study presents a systematic assessment of open space suitability for emergency sheltering in the Mirpur area of Dhaka, employing a multi-criteria approach rooted in the AHP. The findings highlight spatial disparities in quality, capacity, and accessibility across the studied sites, offering a deeper understanding of shelter readiness in a highly vulnerable urban setting. The most critical insight of the analysis is the significant mismatch between shelter demand and the available capacity of open spaces. Although certain sites demonstrated high facilitation efficiency, capacitated accessibility scores remained low for the majority, indicating that many areas would be unable to accommodate their local shelter-seeking populations in the event of a disaster. With only about 42% of the population potentially served under current conditions, this gap underscores the urgent need for alternative shelter strategies, especially in areas with little to no suitable options.

Accessibility constraints also emerged as a substantial barrier to effective shelter deployment. A large portion of the open spaces (68%) are accessible only via narrow tertiary roads, raising concerns about emergency vehicle access and rapid supply delivery. While road blockage potential remains moderate due to the relatively low number of high-RBI buildings, spatial variation suggests that certain areas are still at risk of post-disaster isolation. However, we were not able to implement a full RBI-informed disrupted-network scenario, which would require segment-level fragility data and dynamic re-routing capacity that were beyond the scope of this study. As a result, the accessibility findings presented here reflect baseline network conditions. Future research should build on this framework by incorporating probabilistic blockage models and dynamic network simulations to more accurately capture accessibility under disrupted conditions.

Quality assessment revealed further challenges. Although government ownership of over 70% of the spaces ensures administrative feasibility for rapid deployment, nearly 44% of sites lack sufficient water supply infrastructure, a critical deficiency during prolonged shelter stays. Additionally, exposure to relatively tall-building hazards near 38% of sites highlights the need for contextual hazard mitigation planning. While proximity to medical services was included as a quality indicator to reflect emergency care support, this indicator does not account for possible operational challenges that healthcare facilities themselves may face during severe disasters.

The computed COSI provided a holistic lens through which each site's relative preparedness could be evaluated. While none of the spaces qualified as highly suitable, 18.5% were identified as fairly suitable, and over half fell into the moderately suitable range. These findings suggest that with targeted improvements, particularly in service provision and access, many open spaces could be optimized for shelter use. Importantly, the study produced a ranked list of the most suitable open spaces, with top-ranked sites such as Mirpur College Field, Mirpur Stadium, and Golartek Playground, demonstrating balanced strengths across all three suitability dimensions. These sites should be prioritized for emergency response logistics, including the prepositioning of supplies, medical services, and evacuation routes.

From a planning perspective, the research provides a practical blueprint for tiered sheltering strategies. Highly and fairly suitable sites can be designated as primary shelter locations, while moderately suitable ones should be targeted for infrastructural upgrades. Less suitable sites, on the other hand, should be deprioritized unless no other options are available; even then, contingency improvements, such as access widening or temporary water provisioning, must be made in alignment with site-specific deficiencies.

Areas containing no sufficiently suitable sites must be flagged as crisis hotspots, requiring alternate arrangements and community-based solutions, such as using school yards or community centers with temporary infrastructure. This spatial understanding of suitability can also inform evacuation planning, ensuring that the most accessible and serviceable locations are aligned with high-density or high-risk zones. In sum, this suitability framework offers a replicable and adaptable model for urban emergency shelter planning, particularly in rapidly urbanizing and disaster-prone contexts. By integrating expert judgments, field data, and GIS-based spatial analysis, the approach provides planners, policymakers, and emergency responders with actionable intelligence to optimize disaster readiness, reduce humanitarian risks, and ensure equitable access to life-saving infrastructure in the aftermath of major disruptions.

6. Conclusion:

This study presents a comprehensive framework (COSI-SAFE) for assessing the suitability of urban open spaces for temporary emergency sheltering using a multi-criteria decision-making approach. By integrating quality, capacity, and accessibility indicators through the AHP, the research identifies both priority sites for immediate shelter deployment and areas requiring significant improvement or alternative planning strategies. The findings are intended to support emergency planners and decision-makers by offering actionable insights into shelter site prioritization, evacuation planning, and prepositioning of logistical support. The suitability rankings and spatial distribution analysis serve as valuable tools for optimizing disaster response in the densely populated and infrastructure-constrained context of urban Dhaka. Beyond the immediate scope, this methodology has strong potential for replication and customization in other disaster-prone urban areas, particularly in the Global South where informal settlements and limited resources complicate emergency response. Future research may expand upon this model by integrating real-time hazard simulations, crowd dynamics, or community-based participatory inputs. Additionally, incorporating dynamic data such as mobility patterns, changing land use, or social vulnerability indices can further refine the decision-making framework and enhance resilience planning. Ultimately, this study contributes to the growing body of literature focused on spatial planning for disaster preparedness, offering a scalable, evidence-based tool to guide policymakers toward more inclusive, efficient, and context-sensitive shelter planning strategies.

Author Contributions: The first author was responsible for data collection, map preparation, analysis, and drafting the manuscript. The second author contributed to the research design, provided supervision throughout the study, and assisted in reviewing and revising the manuscript. Both authors read and approved the final version of the manuscript.

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Ethical Considerations: Field surveys conducted as part of this study were limited to non-personal observations of open spaces and basic service availability. No personally identifiable information (PII) or sensitive data were collected. All survey activities were performed with prior permission from relevant local authorities, and all findings are reported in aggregated form to ensure anonymity and privacy. The research adheres to ethical standards for field-based data collection in non-human subject studies.

Data and Code Availability: The datasets supporting this study are derived from publicly available sources (Such as Bangladesh Population Census data 2022). Earthquake damage and casualty data (CDMP, 2009) can be obtained upon request from the Ministry of Disaster Management and Relief, Bangladesh. The open space inventory was created by the authors through digitization of Google Earth imagery. Detailed data provenance is provided in Supplementary Table S5. AHP pairwise matrices, calculated weights, and geoprocessing workflows are included in the Supplementary Materials. Analysis scripts are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

7. References

1. Albris, K., Lauta, K. C., & Raju, E. (2020). Disaster knowledge gaps: Exploring the interface between science and policy for disaster risk reduction in Europe. *International Journal of Disaster Risk Science, 11*(1), 1–12. https://doi.org/10.1007/s13753-020-00250-5
2. Anhorn, J., & Khazai, B. (2015). Open space suitability analysis for emergency shelter after an earthquake. *Natural Hazards and Earth System Sciences, 15*(4), 789–803. https://doi.org/10.5194/nhess-15-789-2015
3. Apu, N., & Das, U. (2021). Tectonics and earthquake potential of Bangladesh: A review. *International Journal of Disaster Resilience in the Built Environment, 12*(3), 295–307.
4. Bakhshi Lomer, A. R., Rezaeian, M., Rezaei, H., Lorestani, A., Mijani, N., Mahdad, M., Raeisi, A., & Arsanjani, J. J. (2023). Optimizing emergency shelter selection in earthquakes using a risk-driven large group decision-making support system. *Sustainability, 15*(5), 4019. https://doi.org/10.3390/su15054019
5. Bangladesh Bureau of Statistics (BBS). (2022). *Population and Housing Census 2022: Preliminary report*. Statistics and Informatics Division, Ministry of Planning, Government of Bangladesh.
6. Cañete, R. M., Lisay, & Mahmud, M. N. S. (2025). Project DINGGIN: Empowering Communities through Risk-Based and Inclusive Cash Transfer in Disaster-Prone Areas in Bangladesh and Philippines. *International Journal of Disaster Risk Management*, *7*(1), 339-366.
7. Celik, E. (2024). Analyzing the shelter site selection criteria for disaster preparedness using best–worst method under interval type-2 fuzzy sets. *Sustainability*, *16*(5), 2127. https://doi.org/10.3390/su16052127
8. Chandler, P. J. (2007). *Environmental factors influencing the siting of temporary housing in Orleans Parish* (Master's thesis, Louisiana State University and Agricultural & Mechanical College).
9. Comprehensive Disaster Management Programme (CDMP). (2009). *Earthquake contingency plan for Dhaka City*. Ministry of Food and Disaster Management, Government of the People's Republic of Bangladesh.
10. Cvetković, V. M., Ronan, K., Shaw, R., Filipović, M., Mano, R., Gačić, J., & Jakovljević, V. (2019). Household earthquake preparedness in Serbia: A study of selected municipalities. Acta Geographica, 59(2), 28–42.
11. Cvetković, V., & Planić, J. (2022). Earthquake Risk Perception in Belgrade: Implications for Disaster Risk Management. International Journal of Disaster Risk Management, 4(1), 69–88.
12. Da Silva, J. (2007). Quality and standards in post-disaster shelter. *Structural Engineer*, *85*(14), 25.
13. Duan, M., Wu, D., Dong, B., & Zhang, L. (2016). Quantitatively measuring transportation network resilience under earthquake uncertainty and risks. *American Journal of Civil Engineering, 4*(4), 174–184. https://doi.org/10.11648/j.ajce.20160404.1
14. Economic and Social Commission for Asia and the Pacific (ESCAP). (2015). *Disasters without borders: Regional resilience for sustainable development* (Asia-Pacific Disaster Report 2015, ST/ESCAP/2730). United Nations Economic and Social Commission for Asia and the Pacific.

15. Federal Emergency Management Agency (FEMA). (2003). *HAZUS®–MH MR1 Technical Manual*. U.S. Department of Homeland Security.
16. Hossen, M. N., Nawaz, S., & Kabir, M. H. (2022). Flood research in Bangladesh and future direction: An insight from the last three decades. *International Journal of Disaster Risk Management*, *4*(1), 15–41
17. Islam, A. B. M., Ahmad, S. I., & Al-Hussaini, T. (2010). Effect of isolation on buildings in Dhaka. In *Proceedings of a Conference* (March, pp. 465–472).
18. Islam, F. (2023). Anticipated role of Bangladesh Police in disaster management based on the contribution of Bangladesh Police during the COVID-19 pandemic. *International Journal of Disaster Risk Management, 5*(2), 45–56.
19. Jiao, H., & Feng, S. (2024). Towards resilient cities: Optimizing shelter site selection and disaster prevention life circle construction using GIS and supply-demand considerations. *Sustainability, 16*(6), 2345. https://doi.org/10.3390/su16062345
20. Ma, Y., Liu, B., Zhang, K., & Yang, Y. (2022). Incorporating multi-criteria suitability evaluation into multi-objective location–allocation optimization comparison for earthquake emergency shelters. *Geomatics, Natural Hazards and Risk*, *13*(1), 2333-2355.
21. Ma, Y., Xu, W., Qin, L., & Zhao, X. (2019). Site selection models in natural disaster shelters: A review. *Sustainability, 11*(2), 399. https://doi.org/10.3390/su11020399
22. Manik, M. H. (2024). Demographic and socio-economic changes in Bangladesh: Evidence from the population census in 2022. *Formosa Journal of Sustainable Research, 3*, 29–38.
23. Mansouri, B., Nourjou, R., & Hosseini, K. A. (2008). Comprehensive GIS-based solution for road blockage due to seismic building collapse in Tehran. In *The 14th World Conference on Earthquake Engineering* (October, pp. 1–6).
24. Nowsheen, K. T. B., Takiya, T. K., Zohra, F. T., & Zaman, M. (2021). Identifying the gap between available and required open space for potential emergency assembly points (EAP) in Dhaka City: A case study of Mirpur area. *International Journal of Latest Research in Humanities and Social Science (IJLRHSS)*, *4*(10), 61–67.
25. Podder, M., Hasan, M. K., & Islam, M. J. (2022). Seismic vulnerability assessment of existing buildings by rapid visual screening method: A study on Ward 27 in Dhaka South City Corporation. *International Journal of Disaster Risk Management*, *4*(2), 77–91.
26. Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. McGraw-Hill.
27. Soltani, A., Ardalan, A., Boloorani, A. D., Haghdoost, A., & Hosseinzadeh-Attar, M. J. (2015). Criteria for site selection of temporary shelters after earthquakes: A Delphi panel. *PLOS Currents Disasters, 7*. https://doi.org/10.1371/currents.dis.16f9730a13eaa68c0b0ecbed3c5b5990
28. Soltani, A., Ardalan, A., Boloorani, A. D., Haghdoost, A., & Hosseinzadeh-Attar, M. J. (2014). Site selection criteria for sheltering after earthquakes: A systematic review. *PLOS Currents, 6*. https://doi.org/10.1371/currents.dis.17ad1f98fb85be80785d0a81ced6a7a6
29. Sphere Project. (2011). *Sphere handbook: Humanitarian charter and minimum standards in humanitarian response*. https://spherestandards.org/handbook-2011/
30. SYNER-G Project. (2013). *Systemic seismic vulnerability and risk analysis for buildings, lifeline networks and infrastructures safety gain: Reference report*. European Commission, Seventh Framework Programme.
31. Tai, C., Lee, Y., & Lin, C. (2010). Urban disaster prevention shelter location and evacuation behavior analysis. *Journal of Asian Architecture and Building Engineering, 9*(1), 215–220. https://doi.org/10.3130/jaabe.9.215
32. Unal, M., & Uslu, C. (2016). GIS-based accessibility analysis of urban emergency shelters: The case of Adana City. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42*, 95–101.
33. United Nations International Strategy for Disaster Reduction (UNISDR). (2013). *Implementation of the Hyogo Framework for Action: Summary of reports 2007–2013*. UNISDR.
34. Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research, 169*(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028
35. Wang, Y., Han, Y., Luo, A., Xu, S., Chen, J., & Liu, W. (2024). Site selection and prediction of urban emergency shelter based on VGAE-RF model. *Scientific Reports*, *14*(1), 14368.

36. Wright, K. C., & Johnston, D. M. (2010). Post-earthquake sheltering needs: How loss of structures and services affects decision making for evacuation. In *2010 New Zealand Society for Earthquake Engineering Conference Proceedings* (Vol. 21, p. 23). Wellington, New Zealand.
37. Zaman, A. A., Sifty, S., Rakhine, N. J., Abdul, A., Amin, R., Khalid, M., Tanvir, M. H., Hasan, K., & Barua, S. (2018). Earthquake risks in Bangladesh and evaluation of awareness among the university students. *Journal of Earth Science & Climatic Change, 9*(7), 482.
38. Zhao, L., Li, H., Sun, Y., Huang, R., Hu, Q., Wang, J., & Gao, F. (2017). Planning emergency shelters for urban disaster resilience: An integrated location-allocation modeling approach. *Sustainability, 9*(11), 2098. https://doi.org/10.3390/su9112098
39. Zhou, J., Nie, G., & Liu, Y. (2024). Multi-criteria comparison analysis of spatial equity for emergency shelters in old and new urban districts: A case study in Wuhua District and Chenggong District of Kunming City, China. *International Journal of Disaster Risk Reduction, 108*, 104547.

Supplementary Materials:

Table S1. Main-criteria AHP (Quality, Capacity, Accessibility)

(a) Pairwise comparison matrix (3 decimals)

	Quality	Capacity	Accessibility
Quality	1.000	0.345	0.792
Capacity	2.895	1.000	2.292
Accessibility	1.263	0.436	1.000

(b) Weights, eigenvalue, and consistency

- Weights (3 d.p.): Quality 0.194, Capacity 0.561, Accessibility 0.245 (sum = 1.000)
- λ_{max}=3, CI = 0.000, CR = 0.000

Table S2. Quality sub-criteria AHP (7×7)

Sub-criteria: Type of open space; Ownership; Secondary hazard; Pollution; Water availability; Medical service; Power/Electricity supply.

(a) Pairwise matrix (3 decimals)

	Type	Ownership	Secondary hazard	Pollution	Water	Medical	Power
Type	1.000	2.500	1.667	5.000	1.667	1.250	5.000
Ownership	0.400	1.000	0.667	2.000	0.667	0.500	2.000
Secondary hazard	0.600	1.500	1.000	3.000	1.000	0.750	3.000
Pollution	0.200	0.500	0.333	1.000	0.333	0.250	1.000
Water	0.600	1.500	1.000	3.000	1.000	0.750	3.000
Medical	0.800	2.000	1.333	4.000	1.333	1.000	4.000
Power	0.200	0.500	0.333	1.000	0.333	0.250	1.000

(b) Local and global weights; eigenvalue & consistency

- Local weights (sum = 1.000): Type 0.263, Ownership 0.105, Secondary hazard 0.158, Pollution 0.053, Water 0.158, Medical 0.211, Power 0.052
- Global weights (multiply by main "Quality" = 0.194; sums to 0.194):
  Type 0.051, Ownership 0.020, Secondary hazard 0.031, Pollution 0.010, Water 0.031, Medical 0.041, Power 0.010
- λ_{max}=7.000, CI = 0.000, CR = 0.000

Table S3. Capacity sub-criteria AHP (2×2)

Sub-criteria: Capacitated accessibility (CAV); Facilitation efficiency (FEV).

(a) Pairwise matrix (3 decimals)

	CAV	FEV
CAV	1.000	2.929
FEV	0.341	1.000

(b) Local and global weights; eigenvalue & consistency

- Local weights (sum = 1.000): CAV 0.745, FEV 0.255
- Global weights (multiply by main "Capacity" = 0.561; sums to 0.561):
  CAV 0.418, FEV 0.143
- λ_{max}=2.000, CI = 0.000, CR = 0.000

Table S4. Accessibility sub-criteria AHP (3×3)

Sub-criteria: Access road type; Proximal road blockage potential; Distance from major road.

(a) Pairwise matrix (3 decimals)

	Access road type	Proximal blockage	Distance (major road)
Access road type	1.000	1.222	2.750
Proximal blockage	0.818	1.000	2.250
Distance (major road)	0.364	0.444	1.000

(b) Local and global weights; eigenvalue & consistency

- Local weights (sum = 1.000): Access road 0.458, Blockage 0.375, Distance 0.167
- Global weights (multiply by main "Accessibility" = 0.245; sums to 0.245): Access road 0.112, Blockage 0.092, Distance 0.041
- λ_{max}=3.000, CI = 0.000, CR = 0.000

Table S5. Data Provenance of Datasets Used in the Study

Dataset	Source	Version / Year	CRS / EPSG	Resolution / Scale	License / Access
Population and Housing Census	Bangladesh Bureau of Statistics (BBS)	2022 (projected)	EPSG:32646 (UTM Zone 46N, WGS84)	Ward-level	Public access
Building Damage and Casualty Data	Comprehensive Disaster Management Program (CDMP), Dhaka Earthquake Risk Assessment	2009	EPSG:32646 (UTM Zone 46N, WGS84)	Ward-level aggregated	Restricted (available on request)
Open Space Inventory	Google Earth satellite imagery (digitized by author)	2021–2022	EPSG:4326 (WGS84)	~0.5–1 m (imagery resolution)	Imagery © Google; digitization by author
Road Network	Comprehensive Disaster Management Programme (CDMP), Dhaka Earthquake Risk Assessment	2023	EPSG:4326 (WGS84)	Street-level	Restricted (available on request)