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Optimizing Evacuation and Emergency Access Routes for Landslide Resilience: A Decadal Incidental Analysis in Chattogram, Bangladesh

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Abstract: Landslides constitute a significant natural hazard in Bangladesh, particularly within the Chattogram metropolitan region, where uncontrolled urban expansion and complex topographical conditions exacerbate vulnerability. This study employs integrated geospatial analysis and network modeling techniques to optimize evacuation routes and emergency response pathways for landslide-affected areas within Chattogram City Corporation (CCC) boundaries, utilizing comprehensive landslide incident data spanning from 2014-2024. The best evacuation paths from high-risk areas to nearby medical facilities and the shortest emergency access routes from fire stations to disaster locations were identified by methodical mapping and spatial analysis of past landslide incidents. Network analysis revealed evacuation distances ranging from 0.563 to 8.849 km (mean: 2.73 km), while emergency access routes extended between 1.204 and 11.002 km (mean: 4.82 km). Critical findings identified Venom Hill as a priority intervention zone due to maximum evacuation and response distances. Bijoynagar, Hathazari, Cantonment, and 3 no Bazar emerged as high-frequency incident locations with prolonged emergency response times. The analysis further revealed service concentration around Bayazid Fire Station, indicating spatial inequality in emergency service coverage distribution. The findings highlight the necessity of strategically decentralizing emergency services and improving transportation infrastructure connectivity in high-risk areas. The methodology contributes to developing resilient emergency response systems and improving disaster risk reduction capacity in vulnerable urban environments.

Keywords: *Landslide; Evacuation; Network Analysis; Resilience; Natural Disaster*

Introduction: One of the most frequent and damaging natural disasters in the world is landslides, which are especially common in hilly and mountainous areas where geological instability continuously threatens human communities [1]. These geological processes, encompassing the downward and outward movement of rock, earth, or debris under gravitational influence, range from rapid rockfalls to gradual soil mass displacement [2]. Between 1998 and 2017, landslides affected approximately 4.8 million individuals worldwide and caused over 18,000 fatalities, with Asia bearing the greatest burden through 184 fatal events between 2000 and 2019, resulting in 9,741 deaths and representing 40% of global economic losses [3,4].

In Bangladesh, the northeastern and southeastern highlands, covering approximately 12% of the national territory, demonstrate particular vulnerability to slope failures due to steep topographical gradients and unstable soil conditions [5]. The Chittagong Hill Tracts have experienced over 350 landslide-related fatalities during the past three decades, accompanied by substantial property damage and socioeconomic disruption [6]. The catastrophic June 2007 Chattogram landslide event, which claimed 129 lives, marked a breaking point moment in national disaster awareness and policy attention [5]. Subsequently, landslide frequency and intensity have increased markedly in southeastern mountainous regions, particularly during monsoon seasons when complex topography amplifies risk conditions [7–9].

Effective evacuation planning represents a critical component of disaster risk reduction, directly contributing to casualty minimization and loss reduction through the systematic movement of populations from high-risk areas to safer locations via designated evacuation routes [10,11]. Despite escalating landslide impacts and their severe socioeconomic consequences, existing research has predominantly emphasized susceptibility mapping, risk assessment, and general disaster preparedness, while evacuation route optimization remains largely unexplored [1,12–15]. Limited evacuation studies in Bangladesh have not specifically addressed landslide scenarios [16].

Global advances in evacuation research have progressed from simple distance-based routing toward sophisticated multi-criteria and dynamic modeling approaches. Contemporary methodologies integrate road hierarchy, accessibility constraints, traffic simulation, and topographical factors to enhance evacuation time estimation accuracy [17,18]. Recent applications in hazard-prone regions, including tsunami evacuation modeling in Italy and earthquake evacuation planning in South Korea, demonstrate the value of incorporating slope, elevation, and road classification into routing analyses [19,20]. However, such methodological advances remain limited in Bangladesh, where landslide research focuses primarily on susceptibility mapping with minimal attention to evacuation logistics [13,21,22].

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Landslide evacuation and emergency accessibility research at the global scale has advanced significantly in recent decades, moving beyond simple distance-based routing toward multi-criteria and dynamic models. For instance, [23] emphasized the integration of road hierarchy and accessibility constraints in evacuation planning, while [24] incorporated traffic simulation to estimate evacuation times more realistically. Recent studies in hazard-prone regions, including tsunami evacuation modeling in Italy [19] and earthquake evacuation in South Korea [20], highlight the value of incorporating slope, elevation, and road class into routing analyses. These approaches illustrate that travel time often differs considerably from network distance, especially in mountainous or densely built urban environments. However, such methodological advances remain scarce in Bangladesh, where landslide-related studies primarily focus on susceptibility mapping [9,12,13,25] with limited attention to evacuation logistics. By applying a GIS-based network analysis, this study contributes to bridging this gap, while also acknowledging the necessity of advancing toward more comprehensive, time-based models in future research.

Despite the growing body of landslide susceptibility mapping in Bangladesh, few studies cross-examine the effectiveness of existing evacuation infrastructure or assess the mismatch between hazard distribution and emergency service coverage. This disconnects leaves policy makers with hazard maps but limited operational guidance on how to respond during actual events. The present study addresses this operational gap by linking landslide incident data directly with hospital and fire station accessibility.

This study addresses the operational gap between hazard identification and emergency response by employing GIS-based network analysis to evaluate landslide-affected areas within Chattogram City Corporation from 2014 to 2024. The research pursues two primary objectives: (1) identifying optimal evacuation routes from landslide-prone areas to nearest medical facilities, and (2) determining emergency access routes for fire service vehicles to incident locations. By linking landslide incident data directly with hospital and fire station accessibility, this investigation provides operational guidance for policy makers and contributes to enhanced disaster preparedness and response capabilities in landslide-vulnerable urban environments.

Materials & Method

Study Area: Chittagong City Corporation (CCC), covering approximately 155.4 km² and home to over six million residents [26], extends from roughly 22°13′ N at its southern boundary to 22°30′ N in the north, and from 91°42′ E in the west to 91°55′ E in the east (Fig. **1**). As Bangladesh's principal seaport, Chattogram functions as the nation's primary hub for international trade, serving as both the country's second‑largest city and its commercial capital [27].

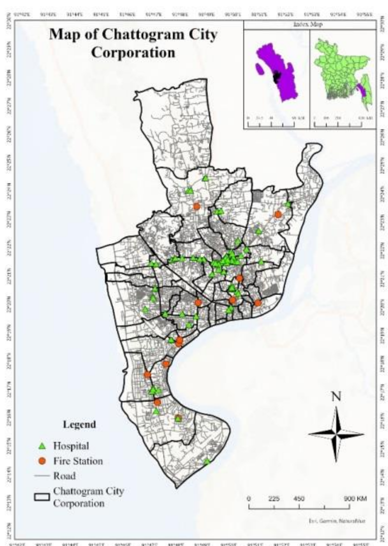

Fig. 1: Map of the study area (Chattogram City Corporation) showing spatial distribution of hospitals and fire stations used for route analysis.

Chittagong City is located on the southern plunge of the asymmetrical Sitakund Anticline, which is characterized by a steep and faulted western flank and a gently dipping eastern flank [28]. In this area, the folded sedimentary layers exhibit significant twisting and deformation [29]. The region experiences its monsoon season from June to September, during which monthly rainfall often exceeds 480 millimeters. Approximately 80 percent of landslides in the surrounding hills are triggered during this period [22]. Consequently, nearly 27 percent of the Chattogram City Corporation falls within landslide-prone zones [30], with areas such as Lalkhan Bazar, Batali Hill, Akber Shah, Lebu Bagan (Andhar Manik), Motijharna, and Pahartali repeatedly affected by slope failures resulting from intense rainfall and unregulated hill cutting [31]. That's how this area turns out to be more vulnerable towards landslides diseaster. The corresponding figure (Fig. **1**) illustrates key infrastructural elements within Chattogram City Corporation, including the spatial distribution of nine fire stations, thirty-eight hospitals, and the associated road network.

Data Acquisition: Table 1 presents a summary of the geospatial data used, including information on data types, timeframes, sources, and formats. This tabular overview provides a comprehensive understanding of the data collection process and supports the methodological framework of the analysis.

Table 1: Summary of data sources used in the study.

Data Type	Year	Source	Format
Landslide points	2014-2024	[32-38]	Shapefile (Point data)
Fire station location	2025	Fire Service and Civil Defence, Chattogram (Fire Station list)	Shapefile (Point data)
Hospital location	2025	The Humanitarian Data Exchange (HDX)	Shapefile (Point data)
Road network	2025	Open Street Map (Bangladesh Road Data)	Shapefile (Line data)

Geospatial Data Processing: All spatial datasets were first standardized into a common coordinate system (UTM, Zone 46N) to ensure consistency in distance and area calculations across layers [34]. Road network data were cleaned to eliminate topological errors such as overshoots, undershoots, and gaps between adjoining segments, thereby ensuring logical connectivity for subsequent routing [35].

The landslide incident dataset covered the period 2014–2024. For 2014– 2017, incident points were obtained from a previously published inventory. To extend coverage to 2024, additional events were digitized based on geographic descriptions from verified news portals, government bulletins, and secondary reports. For each case, incident locations were cross-checked against multiple sources when available, and their placement was aligned with identifiable landmarks such as intersections, institutional buildings, or natural features. Events with vague or inconsistent geographic descriptions were excluded. This procedure reduced potential positional uncertainty, although a small margin of error remains inherent to manual digitization.

Hospital and fire station datasets were similarly standardized and spatially cross-verified against official registries and open-access humanitarian databases. Duplicate or overlapping entries were removed, and facility attributes were harmonized to allow consistent interpretation during network analysis.

To prepare the network dataset, a new impedance attribute was created based on the physical length of each road segment. Connectivity was defined through node-to-node linkages at intersections, enabling the computation of continuous routes across the network. No restrictions were applied for slope or road class in this study due to data limitations, meaning all roads were assumed to be equally traversable. While this provides a first-order assessment of evacuation and emergency accessibility, it may underestimate actual travel times in steep or congested areas.

This data preparation and verification process ensured that the final spatial layers were logically integrated, topologically correct, and suitable for subsequent network-based evacuation and emergency access modeling.

Network Dataset Development: To enable the analysis of evacuation and emergency accessibility, a network dataset was constructed from the road network. Preparation began by assigning a calculated length attribute to each road segment, which was the primary measure of travel impedance (Fig. 2). All distances were measured in kilometers to make it consistent with facility datasets.

Topological validation was performed so that road segments would be properly joined at intersections. Dangles, overshoots, or undershoots of small dimensions were repaired, and isolated segments were introduced into the network wherever required [35]. It was crucial for the construction of unbroken paths of travel around the study area because anything short of full connectivity would have artificially lengthened routes or made nodes inaccessible [36].

Connectivity was developed through an endpoint junction rule [37], such as, movement along the network occurred only wherever road segments interleave physically. The assumption provides rational and realistic routing behavior for both cars and pedestrians [38]. The resulting dataset thus permitted the development of continuous travel paths between landslide locations, hospitals, and fire stations [39].

Physical distance was used as the sole impedance factor during analysis. This was because there was not enough data available on attributes such as road class, width, slope, or travel restrictions [40]. Therefore, all roads were considered equally accessible regardless of terrain or condition. Although this makes the analysis simpler and comparable across the city, it will be inclined to underestimate travel times, especially in hilly regions or in areas of congestion [41]. Yet, the network simulated presents a uniform first-order model for measuring spatial accessibility in landslide disasters.

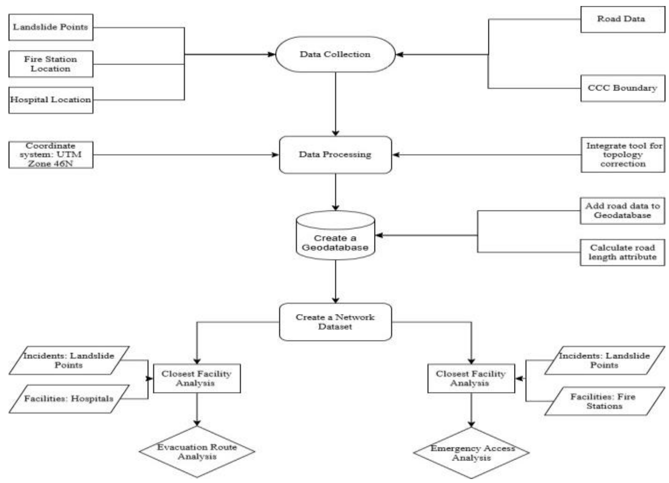

Fig. 2: Methodological flowchart illustrating the sequential steps of the study.

Evacuation Route Analysis: Evacuation route analysis was performed to determine shortest paths from landslide-affected areas to the nearest hospitals. Landslide event points between the years 2014–2024 were utilized as demand nodes, and hospitals served as service facilities. Both data sets were added to the road network that had previously been created in order to preserve spatial reference and connectivity consistency.

The model was designed to determine the shortest-distance path from any of the demand nodes to the closest available facility. Each of the landslide points was associated with a single hospital, as evacuees were considered to automatically proceed to the closest available health care in the event of a calamity. There was no cut-off distance applied, which allowed the model to consider all the possible connections in the network without limitations on the maximum distance that the travel distance can be [42].

The impedance attribute that was employed in the analysis was a function of physical road segment length, which is reproducible, but it does not capture slope variation, traffic delay, or road surface conditions [40]. The outcome of this analysis were route maps showing the optimal evacuation routes, and tabular outputs that provided summaries of the distances between each incident site and the nearest hospital [43]

Emergency Access Route Mapping: Parallel to evacuation analysis, a complementary analysis was conducted to evaluate the accessibility of landslide sites to fire stations. Fire stations in this case represented the service facilities, and landslide incident sites represented the demand nodes. The same standardized road network and distance-based impedance measure were used to allow comparability between emergency service and evacuation analyses.

For each landslide site, the model determined the shortest travel distance from the nearest fire station, thereby allocating each demand point a primary responding facility for emergency response [44]. As with the evacuation analysis, a single demand point was only allocated one facility, which reflects real-world response strategies where the closest available responder is most likely dispatched. No cut-off value was used, so each incident was allocated a responding station regardless of the distance covered [42]

The routes created quantified measures of emergency response access and spatially explicit maps of service coverage. Through the comparison of emergency access and evacuation results, it was possible to identify areas where residents face both long hospital evacuation distances and long emergency response times [41]. Such areas of heightened risk, often in peripheral or high-elevation areas, demonstrate the unequal distribution of emergency services within the city and form the basis of policy recommendations that follow.

Data and Methodological Assumptions: The methodological framework adopted in this study is constrained by several limitations that must be acknowledged. First, the landslide dataset comprises only 27 documented incidents from 2014–2024, which were sourced from scientific articles, governmental reports, and verified news outlets. Only events with clearly identifiable geographic references were included, while those with ambiguous descriptions were excluded to minimize positional errors. Despite cross-verification with multiple sources, the manual digitization of several incidents introduces potential spatial uncertainty.

Second, the network analysis relies solely on physical distance as the impedance factor, assuming all roads are equally navigable. This assumption, though practical for a preliminary assessment, oversimplifies the hilly terrain and variable road quality in Chattogram. In reality, slope gradients, surface conditions, and traffic congestion substantially affect travel time, particularly during monsoon-triggered emergencies. The absence of these attributes in the model likely underestimates true evacuation and response times. Future research should incorporate digital elevation models (DEMs), road class attributes, and traffic datasets to develop more realistic travel-time models.

Finally, hospitals and fire stations were treated as static facilities, whereas expansions, relocations, or temporary service centers could significantly alter accessibility patterns. These limitations suggest that the present results should be interpreted as indicative rather than definitive, while providing a foundation for more advanced models in subsequent studies.

Results and Discussion

Evacuation Route Assessment: Fig. 3 visualizes the evacuation routes from landslide-prone areas to their respective nearest hospitals, as determined through Closest Facility analysis. During the analysis, A total of 93 hospitals were initially considered, from which 10 unique hospitals were identified as destinations for 27 mapped landslide points. The distribution of hospitals (red triangles) is relatively widespread across the city; however, certain clusters of landslide-prone zones (black circles) are situated at a considerable distance from these medical facilities.

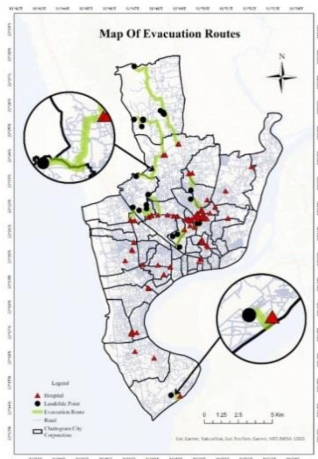

Fig. 3: Evacuation route map showing the shortest paths from landslide incident points (2014–2024) to the nearest hospitals.

Table 2 presents a comprehensive list of evacuation routes, detailing each incident-to-hospital pair along with the corresponding travel distances. As per (Table 2), The analysis reveals that evacuees in CCC must travel between 0.563 km and 8.849 km to reach the nearest hospital from landslide-affected locations. The average evacuation distance was found to be 2.73 km, indicating that a majority of incidents are situated relatively close to accessible medical services.

Table 2: List of evacuation routes from individual landslide incidents to the nearest hospitals.

Landslide incident	Hospital	Distance (kilometer)
Venom Hill	Cantonment General Hospital	8.849
Foy's Lake	Eye infarmary and training complex	1.456
Foy's Lake	Chittagong diabetic and general Hospital	2.533
Chittagong Cantonment	Cantonment General Hospital	3.321
Chanmari Bi Lane	Police Lines Hospital	0.797
Medical Hill	Desh medical Services	0.578
Medical Hill	Desh medical Services	0.563
Hathazari Cantonment Road	Army Medical College Chattogram	4.392
Hathazari Cantonment Road	Army Medical College Chattogram	4.357
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	3.631
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	3.659
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	3.644
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	4.474
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	3.619
Hathazari Cantonment 3 Number Bazar	Army Medical College Chattogram	3.652
Bhatiari-Hathazari Link Road	Police Lines Hospital	1.461
Lal Pahar	Eye infarmary and training complex	1.147
Chittagong Cantonment	Cantonment General Hospital	2.832
Chittagong Cantonment	Cantonment General Hospital	3.078
Chittagong Cantonment	Cantonment General Hospital	2.919
Momin Bagh Road	Fayezia Medico	1.717
Bijoynagar	Turna Medical Hall	1.095
Akbar Shah Colony	Eye infarmary and training complex	1.301
Bayazid Link Road	Army Medical College Chattogram	3.932

Firojshah colony	New Alankar Pharmacy	1.287
Tiger Pass Road	Police Lines Hospital	1.687
IW Colony	Ekushe Hospital	1.709

Specifically, 13 of the 27 evacuation routes fall below this average, while the remaining 14 exceed it, reflecting a moderately balanced distribution in terms of proximity. The distribution of distances suggests moderate service availability, but critical outliers such as Venom Hill highlight that averages mask severe accessibility gaps. Nonetheless, this distribution remains suboptimal, as several landslide-prone sites in the northeastern sector continue to experience significantly extended evacuation distances. For example, from Venom Hill to Cantonment General Hospital (8.849 km) is considered as one of those outlier distances which highlights substantial spatial service gaps [45] in certain peripheral or elevated regions. Furthermore, in the northern sector of the CCC, locations such as Hathazari Cantonment Road, Chittagong Cantonment, and Hathazari Cantonment 3 Number Bazar exhibit evacuation distances that exceed the mean value. As prviously said that despite the presence of 93 hospitals in the dataset, only ten were utilized as evacuation destinations, indicating concentrated demand on a limited subset of facilities. In particular, Army Medical College Chattogram served nine evacuation routes, predominantly in the Hathazari region, while Eye Infirmary and Training Complex and Cantonment General Hospital were each selected multiple times. This pattern reflects a heavy reliance on a small number of healthcare providers and underscores potential capacity pressures during landslide emergencies.

Emergency Access Route Assessment: As illustrated in Fig. 4, emergency access routes were generated using the Closest Facility tool, linking the nearest fire station to each landslide incident point based on network distance. Out of the nine fire stations available within the CCC, only four were actively assigned to serve all 27 landslide locations.

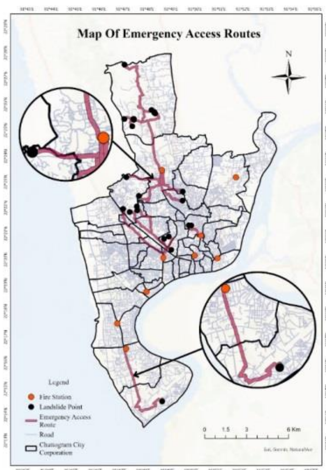

Fig. 4: Emergency access route map illustrating the shortest paths from fire stations to landslide incident points.

The spatial distribution of fire stations (represented by orange circles) appears relatively clustered within central areas of the city. Consequently, most landslide points were repeatedly linked to a limited subset of fire stations, indicating a lack of evenly distributed emergency service coverage across the current area, while many landslide-prone areas lie in the northern peripheral zones of CCC.

Table 3 presents the emergency access routes linking each landslide incident to its nearest fire station, along with the corresponding travel distances. The computed distances ranged from 1.203 km to 11.002 km, with a mean of 4.82 km, substantially exceeding the average evacuation distance of 2.73 km. Of the 27 routes analyzed, only 9 fell below this average, while the remaining 18 exceeded it. Despite the availability of nine fire stations within CCC area, only four (Bayazid, Agrabad, Chandanpura, and KEPZ) were actively assigned to serve all landslide sites. Among these, Bayazid Fire Station alone accounted for more than half of the total assignments, revealing a significant reliance on a single facility for emergency response coverage.

Table 3: List of emergency access routes from fire stations to landslide incident points.

Landslide incident	Fire station	Distance (km)
Venom Hill	Bayazid Fire Station	11.002
Foy's Lake	Agrabad Fire Station	5.073
Foy's Lake	Bayazid Fire Station	4.525
Chittagong Cantonment	Bayazid Fire Station	5.718
Chanmari Bi Lane	Agrabad Fire Station	2.018
Medical Hill	Chandanpura Fire Station	1.672

Medical Hill	Chandanpura Fire Station	1.757
Hathazari Cantonment Road	Bayazid Fire Station	5.800
Hathazari Cantonment Road	Bayazid Fire Station	5.766
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.039
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.067
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.053
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.882
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.027
Hathazari Cantonment 3 Number Bazar	Bayazid Fire Station	5.060
Bhatiari-Hathazari Link Road	Agrabad Fire Station	1.673
Lal Pahar	Agrabad Fire Station	4.945
Chittagong Cantonment	Bayazid Fire Station	5.341
Chittagong Cantonment	Bayazid Fire Station	5.587
Chittagong Cantonment	Bayazid Fire Station	5.427
Momin Bagh Road	Bayazid Fire Station	3.216
Bijoynagar	KEPZ Fire Station	7.756
Akbar Shah Colony	Agrabad Fire Station	5.068
Bayazid Link Road	Bayazid Fire Station	3.152
Firojshah colony	Agrabad Fire Station	5.446
Tiger Pass Road	Agrabad Fire Station	1.204
IW Colony	Bayazid Fire Station	3.548

This asymmetry highlights a core issue in disaster response planning as emergency services are not always spatially aligned with the distribution of hazard-prone areas. The overdependence on select fire stations, particularly Bayazid raises critical concerns regarding response capacity, logistical bottlenecks [46], and the risk of delayed intervention during concurrent or high-frequency landslide events, especially during the monsoon season. For instance, Venom Hill (11.002 km from Bayazid Fire Station) and Bijoynagar (7.756 km from KEPZ Fire Station) represent critical outliers, suggesting spatial service gaps [45] that may translate into life-threatening delays.

The over-reliance on Bayazid Fire Station indicates that a single-point failure or congestion at this facility could jeopardize half the city's emergency coverage. This underscores the structural vulnerability of Chattogram's disaster response system.

High Risk or Isolated Areas: The spatial analysis identified several zones within CCC that experience disproportionately long evacuation and emergency response routes, classifying them as high-risk or isolated areas. Table 4 summarizes the five longest routes, revealing that Venom Hill presents the most extreme accessibility challenge, with an evacuation distance of 8.849 km to Cantonment General Hospital and an emergency access route of 11.002 km to Bayazid Fire Station. This dual extremity underscores the acute isolation of Venom Hill, where residents face extended travel times both to seek medical care and to receive aid. Bijoynagar also demonstrates significant isolation, requiring a 7.756 km journey to the KEPZ Fire Station. Furthermore, two sites in the northern Hathazari Cantonment 3 Number Bazar (5.882 km) and Cantonment Road (5.800 km) to Bayazid Fire Station, appear among the longest access routes, indicating a persistent cluster of service deficiencies on the city's periphery.

Table 4: Summary of the top five longest evacuation and emergency access routes.

Route Type	Incident Location	Destination Facility	Distance (km)
Emergency Access	Venom Hill	Bayazid Fire Station	11.002
Evacuation	Venom Hill	Cantonment General Hospital	8.849
Emergency Access	Bijoynagar	KEPZ Fire Station	7.756
Emergency Access	Hathazari Cantonment 3 No Bazar	Bayazid Fire Station	5.882
Emergency Access	Hathazari Cantonment Road	Bayazid Fire Station	5.8

In addition to route length, the frequency of landslide events further delineates high-risk zones. Between 2014 and 2024, areas such as Hathazari Cantonment 3 Number Bazar, Foy's Lake, Medical Hill, Hathazari Cantonment Road, and Chittagong Cantonment experienced multiple landslide incidents. Hathazari Cantonment 3 Number Bazar recorded six separate events, marking it as the most recurrently affected site and reinforcing its classification as a high-risk area. Both Hathazari Cantonment 3 Number Bazar and Hathazari Cantonment Road exhibit emergency access distances (5.882 km and 5.800 km, respectively) that exceed the average response distance of 4.82 km, further illustrating the compounded vulnerability of these locations.

Composite Priority Index for High-Risk Areas: To strengthen the interpretation of evacuation and access challenges, a Composite Priority Index (CPI) was developed to integrate three factors: (i) average evacuation distance, (ii) average emergency access distance, and (iii) frequency of landslide incidents at each location. Each factor was normalized to a 0–1 scale and equally weighted to derive a composite score, where higher values indicate greater priority for intervention.

Table 5: Composite Priority Index (CPI) ranking of high-risk landslide-prone areas in CCC.

Location	Risk Level	Location	Risk Level
Venom Hill	High	Medical Hill	Medium
Bijoy Nagar	High	Foy’s Lake	Medium
Hathazari Cantonment 3 No Bazar	High	Others	Low

The results (Table 5) reveal that Venom Hill ranks as the highest-priority area due to its extreme evacuation (8.849 km) and emergency access distances (11.002 km), combined with recurrent incidents. Bijoynagar also emerges as a critical hotspot, with a long emergency response distance (7.756 km) despite relatively shorter evacuation routes. Similarly, Hathazari Cantonment 3 No Bazar demonstrates both recurrent landslides and extended access distances, reinforcing its vulnerability. These findings highlight the necessity of targeted infrastructure improvements and decentralized service provision in these specific neighborhoods.

Discussion: The analysis demonstrates clear disparities between evacuation and emergency access distances in landslide-prone neighborhoods of Chattogram. On average, evacuees must travel 2.73 km to reach hospitals, while emergency vehicles travel nearly double that distance (4.82 km) to reach incident sites. These findings reveal a structural imbalance between healthcare accessibility and emergency service deployment, with severe consequences for timely disaster response. Locations such as Venom Hill and Bijoynagar not only exhibit the longest travel distances but also experience recurrent incidents, underscoring their compounded vulnerability.

The CPI results further indicate that reliance on central fire stations, particularly Bayazid, creates service bottlenecks in peripheral neighborhoods. This confirms international evidence [47] that clustered emergency services lead to delays in hazard-prone regions. From a resilience perspective, decentralizing emergency services through satellite fire posts, mobile rescue units, or temporary medical shelters would significantly reduce life-threatening delays. Additionally, urban planning should integrate hazard-informed road design, ensuring that evacuation routes are not only short but also traversable during monsoon seasons.

The findings of this analysis have significant implications for both timely response and public safety. The mapped evacuation and emergency access routes, along with their corresponding distances, provide valuable spatial information for both evacuees and first responders. For evacuees, this information enables informed decision-making regarding the nearest hospitals during a crisis. Simultaneously, emergency responders, particularly fire service teams, can utilize the identified routes to pre-plan rescue operations more efficiently. The mapped evacuation and emergency access routes, along with their corresponding distances, provide valuable spatial information for both evacuees and first responders. For evacuees, this information enables informed decision-making regarding the nearest hospitals during a crisis. Simultaneously, emergency responders, particularly fire service teams, can utilize the identified routes to pre-plan rescue operations more efficiently [48]. By highlighting the distance-based disparities in evacuation and emergency access routes, the findings underscore the need to prioritize isolated areas, as such spatial insights are essential for optimizing response time and enhancing disaster preparedness.

Three primary factors shaped the efficiency of both evacuation and emergency access routes in this study. First, the spatial distribution of critical facilities determined travel distances: a greater number of evenly dispersed hospitals reduced average evacuation lengths, whereas the limited and clustered placement of fire stations led to longer response routes in peripheral zones. Second, the connectivity and density of the road network were essential for seamless routing well-connected, uninterrupted street segments enabled the solver to generate direct paths, while any gaps or overshoots would have introduced artificial detours. Finally, the accuracy of spatial data, especially the manually digitized landslide points for 2018–2024, underpinned all network calculations. Rigorous cross-validation against multiple sources and alignment with known landmarks ensured that incident locations were mapped precisely, thereby reinforcing the reliability of the resulting route analyses.

Poorly connected road networks in high-risk zones (e.g., Venom Hill) significantly hinder both evacuation and access. The absence of a comprehensive hill management framework in the urbanized hill districts has contributed to the proliferation of informal settlements on landslide-prone slopes, particularly within the jurisdiction of CCC [49]. Unauthorized hill cutting and the construction of housing on hazardous slopes, often in violation of the city’s master plan, constitute the primary triggers of landslides in the Chattogram Metropolitan Area [50]. These events inflict direct damage on transportation infrastructure, including partial or complete road collapse and blockages, and give rise to indirect impacts such as traffic disruptions and regional isolation [51].

The terrain of the CCC area, marked by elevated slopes and fragmented hills, inherently limits road design and connectivity. Areas like Foy's Lake and Lal Pahar, though geographically close to medical facilities, still reflect suboptimal routes due to elevation differences. High built-up density, such as in Akbar Shah Colony or Bijoynagar, introduces chokepoints, restricting the speed and maneuverability of emergency vehicles.

Both the present study and prior research have extensively utilized GIS-based network analysis for modeling evacuation and emergency access. Numerous studies have applied tools such as ArcGIS Network Analyst and shortest-path algorithms, including Dijkstra's algorithm, to determine optimal evacuation routes and associated travel distances. For instance, [17] implemented a GIS-based evacuation model using ArcView to calculate the shortest and most efficient routes from hazard zones to designated safe areas. However, in the context of Bangladesh, most existing landslide-related research has primarily focused on susceptibility mapping and community vulnerability assessments, often neglecting the logistical aspects of evacuation planning. While these studies [13,21,22] have contributed to understanding at-risk regions, they typically do not quantify evacuation distances or assess the responsiveness of emergency services. In contrast, the current study advances the discourse by evaluating the post-landslide accessibility of affected areas through road network analysis. Though there has not been any studies based on this, several international studies have demonstrated the potential of GIS-based evacuation modeling across various hazard contexts. For instance, [20] examined evacuation site accessibility for earthquakes in Daegu, South Korea, utilizing Network Analyst tools in ArcGIS. [18] developed an evacuation route plan for flood-prone areas in Siraha Municipality, Nepal, via closest facility tool to optimize emergency routing, an approach mirrored in this study. Additionally, [19] applied GIS methods to simulate tsunami evacuation routes on Stromboli Island, Italy. These international precedents affirm the relevance and applicability of network-based spatial analysis for hazard response planning, thereby supporting the methodological grounding of this study.

From a policy and planning perspective, the evidence calls for the establishment of additional fire stations in high- risk, peripheral zones such as Hathazari Cantonment and Venom Hill. Locally accessible firefighting capacity would reduce the burden on central stations like Bayazid and Agrabad and shrink critical response gaps. Equally important is the development and maintenance of evacuation- friendly road networks wide, well- surfaced, and interlinked to facilitate both mass egress and emergency- vehicle ingress under duress. Adoption of geospatial tools like Network Analyst and hazard mapping in city planning can enhance emergency preparedness.

Beyond infrastructure, community-based measures such as training volunteers for first response, designating temporary neighborhood shelters, and mapping informal evacuation paths could supplement formal services. Integrating community perspectives with GIS-based analysis would provide a more comprehensive understanding of local capacities and constraints, especially in informal settlements on hazardous slopes.

Finally, the study's limitations point to avenues for refinement. Manual digitization of landslide locations may introduce minor positional errors, and the omission of real- time traffic and elevation- based slope difficulty likely understates actual travel times. Moreover, treating hospitals and fire stations as fixed entities overlooks planned expansions or relocations.

Conclusions: This study applied GIS-based network analysis to 27 documented landslide incidents in CCC from 2014 to 2024, mapping optimized evacuation paths to hospitals and emergency access routes from fire stations. In total, 10 distinct hospitals and 4 fire stations were engaged in the route analysis. Evacuees face an average travel distance of 2.73 km to reach medical care, while emergency responders travel an average of 4.82 km to incident sites. High-risk or isolated zones such as Venom Hill and Bijoynagar exhibited the longest route distances, reflecting critical service gaps. These spatial analyses reveal pronounced disparities in facility coverage and network connectivity, underscoring critical areas where access to lifesaving services is most limited. The research presents a practical use of GIS-based network analysis for landslide-related evacuation and emergency access planning in CCC. By directly mapping landslide points from the past decade alongside health and fire service facilities, this work provides a framework that local authorities can use to improve response times. This method supports disaster management by offering clear, location-based guidance instead of relying on general assumptions. To reduce response delays in high-risk areas, authorities should focus on upgrading infrastructure in locations like Venom Hill that lack adequate access. Setting up temporary or mobile emergency service units in these vulnerable neighborhoods could ensure faster responses during disasters. Additionally, incorporating GIS tools into regular urban planning and emergency preparation can help support better decision-making in CCC. The study highlights critical spatial gaps in disaster preparedness within Chattogram. Venom Hill, for example, requires nearly 9 km for hospital access and over 11 km for fire station response, distances that are impractical during emergencies. Establishing a fire substation within 3–4 km of this neighborhood could potentially reduce response times by more than 50%. Similarly, Bijoynagar and Hathazari Cantonment areas demand immediate attention for infrastructure upgrades and decentralized service delivery. Although this study is focused on Chattogram, the methodological approach is adaptable to other secondary cities in Bangladesh where hilly terrain and rapid urban growth intersect, such as Cox's Bazar and Bandarban. Extending the framework nationally could support integrated disaster risk management at multiple governance scales. While the GIS-based network approach offers actionable insights, limitations related to dataset size, manual digitization, and distance-only modeling restrict the precision of results. Future research should incorporate slope-adjusted travel-time models, real-time traffic data, and field validation of incident locations. Despite these limitations, the study provides a replicable framework for integrating geospatial tools into local disaster risk reduction strategies and offers evidence-based guidance for policymakers seeking to strengthen landslide resilience in Chattogram.

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