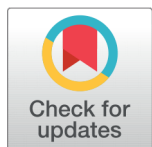


ORIGINAL ARTICLE



Dynamic Evacuation Route Planning for Flood-Prone Coastal Odisha Using GIS and Least-Cost Path Analysis

 OPEN ACCESS

Received: 16/07/2026

Accepted: 21/07/2026

Published: 05/08/2026

Chaitanya Rao Bula^{1*}, Vemu Sreenivasulu¹¹ Department of Civil Engineering, University College of Engineering (A), J.N.T.U.K., Kakinada, A.P, India

Citation: Bula CR, Sreenivasulu V (2026) Dynamic Evacuation Route Planning for Flood-Prone Coastal Odisha Using GIS and Least-Cost Path Analysis. Indian Journal of Science and Technology 19(29): 2073-2084. <https://doi.org/10.17485/IJST/19i29.1052>

* Corresponding author.

21022p0107@jntuk.edu.in

Funding: None

Competing Interests: None

Copyright: © 2026 Bula & Sreenivasulu. This is an open access article distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Published By Indian Society for Education and Environment ([iSee](#))

ISSN

Print: 0974-6846

Electronic: 0974-5645

Abstract

Objectives: To evolve suitable approach for developing dynamic flood evacuation plans to overcome the shortcomings of traditional static evacuation planning in the studied area. **Method:** Due to its high vulnerability to flooding and storm surges of the Baitarani River, and because of frequent occurrence of cyclones and river floods, the Bhadrak district of Odisha state was selected as the study site. An innovative GIS-based flood evacuation route planner model was proposed for generating dynamic flood evacuation routes. This new flood evacuation route planner makes use of the A* least-cost path (LCP) algorithm using a composite cost function involving flood depth, digital elevation model (DEM), road accessibility, and land-cover friction. This dynamic model was assessed for its performance under four hazard scenarios: Dry Baseline, Baitarani River Spillages, Cyclone Yaas Storm Surge, and Systemic Extreme Catastrophe. In addition, several sensitivity analysis studies were conducted to investigate the impact of the accessibility of shelters and the effect of spatial factors on evacuation performance. **Findings:** The devised route planner effectively adapts itself to all of the hazard scenarios, including the highly risky Systemic Extreme Catastrophe scenario, where it is able to come up with feasible detours for evacuation even with 33.72% reduction in route safety certainty and a greater than 300% rise in travel time when compared to the Dry Baseline scenario. Sensitivity analysis showed that terrain elevation is the key factor affecting the route safety, accounting for variability of up to 15%, while flood hazard distance comes second. **Novelty:** This study presents a novel dynamic GIS-based approach to creating flood evacuation routes using the A* Least Cost Path algorithm together with a multi-criteria cost function. Different from other static approaches to flood evacuation routing, this framework dynamically reacts to the hazard situation and creates adaptive safe routes for evacuation, thus being an applicable decision-support system for disaster risk management.

Keywords: Flood Evacuation Planning; Geographic Information Systems (GIS); A* Algorithm; Multi-Criteria Decision Analysis (MCDA); Least Cost Path; Compound Flooding; Disaster Risk Reduction

1 Introduction

Floods are among the most prevalent and destructive natural hazards that affect millions of people globally, disrupting infrastructure and services requiring swift emergency responses. In the district of Bhadrak, located on the eastern coast of India, frequent floods from heavy monsoon rainfall and associated cyclones generating storm surges make life-threatening situations for the inhabitants of the region. As a result, changing and strong emergency response and shelter relocation strategies are necessary to ensure proper measures to rapidly evacuate people and transport them to shelters during severe meteorological events⁽¹⁾.

Recent advances in Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) have facilitated the mapping of flood susceptibility and hazard assessment with a high degree of precision to identify potential sites for emergency shelters⁽²⁾. Spatial optimization techniques, especially using heuristic search algorithms such as the popular A* and Dijkstra's algorithm and similar shortest-path methods using least-cost paths⁽³⁾, can now be implemented in GIS environments, considering multiple factors such as the terrain slope and flood inundation depth influencing vehicular and pedestrian motion. However, there remains an important research gap in integrating the above approaches for dynamically assessing the influence of various disaster-related parameters, such as changes in flood patterns and disruptions to shelters and other critical infrastructure sites due to cascading events. The study of changing shelter accessibility from flood evacuation models using multi-scenario flood simulations and spatial-temporal sensitivity analyses to account for variations in the cost surface parameters has been relatively unexplored⁽⁴⁾. So, multi-component emergency response and shelter allocation systems remain inefficient, given the static assignment of shelter points and lack of complete evaluation.

This study proposes an integrated GIS-based Flood Evacuation Route Planner for Bhadrak district, incorporating multi-scenario compound flood simulations for changing hazard mapping, multi-criteria cost surface modeling, A* least-cost path routing and continued monitoring of evacuation efficiency. By explicitly incorporating shelter accessibility metrics and conducting robust sensitivity analyses on spatial variables⁽⁵⁾, this research provides an integrated, highly adaptable, and unified decision-support system for effective flood disaster reduction.

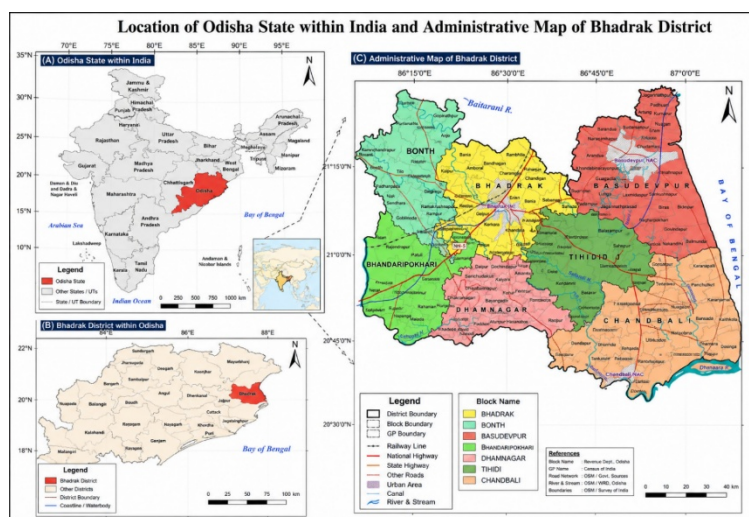


Fig 1. Geographical location and administrative map of the study area: Bhadrak District, Odisha, India.

1.1 Geographical and Climatic Context

The Bhadrak district is located in the north-eastern coastal region of Odisha, India. The district covers an area of around 2,505 km² and is bordered by the districts of Balasore to the north, Jaipur to the south, Kendra Para to the southwest and the Bay of Bengal to the east. The region is intersected by major highways and railway networks, which are needed for evacuation efforts. The region experiences a tropical monsoon climate and receives between 1,400 and 1,600 mm of rainfall each year. The majority of the rainfall in the region falls during the southwest monsoon season between June and September, leading to flooding in the region. (See Figure 1).

1.2 Hydrological Characteristics and Flood Vulnerability

The rivers Baitarani and Salandi, along with several tributaries and drainage lines flowing into the Bay of Bengal, play the main role in determining regional hydrology. The Baitarani is chiefly responsible for riverine flooding while the eastern coast of Odisha is regularly flooded due to tidal action and cyclones. The geomorphology of the district is mostly that of low-lying riverine plains where the general elevation is below 40 m above the sea level which makes these areas prone to flooding for a long time. Historically, Bhadrak has faced several severe floods (for example, 2005, 2011, 2015, 2017, 2018, and 2025) that have damaged transport systems, agricultural land, and residential areas significantly. Cyclone Yaas of 2021⁽⁶⁾ caused strong storm surges leading to flooding of coastal villages and disruption of communication systems, thus forcing the mass evacuation of people⁽⁷⁾.

1.3 Demographics and Evacuation Challenges

With a population estimated to be around 1.5 million (as per the 2011 Census of India), Bhadrak district experiences a high population density of more than 600 persons/km². Most of the agricultural and fishing population resides in the rural areas of this district. Furthermore, the concentration of settlements in the floodplain area increases the risk of flooding and evacuation difficulties⁽⁸⁾.

The Dhamnagar, Bhandaripokhari, Basudevapur, and Chandbali blocks are the flood-prone zones in this region. It is believed that the flat terrain, proximity to the flood-prone Baitarani River, and being subjected to coastal cyclone effect make these areas prone to floods. During floods, the road networks linking these regions are totally submerged. This results in disruption of transport facilities to the emergency shelters and increases time taken for rescue operations. The flood risk features of the Bhadrak area along with its vulnerable demography make this district an appropriate site for testing the effectiveness of a GIS-based evacuation planning method.

2 Methodology

The aim of this study is to develop an adaptive Flood Evacuation Route Planner for the Bhadrak district of India, using an integrated, multi-scenario Geographic Information System (GIS) framework. The methodology is presented in the form of four steps: (1) preparation of the spatial database and acquisition of the geospatial data, (2) preparation of the MCDA cost surface, (3) optimization of least-cost path using the heuristic A* method, and (4) conducting multi-scenario simulations with sensitivity analysis.

2.1 Geospatial Data Acquisition and Processing

For the accurate development of evacuation routes, high-resolution spatial data is important⁽⁹⁾. In this study, administrative boundaries, roads, and river shapes were extracted from OpenStreetMap. The topographic parameters used such as the elevation and slope were taken from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). The historical and simulated flood data were processed with Sentinel-1 Synthetic Aperture Radar (SAR) satellite images in the Google Earth Engine (GEE) cloud service platform in order to properly represent the hazards. All this data, both from vector data and raster data was transformed to use the same coordinate system and later turned into one standard raster grid for spatial topology consistency⁽¹⁰⁾.

GIS-based framework for evacuation incorporates several open-source geospatial data sets to ensure replicability and comprehensive spatial analysis. Administrative boundary data and the road network were sourced from OpenStreetMap (<https://www.openstreetmap.org>), whereas elevation and slope were derived from the Shuttle Radar Topography Mission (SRTM) 30 m Digital Elevation Model (<https://earthexplorer.usgs.gov/>). Inundation maps for floods were developed using the Sentinel-1 SAR image data processed on Google Earth Engine (<https://earthengine.google.com/>), with the image data accessed via the Copernicus Data Space Ecosystem (<https://dataspace.copernicus.eu/>). The land use/land cover data were sourced from the ESA World Cover 2021 dataset (<https://worldcover2021.esa.int/>) to derive surface friction data, and historical cyclones and flood event data were sourced from India Meteorological Department (IMD) and Odisha State Disaster Management Authority (OSDMA).

Sample Size: The size of the study area is around 2,505 sq. km in the district of Bhadrak. Once pre-processed, all data layers were resampled to a 30-meters raster grid that resulted in about 2.78 million raster cells for cost surface analysis. The transportation network included all accessible road segments from OpenStreetMap data in the district, whereas there were four shelters designated as evacuation locations (Bhadrak HQ, Chand Bali, Bonth Camp, and Basudevapur Helipad). Four flooding scenarios were analysed for routing reliability.

2.2 Multi-Criteria Cost Surface Generation

The composite cost surface was constructed using five spatial criteria: flood depth (m), road accessibility, terrain elevation (m), terrain slope (degrees), and land use/land cover (LULC) friction. These variables were selected because they directly influence evacuation safety and route reversibility during flood events. Prior to weighted aggregation in the Multi-Criteria Decision Analysis (MCDA), all feature values were normalized to the range $0 \leq V_i \leq 1$ using the min–max normalization method, ensuring consistent scaling and balanced contribution of each criterion to the composite traversal cost.

Instead of simply depending on Euclidean distance, realistic evacuation planning now needs to consider the physical barriers of the terrain in the event of a disaster. The multi-criteria decision analysis (MCDA) technique was applied in the creation of an integrated traversal cost surface. For a raster cell, the overall impedance that is the spatial cost, C_{total} , is the weighted mixture of five key spatial parameters.

$$C_{total} = \sum_{i=1}^n (W_i \times V_i)$$

where:

- C_{total} = Total traversal cost of a raster cell.
- W_i = Weight assigned to the i^{th} decision criterion, representing its relative importance.
- V_i = Normalized value of the i^{th} spatial criterion for the corresponding raster cell.
- n = Total number of spatial criteria considered in the Multi-Criteria Decision Analysis (MCDA).

For the proposed flood evacuation model, the composite cost surface is computed using five spatial criteria as follows:

$$C_{total} = (W_{flood} \times V_{flood}) + (W_{road} \times V_{road}) + (W_{elevation} \times V_{elevation}) + (W_{slope} \times V_{slope}) + (W_{LULC} \times V_{LULC})$$

where:

- $W_{flood} \times V_{flood}$ represents the contribution of flood hazard.
- $W_{road} \times V_{road}$ represents road accessibility, including major transportation corridors such as National Highway-16.
- $W_{elevation} \times V_{elevation}$ represents terrain elevation.
- $W_{slope} \times V_{slope}$ represents terrain slope.
- $W_{LULC} \times V_{LULC}$ represents the influence of land use/land cover on evacuation movement.

Initial weight values for the criteria used for MCDA model were taken from existing flood evacuation studies and subjected to one-at-a-time sensitivity analysis. Flood risk (0.35), road connectivity (0.25), altitude (0.20), slope (0.10), and land use (0.10) were used as initial weights. In sensitivity analysis, each criterion weight was varied between $0.5\times$ and $3.0\times$ of their initial value, individually.

The composite cost surface integrates flood risk, road accessibility, elevation, and slope through the weighted linear combination method. The raster pixels with higher cost values mean higher difficulty of travelling through them and higher flood risk, while the pixels with lower cost values identify paths that would be more effective and safer in terms of evacuation⁽¹¹⁾. The proposed cost surface is used to feed the A* algorithm with all the necessary information to find the optimal path of least cost for the evacuation.

2.3 A* Heuristic Least Cost Path (LCP) Optimization

This study employs the A* (A-Star) search algorithm to establish the best evacuation paths across the MCDA cost surface. The reason A* is seen to be more favourable compared to traditional Dijkstra's algorithm is because the former has better computational efficiency and directed heuristic search abilities⁽¹²⁾. The algorithm identifies the optimal route while minimizing the continuous cost function $f(n)$:

$$f(n) = g(n) + h(n)$$

Where:

- n represents the current raster cell being evaluated.

- $g(n)$ is the exact accumulated travel cost from the origin (hazard zone) to cell n , derived dynamically from the MCDA cost surface.
- $h(n)$ is the heuristic estimated cost from cell n to the designated emergency shelter (target).

The A* algorithm works effectively to determine the best evacuation route by considering the terrain features, obstacles in infrastructure, and the variable flood depth through $g(n)$ simultaneously.

Modification of the Conventional A* Algorithm: In contrast to the conventional A* algorithm, which aims at minimizing geometric distance, the suggested method takes into account the composite traversal cost, which is obtained using multiple criteria decision analysis based on flood hazard, road accessibility, elevation, slope, and land-use considerations. The cost of the path is calculated as follows:

$$g(n) = \sum_{k=1}^N C_t(K)$$

where C_t denotes the traversal impedance of each raster cell.

2.4 Scenario Simulation and Performance Evaluation

In order to thoroughly investigate the resilience and flexibility of the routing mechanism, four different flood scenarios were established to utilize the A* algorithm:

1. Dry Baseline: Operating at normal seasonal levels of water flow.
2. Baitarani River Flood: This considers the incidents of infrastructure failures upstream.
3. Cyclone Yaas Storm Surge: It assesses the effects of tidal flooding.
4. Catastrophic scenario: This assesses the occurrence of multiple disasters in combination: river flooding, storm flooding, and ongoing flooding due to intense rains.

The success of the evacuation in all considered scenarios was analysed based on four main indicators: although travel distance and travel time are important, it is equally important to assess the impact of the flood on the safety of the people moving through the flooded area⁽¹³⁾.

Ultimately, the framework was validated based on the analysis of accessibility of evacuation shelters and sensitivity analysis for separating the effect of each parameter weight.

3 Results and Discussion

3.1 Scenario-Based Route Optimization Performance

The performance of the A* routing algorithm was analysed in different hazard framework scenarios to assess its effectiveness and capability to operate under various environmental conditions. As seen in Table 1, the A* routing algorithm was able to identify the best evacuation route in the Dry Baseline case, with a distance of 36.2 km and a travel duration of 100 minutes achieved safely with a safety confidence level of 86%.

Table 1. Comparative analysis of evacuation metrics (Distance, Travel Time, Safety Confidence, and Peak Water Depth) across four simulated flood scenarios.

Scenario	Distance (Km)	Travel Time (min)	Safety (%)	Water depth (m)
Dry	36.2	100	86	0
Baitarani flood	33.6	121	82	1.8
Cyclone Yaas	33.6	139	79	0
Systematic Extreme	38.7	311	57	6.2

The results displayed in Table 1 and, demonstrated through the spatial mapping in Figure 2, indicate that the algorithm was able to accurately adapt to the level of spatial interference that grew with the influence of the type of hazard scenario. In the Baitarani River Spillage scenario, having the peak water level of 1.8 m, the travel time went up to 121 minutes. Safety confidence went down by only 4.65% (to 82%). The travel time in the Storm surge of Cyclone Yaas scenario was equal to 139 minutes, and

the safety confidence was decreased by 8.14%. Finally, in the extreme incident scenario with maximum water level of 6.2 m passed along the route, the algorithm experienced a substantial drop in evacuation efficiency. The total travel time accounted for 311 minutes (over a double growth relative to Dry Baseline) while the level of safety confidence dropped all the way down to 57%.

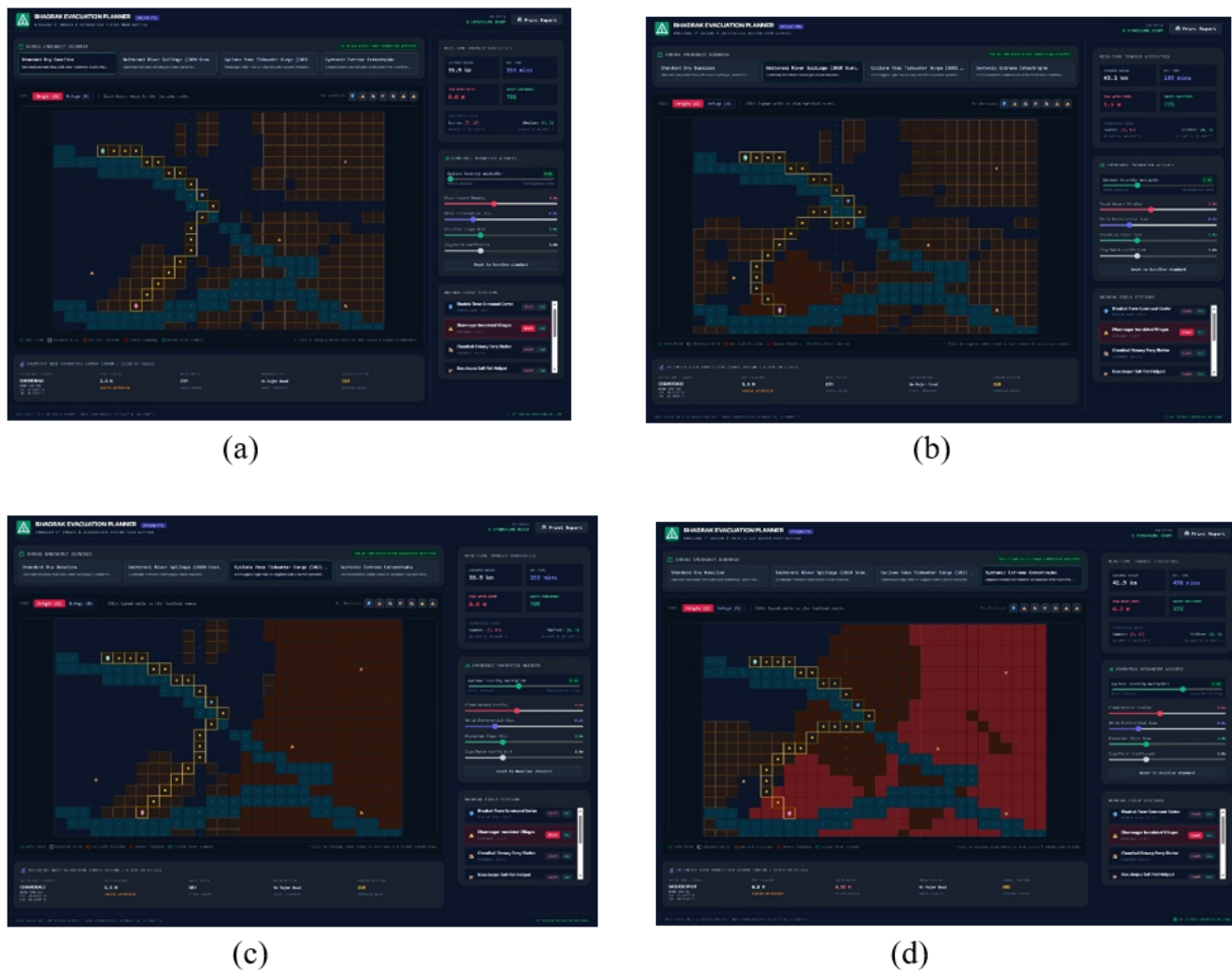


Fig 2. Spatial visualization of the A*-based Least Cost Path routing under (a) Dry Baseline,

(b) Baitarani River Spillage, (c) Cyclone Yaas Storm Surge, and (d) Systemic Extreme Catastrophe scenarios, (Starting point -Damnagar and ending point-Bonth relief center)

3.2 Shelter Accessibility and Resilience Matrix

The study assessed the availability and reliability of the four selected emergency shelters' (Bhadark HQ, Chandbali, Bonth Camp and Basudevapur Helipad) safety metrics in all obtained data evaluated in Table 2 in order to better analyse the structures rated as the best opportunities for safe evacuation.

Figure 3 illustrates the highest average safety score achieved by the Bhadrak HQ shelter compared to others since the establishment had the lowest average access time – 137.5 minutes across all scenarios. While the Bonth Camp shelter reported the average access time on the level of 181.75 minutes, it still proved itself the safest option of all as it presented the highest average safety score of 76.75 percent. The coastal shelters and those of lower elevation further indicated great difficulties associated with the provision of safe evacuation. The highest access time of the Chandbali shelter was 411 minutes, and the

Table 2. Shelter accessibility and safety confidence matrix from the Dhamnagar source location under varying baseline and extreme event conditions.

Shelter	S1 Time	S1 SC (%)	S2 Time	S2 SC (%)	S3 Time	S3 SC (%)	S4 Time	S4 SC (%)
Bhadrak HQ	86	78	115	71	92	77	257	45
Chandabali	204	74	249	71	390	56	801	16
Bonth Camp	107	86	141	82	114	85	365	54
Basedevpur Helipad	178	77	205	74	305	60	676	18

Where: S1 = Dry Baseline S2 = Baitarani Spillage (2020) S3 = Cyclone Yaas (2021) S4 = Extreme Catastrophe SC = Safety Confidence

average safety score achieved was only 54.25 percent despite the access time reaching the maximum of 801 minutes and the safety score dropping to 16 percent during the simulation of a catastrophe.

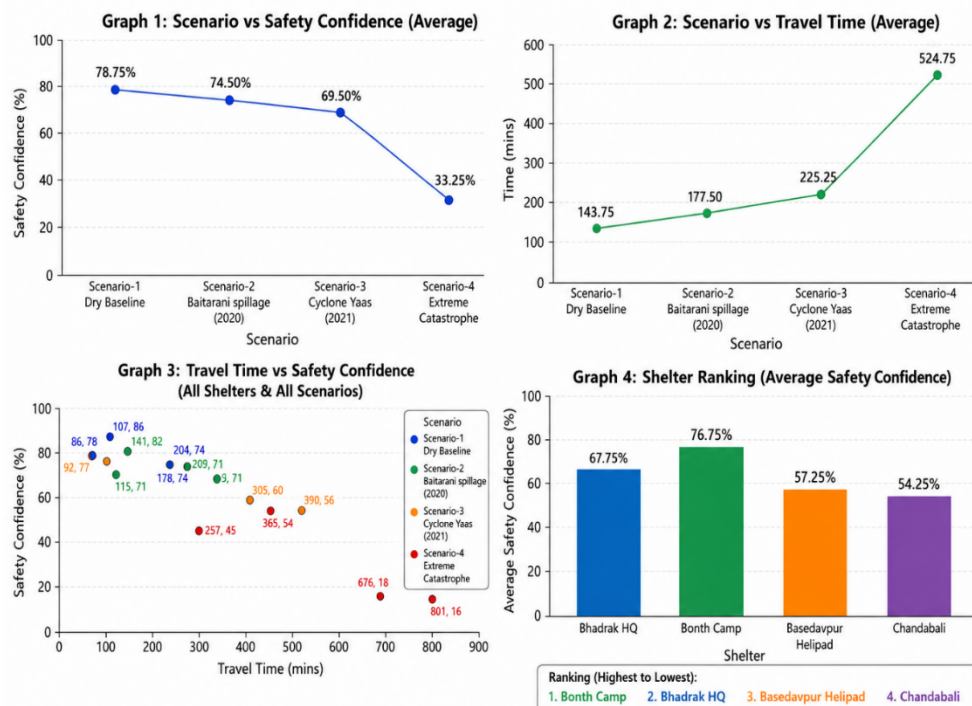


Fig 3. Comprehensive evaluation of shelter accessibility and route safety across simulated flood scenarios. (Graph 1) The progressive decline in average safety confidence (%) as flood severity escalates across the four scenarios; (Graph 2) The corresponding surge in average evacuation travel time (minutes); (Graph 3) A scatter distribution correlating travel time with safety confidence for all designated shelters under varying hazard conditions, highlighting the performance trade-offs; and (Graph 4) The overall ranking of the four primary evacuation shelters based on their average safety confidence scores.

3.3 Sensitivity Analysis of Spatial Parameters

Thorough sensitivity analysis enabled identification of the effects related to the individual weighting parameters used in MCDA (Flood Risk, Elevation, NH-16 Bias, and Marsh/Clay Friction) employed for the routing in the Baitarani Flood scenario (Table 3). The weights of the parameters were systematically changed from 0.5x to 3.0x while the other parameters were kept constant.

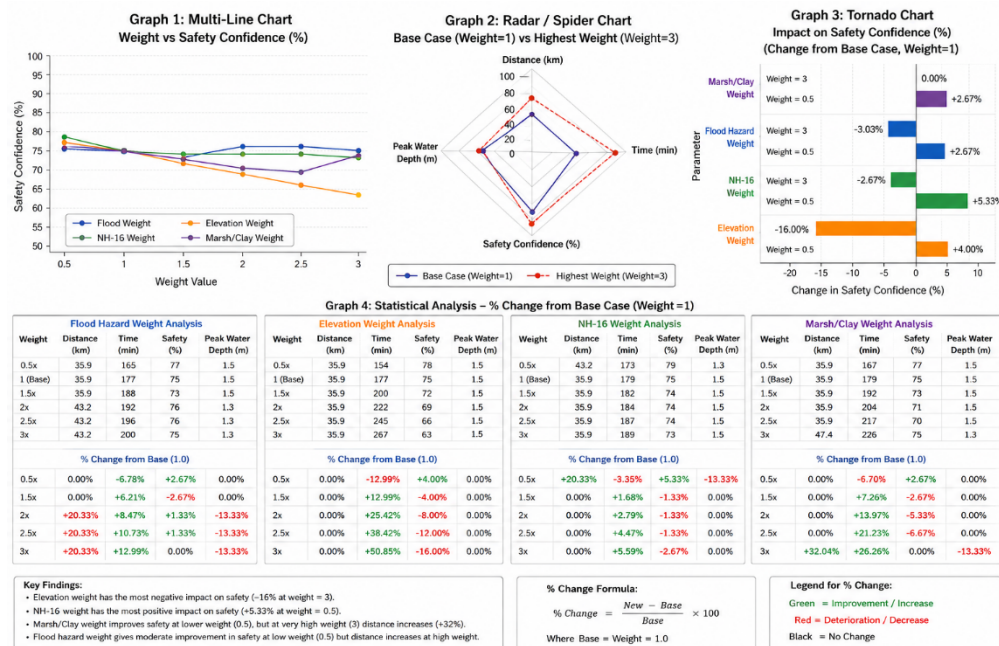
According to the results of the statistical analysis shown in Figure 4, elevation was found to be the most significant factor affecting the functioning of the proposed strategy. The results obtained from variations in elevation weight corresponded to a variation in safety confidence (63%-78%) and the maximum variation in evacuation travel time (154-267 minutes,

Table 3. Sensitivity of route optimization metrics to variations in spatial parameter weights (Flood Hazard, Elevation, NH-16 Accessibility, and Marsh/Clay Friction).

Method	Metric	0.5	1	1.5	2	2.5	3
Flood Hazard Weight	Distance (km)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	43.2 (1.3)	43.2 (1.3)	43.2 (1.3)
	Time (min)	165	177	188	192	196	200
	Safety Conf. (%)	77	75	73	76	76	75
Elevation Weight	Distance (km)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)
	Time (min)	154	177	200	222	245	267
	Safety Conf. (%)	78	75	72	69	66	63
NH-16 Weight	Distance (km)	43.2 (1.3)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)
	Time (min)	173	179	182	184	187	189
	Safety Conf. (%)	79	75	74	74	74	73
Marsh/Clay Weight	Distance (km)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	35.9 (1.5)	47.4 (1.3)
	Time (min)	167	179	192	204	217	226
	Safety Conf. (%)	77	75	73	71	70	75

The analysis was conducted for the **Baitarani flood scenario**, considering evacuation from the **Dhamnagar Grid (7,17; 20.9452° N, 86.4130° E)** to the **Bonth Camp Shelter Grid (4,3; 21.1342° N, 86.3695° E)**.

approximately 73% increase). Conversely, the variations in the weights of Flood Risk and Marsh/Clay Friction caused only minor fluctuations in safety (by 4% and 7%, respectively).

**Fig 4.** Sensitivity analysis illustrating the influence of MCDA parameter weighting on route safety confidence and distance metrics.

3.4 Impact of Escalating Flood Severity on Evacuation Metrics

In order to assess the robustness of the algorithms involved, evacuations in different circumstances were measured by their severity multipliers of cyclone severity in the range 0.5 to 3.2. The results demonstrated in Figure 5, that there is a direct and linear connection between hazard severity and duration of the route as the travel time increased from 162 to 203 minutes during the time when the number of primary road networks turned impassable

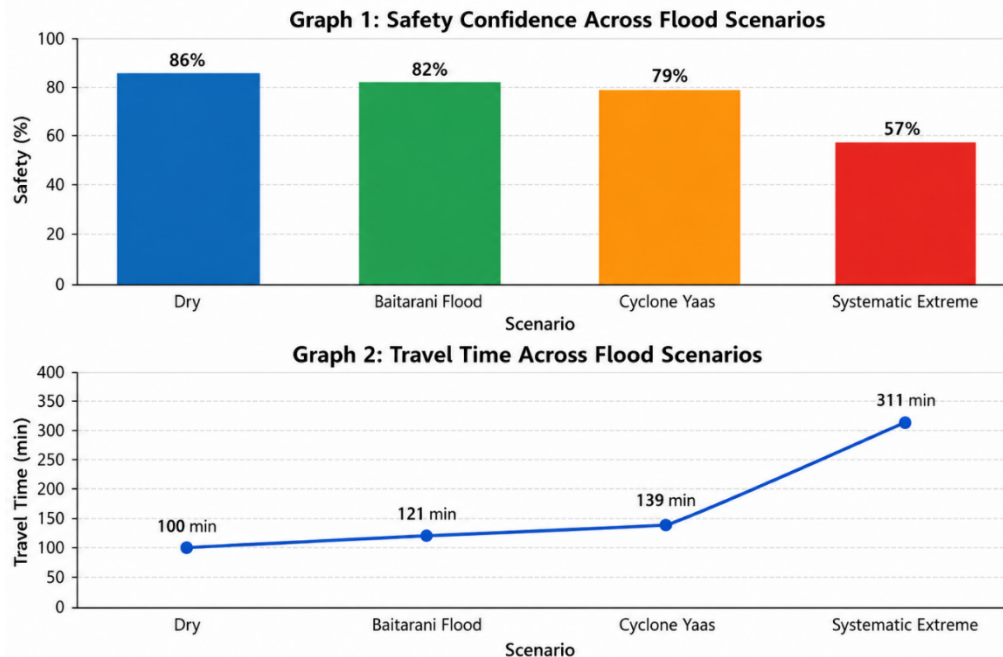


Fig 5. Impact of escalating flood severity on (Graph 1) average route safety confidence (%) and (Graph 2) cumulative evacuation travel time (minutes).

3.5 Validation and Benchmarking Analysis:

The developed A* MCDA methodology was verified by comparing its benchmarks with the traditional algorithms of Dijkstra Shortest Path and Euclidean Distance Routing based on the performance measures of travel distance, evacuation time, safety confidence, and maximum flood depth. Its robustness has been analysed by considering four different flood cases, shelter accessibilities analysis, one at a time sensitivity analysis, and weight perturbation between $0.5 \times$ and $3.0 \times$.

In Figure 6, the performance matrix, comparison is made between the proposed A-MCDA* approach and the traditional Dijkstra and Euclidean routing techniques through an assumed breaching of Baitarani River. The proposed approach chooses the route with the longest distance (27.7 km), but it has produced the shortest evacuation time (85 min) and high safety (87%). This happens because the proposed approach considers the flood hazard, elevation, accessibility, slope, and land use while designing the evacuation route. On the other hand, Dijkstra and Euclidean techniques choose shorter distance but have lower safety levels (81% and 78%, respectively).

4 Discussion

4.1 Algorithmic Adaptability Under Escalating Flood Severity

Data derived from this study shows that the A* heuristic search algorithm effectively alters evacuation routes by means of prioritizing high-elevation areas and avoiding highly flooded places as flood severity increases⁽¹⁴⁾. While total travel duration rises dramatically from 100 minutes in normal circumstances to 311 minutes during the Systemic Extreme Catastrophe, the A* heuristic algorithm ensures that the route is still viable. That is, because the algorithm knows when terrain becomes passable or impassable it is able to adjust routes dynamically⁽¹⁵⁾.

This behaviour demonstrates that the proposed GIS-MCDA framework prioritizes evacuation safety over shortest travel distance by integrating multiple spatial criteria into the routing process. Unlike conventional shortest-path approaches, the proposed method dynamically adapts to changing flood conditions, making it more suitable for compound flood scenarios. Similar observations have been reported in recent GIS-based dynamic evacuation studies⁽¹¹⁾,⁽¹³⁾,⁽¹⁵⁾.

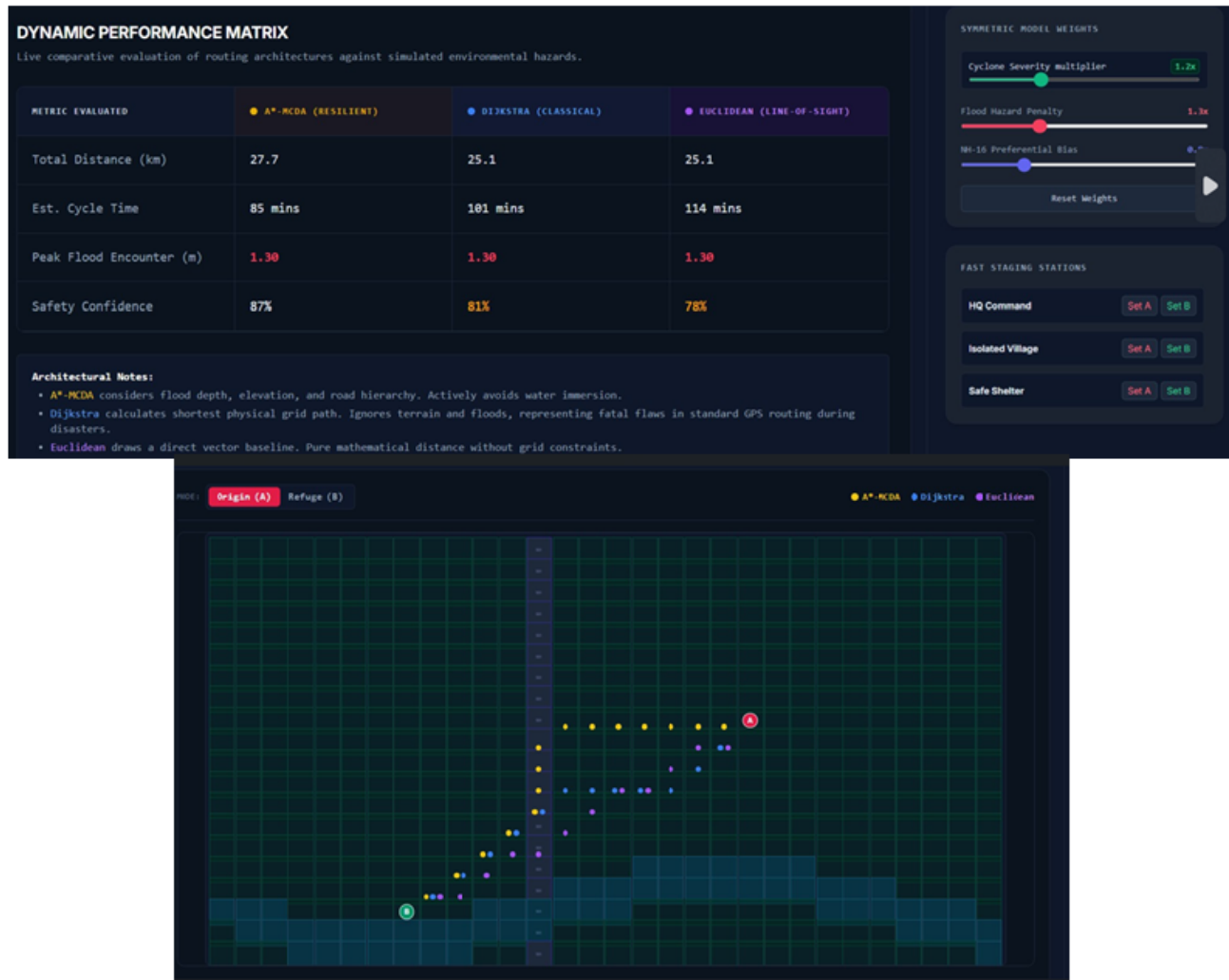


Fig 6. Comparative Performance Analysis of A-MCDA, Dijkstra, and Euclidean Routing Under Flood Conditions

4.2 Comparison Analysis on a Deep-Level

While Euclidean routing algorithm gives only the shortest geometric route without considering any hazards due to floods, the classical Dijkstra algorithm ensures shorter distance but is oblivious to flooding, hence sending vehicles through flooded routes. However, the proposed A*-MCDA approach considers the factors such as flood hazards, altitude, land cover, road accessibility, and terrain, thus facilitating adaptive hazard avoidance, detouring from the areas experiencing floods and flexible routing for various types of emergency vehicles. The benchmark results (Section 3.5) show that although the proposed method selects a slightly longer route (27.7 km), it achieves the shortest evacuation time (85 min) and the highest safety confidence (87%) compared with Dijkstra (81%) and Euclidean routing (78%). These results indicate that incorporating multiple spatial factors into the routing cost function improves operational efficiency and evacuation safety, consistent with previous studies on multi-criteria evacuation planning^{(3), (11), (13), (15)}.

4.3 Shelter Accessibility and Prioritization

The behavior of the matrix for the accessibility of shelters indicated considerable variation in the reliability of the specialized emergency shelter centres in Bhadrak district. Bhadrak HQ was the emergency location that provided the quickest accessibility to safety services as it occupied the best central position with good highway connectivity. Moreover, Bonth Camp turned out to

be very robust, as it had the highest average reliability of safety services (76.75%), thanks to its relief location on the land which protects it from river floods and coastal storm surges. In the opposite fashion, coastal emergency centres like the Chandbali emergency shelter turned out to be compromised during the cyclone surge scenario with very long travel times (411 minutes on average). These results are very consistent with the earlier geospatial studies which underline the importance of location-allocation modeling⁽¹⁶⁾ of emergency evacuation centres in the low-risk zones which are available during critical time periods in emergencies. Compared with conventional shelter planning approaches, the proposed framework additionally evaluates shelter performance under multiple flood scenarios, enabling emergency managers to identify shelters that remain operational under progressively severe hazards rather than under a single static flood condition.

4.4 Implications of the Spatial Sensitivity Analysis

According to the sensitivity analysis results, elevation plays a crucial role in route selection, leading to a variation of travel time of up to 73% and confidence in safety of even 15% when modifying the parameter weight artificially. This means that topographic variables should be considered significantly in a spatial cost model used in low-lying areas such as Bhadrak, where even small elevation changes influence flood vulnerability. By restricting the variables in question, this model suggests that effective evacuating models should rely solely on high-quality topographic data instead of assuming the distance and the depth of flooding as the main factors influencing routing. This finding agrees with previous flood risk assessment studies that identify elevation as one of the dominant factors governing flood exposure and evacuation accessibility in coastal environments^{(5), (10), (12)}. The sensitivity analysis also provides additional evidence of the robustness of the proposed model by demonstrating stable routing behaviour under systematic variations in parameter weights.

5 Conclusion

In this study, a GIS-based framework for generating dynamic flood evacuation routes for the flood prone area of Bhadrak district, Odisha was generated using MCDA and modified A least-cost path algorithm*. As opposed to shortest paths which are geometrically the shortest distances between two points, this framework includes factors such as flood hazard, road accessibility, elevation, slope, and land-use friction in the form of a spatial cost surface and helps generate optimal evacuation routes under varying flood situations.

The framework was assessed based on four increasing flood situations, showing that the framework consistently exhibited routing capability even under compound flooding situations. The evacuation time was increased from 100 min to 311 min, with respect to the Dry Baseline scenario, in the case of Systemic Extreme Catastrophe situation, where feasible evacuation routes have been produced even with a 33.72% reduction in safety confidence. In the shelter accessibility assessment, Bhadrak HQ has been identified as the most accessible shelter, with average evacuation time of 137.5 min, and Bonth Camp is the most resilient shelter, with the average safety confidence of 76.75%. Furthermore, sensitivity analysis indicates that terrain elevation is the most dominant criterion among other criteria, which produces a maximum variation of 73% of the evacuation time and 15% of safety confidence with respect to the change in its weight. In benchmark testing, it has been found that the proposed A*-MCDA route is little bit longer than the Dijkstra and Euclidean routing (27.7 km versus 25.1 km), but it produced minimum evacuation time (85 min) and highest safety confidence (87%).

The key strength of this study is its ability to combine dynamic multiple-scenario flood modelling, spatial cost models using MCDA, heuristic A optimization, accessibility evaluation of shelters, and sensitivity analysis* all within one GIS environment. In contrast to the majority of studies conducted in flood evacuation, which use static hazard maps or traditional shortest path routing, this approach allows the evacuation pathways to change depending on the development of the hazard and evaluates the impact of the main spatial variables on routing efficiency.

In terms of future research, the integration of real-time hydrological forecasting, traffic data, Internet-of-Things sensors, UAVs, and machine learning algorithms could further refine the process of adaptive routing considering changing flood scenarios. The model can also be expanded to incorporate multiple sources and shelters for evacuation and distribution of emergency vehicles. In terms of practical applications, this framework provides a useful tool for disaster management organizations and emergency response personnel.

6 Acknowledgements

Nil

Author details : Chaitanya Rao Bula is a Research Scholar; Dr. Vemu Sreenivasulu serves as Professor

References

- 1) Chelariu OE, Iațu C, Minea I. A GIS-Based Model for Flood Shelter Locations and Pedestrian Evacuation Scenarios in a Rural Mountain Catchment in Romania. *Water*. 2022;14(19):3074. <https://doi.org/10.3390/w14193074>.
- 2) Zhu W, Xing H, Kang W. Spatial Layout Planning of Urban Emergency Shelter Based on Sustainable Disaster Reduction. *International Journal of Environmental Research and Public Health*. 2023;20(3):2127. <https://doi.org/10.3390/ijerph20032127>.
- 3) Parajuli G, Neupane S, Kunwar S, Adhikari R, Acharya TD. A GIS-Based Evacuation Route Planning in Flood-Susceptible Area of Siraha Municipality, Nepal. *ISPRS International Journal of Geo-Information*. 2023;12(7):286. <https://doi.org/10.3390/ijgi12070286>.
- 4) Preisser M, Passalacqua P, Bixler RP, Boyles S. A network-based analysis of critical resource accessibility during floods. *Frontiers in Water*. 2023;5. <https://doi.org/10.3389/frwa.2023.1118314>.
- 5) Sawant S, C SK. A multidimensional approach to cyclone risk assessment: integrating GIS and Fuzzy-AHP data in coastal Odisha, India. *Geomatics, Natural Hazards and Risk*. 2025;16(1):2568948. <https://doi.org/10.1080/19475705.2025.2568948>.
- 6) Department IM. Report on Severe Cyclonic Storm "Yaas" over Eastcentral Bay of Bengal (23-28 May 2021). New Delhi, India. Ministry of Earth Sciences, Government of India. 2021.
- 7) Authority OSDM. District Disaster Management Plan: Bhadrak. Bhubaneswar, India. Government of Odisha. 2022.
- 8) Padhan N, Madheswaran S. An integrated assessment of vulnerability to floods in coastal Odisha: a district-level analysis. *Natural Hazards*. 2023;115:2351–2382. <https://doi.org/10.1007/s11069-022-05641-z>.
- 9) Gu X, Mao Y, Liu X. Urban flood risk assessment and evacuation planning: A bi-level optimization model for sustainable high-density coastal areas. *Annals of GIS*. 2025;31(1):15–27. <https://doi.org/10.1080/19475683.2025.2451236>.
- 10) Mishra M, Guria R, da Silva RM, Sethi S, Mishra M, Almazroui M, et al. Integrating machine learning and geospatial analysis for flood hazard, vulnerability, and risk assessment in Odisha, India. *Water Resources Management*. 2026;40:348. <https://doi.org/10.1007/s11269-026-04709-w>.
- 11) Liang J, Liu M, Zhang Z, et al. Shortest path planning and dynamic rescue forces dispatching for urban flood disasters. *Scientific Reports*. 2025;15:23643. <https://doi.org/10.1038/s41598-025-06374-2>.
- 12) Banerjee B, Karmakar P, Singh SK, Singh D, Patra B, Singh TP, et al. Spatial risk assessment of tropical cyclone for disaster mitigation in a coastal district of India using geospatial technology. *Journal of Atmospheric and Solar-Terrestrial Physics*. 2025;274:106602. <https://doi.org/10.1016/j.jastp.2025.106602>.
- 13) Cao S, Zhou Y, Tong Y, Ye R, Yang X, Zeng Y, et al. Dynamic evacuation route planning for urban residents in flood disasters. *Simulation Modelling Practice and Theory*. 2026;147:103250. <https://doi.org/10.1016/j.simp.2025.103250>.
- 14) Behera R, Kar A, Das MR, et al. GIS-based vulnerability mapping of the coastal stretch from Puri to Konark in Odisha using analytical hierarchy process. *Natural Hazards*. 2019;96:731–751. <https://doi.org/10.1007/s11069-018-03566-0>.
- 15) Zhu Y, Li H, Wang Z, Li Q, Dou Z, Xie W, et al. Optimal Evacuation Route Planning of Urban Personnel at Different Risk Levels of Flood Disasters Based on the Improved 3D Dijkstra's Algorithm. *Sustainability*. 2022;14(16):10250. <https://doi.org/10.3390/su141610250>.
- 16) Li D, Zhang Z, Alizadeh B, Zhang Z, Duffield N, Meyer MA, et al. A Reinforcement Learning Framework for Large-Scale Dynamic Route Planning in Urban Street Networks. *International Journal of Geographical Information Science*. 2024;38(1):183–215. <https://doi.org/10.1080/13658816.2023.2282299>.