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A GIS-BASED MULTICRITERIA APPROACH FOR IDENTIFYING OPTIMAL REFUGE LOCATIONS FOR SEVERE STORMS: A CASE STUDY IN CLUJ COUNTY, ROMANIA

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Abstract

In recent years, Romania has experienced an increasing frequency and intensity of severe storms, driven by climate change and resulting in amplified weather-related risks such as heavy rainfall, windstorms, and flash flooding. To enhance regional preparedness and support risk mitigation, this study proposes a GIS-based multi-criteria decision-making framework using the Analytic Hierarchy Process to identify optimal locations for severe storm refuges in Cluj County, Romania. Seven spatial factors were selected, consisting of elevation, slope, land use/land cover, population density, and proximity to roads, rivers, and healthcare facilities. Each factor was reclassified and weighted based on expert input and AHP pairwise comparisons, followed by a weighted overlay analysis in ArcGIS. The final suitability map categorizes the county into five classes: not suitable, less suitable, moderately suitable, suitable, and highly suitable. Results indicate that 68.67% of the total area (4569.5 km²) is moderately suitable, while only 0.07% (4.3 km²) is classified as highly suitable for refuge development. The most favourable areas are found near Cluj-Napoca, due to optimal elevation, gentle slopes, built-up and vegetated land cover, and high accessibility to infrastructure and services. This spatial approach offers a replicable model for enhancing disaster resilience in storm-affected regions of Eastern Europe.

Key words: *GIS, disaster preparedness, climate change, geospatial data, hierarchy classification.*

INTRODUCTION

In recent decades, high-intensity weather events - including cyclones, windstorms, and severe convective storms - have intensified globally (Hussainzad & Gou, 2024). While tropical cyclones are well-monitored, temperate regions now face more frequent non-cyclonic storms, such as derechos and tornadic supercells. These short-lived, localized events can produce flash floods, infrastructure damage, and fatalities, rivalling the impact of larger systems (Bammou et al., 2024). Between 1970 and 2019, such disasters caused nearly 1.9 million deaths and $1.965 trillion in losses worldwide, with risks amplified by urban sprawl, aging infrastructure, and limited preparedness. To mitigate these threats, monitoring systems and spatial risk assessment are essential (Sbihi et al., 2024). Tools like real-time mapping and geospatial modelling help identify hazard-prone zones and inform emergency planning. The integration of Geographic Information Systems (GIS) with multi-criteria decision analysis (MCDA), particularly the Analytic Hierarchy Process (AHP), has proven effective for vulnerability mapping and storm shelter planning (Mamun et al., 2024), strengthening both response strategies and long-term resilience.

In Romania, convective storms are becoming more frequent and intense, especially in regions like Cluj County. These events bring damaging winds, hail, floods, and tornado-like conditions, with thunderstorm activity reaching 270 to 390 hours annually. Wind gusts exceeding 30 m/s often disrupt infrastructure, and over 760,000 lightning flashes occur each year (Calotescu et al., 2024). Climate change has intensified these hazards through increased moisture, rising temperatures, and shifting airflows (Oprea, 2009), while thunderstorms have surpassed synoptic winds as the main driver of Romania's extreme wind climate (Cristian et al., 2024).

In this context, GIS has become essential for hazard mapping and shelter site selection (Bilașco et al., 2021). By integrating layers such as terrain, land use, hydrology, infrastructure, and demographics, GIS enables spatial analysis for planning and evacuation (Parajuli et al., 2023). Weighted overlays and remote sensing help classify land into suitability zones, improving infrastructure and emergency coordination (Khalaj et al., 2021).

AHP further supports this by ranking decision criteria through expert-driven pairwise comparisons (Das et al., 2024). It accommodates both physical and socio-economic factors (Swain et al., 2020), and its outputs, like weights and consistency ratios, increase transparency and replicability. Widely applied in shelter and hazard mapping (Hasan et al., 2024), AHP becomes more effective when embedded in GIS.

This study presents a GIS-AHP-based methodology to assess storm refuge suitability in Cluj County, Romania, an increasingly vulnerable region. It integrates environmental and infrastructural variables such as elevation, slope, land cover, proximity to rivers, roads, hospitals, and population density. By combining reclassification, weighted overlay, and spatial validation, it produces a suitability map to aid local planning. The approach enhances climate resilience in Central and Eastern Europe and serves as a replicable model for disaster preparedness in other hazard-prone regions.

MATERIALS AND METHODS

Study Area

Cluj County, situated in the heart of Transylvania, Romania, serves as the focal area for this study (Figure 1). Covering an area of 6,674 square kilometers, it ranks as the 12th largest county in the country, accounting for approximately 2.8% of Romania's total land area. Geographically, Cluj County is positioned between latitudes 46°24' and 47°28' N, and longitudes 23°39' and 24°13' E, encompassing a diverse landscape that includes the Apuseni Mountains, the Someș Plateau, and the Transylvanian Plain.

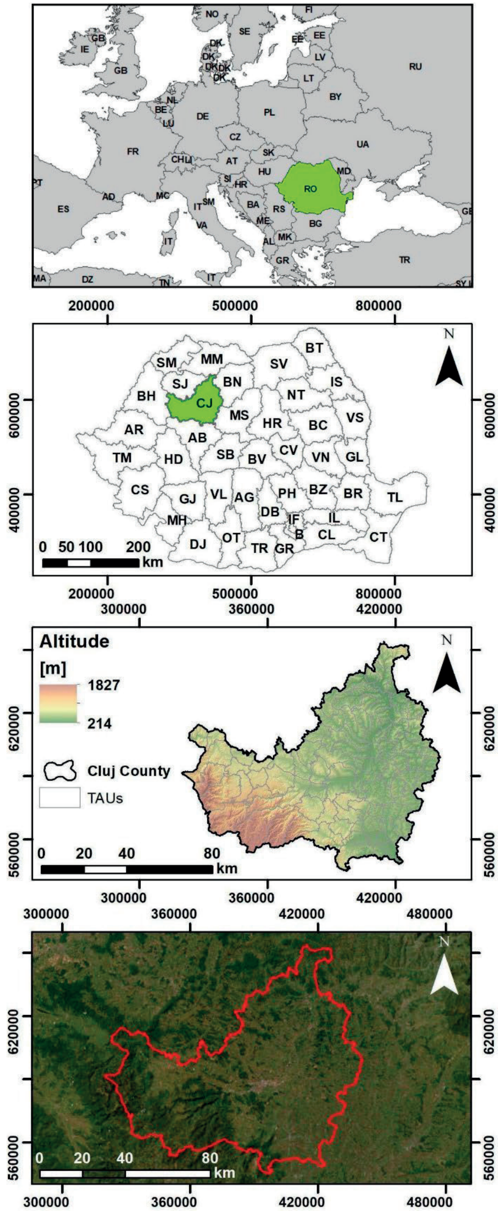

Figure 1. Location and geographic context of Cluj County, Romania. The panels show its position in Europe and within Romania, along with elevation variation and satellite imagery

Cluj-Napoca, the administrative centre of Cluj County and Romania's second-most populous city, is a major cultural and economic hub. The county features a mix of mountainous terrain and plains, creating diverse climate patterns that influence both weather conditions and

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infrastructure planning. This varied landscape necessitates tailored hazard mapping and shelter strategies, as local topography directly affects environmental risk and emergency preparedness.

Cluj County was selected due to its increasing exposure to severe convective storms and its strategic role in national disaster planning. Between 2013 and 2022, the county experienced 12 storm-related damage events, including a notable storm on September 17, 2017, with gusts reaching 28.4 m/s. Though historically not a tornado hotspot, Cluj has recorded events like the June 12, 1961, tornado, and rising mesocyclone activity suggests increasing vulnerability (Antonescu & Bell, 2015). Its position along the Carpathian foothills, combined with orographic and climatic factors, leads to frequent summer thunderstorms and high lightning activity (Stan-Sion & Antonescu, 2006). These conditions, especially in the Cluj-Napoca peri-urban zone, highlight the urgency for systematic refuge planning supported by geospatial analysis.

Methodological Approach

This study's methodological framework aims to identify optimal storm refuge locations in Cluj County, Romania, by integrating geospatial data with multicriteria decision-making. The approach includes spatial data collection, preprocessing, AHP-based evaluation, and GIS-weighted overlay analysis. The overall workflow is illustrated in Figure 2. The first step defined the study area within Cluj County, Romania, selected for its rising exposure to severe convective storms and recent documented damage. Geospatial datasets representing seven key variables, elevation, slope, land use/land cover (LULC), population density, and proximity to rivers, roads, and healthcare facilities, were collected from open-access and national sources to ensure spatial consistency for hazard mapping (Nap et al., 2022).

In the preprocessing phase, all data were harmonized in spatial resolution, coordinate system (Stereographic 1970), and study extent. Raster layers were resampled and reclassified into five ordinal suitability classes (1 to 5), enabling comparability and standardized overlay analysis.

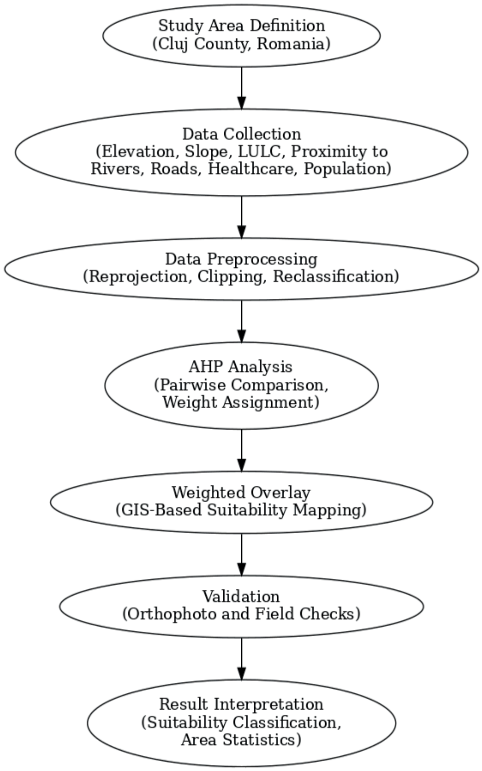

Figure 2. Methodological workflow used for severe storm refuge suitability assessment in Cluj County, Romania, integrating geospatial analysis, AHP-based factor weighting, GIS overlay, and validation steps

To assign importance to each criterion, the Analytic Hierarchy Process (AHP) was applied. Expert-based pairwise comparisons generated weights via the principal eigenvector method, and a consistency ratio ($CR < 0.1$) validated matrix coherence. This ensured a structured, transparent weighting process.

The core analysis used ArcGIS's weighted overlay tool. Each raster was multiplied by its corresponding AHP weight, and the weighted layers were then summed to generate a final suitability index, which was classified into five categories ranging from 'Not Suitable' to 'Highly Suitable'. Each raster was multiplied by its AHP weight, and the layers summed to produce a final suitability index, classified into five categories: not suitable to highly suitable. The resulting map identified optimal zones for storm shelters or natural refuges.

Model outputs were validated through visual comparisons with 2022 orthophoto imagery and expert review of known safe zones. "Highly suitable" areas were field-verified for feasibility. Spatial statistics and area metrics summarized storm preparedness potential across Cluj County.

Data Sources and Processing

The methodological strength of this study lies in the integration of geospatial datasets capturing Cluj County's physical, infrastructural, and demographic attributes. These serve as the foundation for the GIS-based multi-criteria analysis aimed at identifying optimal storm refuge sites (Bammou et al., 2024). Seven key thematic layers were selected, elevation, slope, land use/land cover (LULC), population density, and proximity to rivers, roads, and healthcare facilities, due to their relevance in assessing terrain accessibility, environmental risk, and infrastructure connectivity. As in comparable studies, these diverse datasets were converted into standardized raster layers with a uniform spatial resolution and reclassified on a common scale from 1 (not suitable) to 5 (highly suitable). This standardization ensured consistency and enabled integration through weighted overlay analysis. The careful selection and processing of these layers reflect local geographic realities while aligning with international disaster resilience frameworks, thereby enhancing the model's reliability, transferability, and practical relevance.

The geospatial database for this study was meticulously assembled to enable a robust multi-criteria evaluation of storm refuge suitability in Cluj County. Diverse spatial datasets were acquired based on their relevance to storm exposure, accessibility, and demographic vulnerability. Processing was conducted primarily using ArcGIS 10.8, which supported data reprojection, rasterization, reclassification, and spatial analysis (Sestras et al., 2019).

A core input was the 25 m/pixel resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM), from which both elevation and slope layers were derived - critical for assessing runoff, flood risk, and structural vulnerability (Sestras et al., 2023).

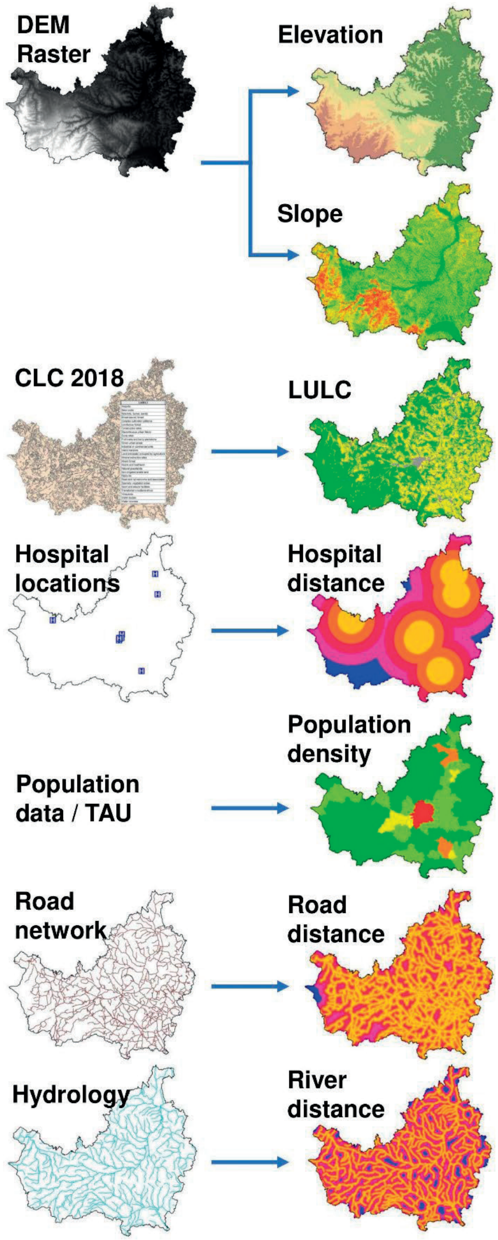

Figure 3. Input geospatial datasets used for storm refuge suitability assessment in Cluj County, including elevation, slope, land use/land cover (CLC 2018), distance to hospitals, population density, road network proximity, and distance to rivers

Land use and land cover were sourced from the Corine Land Cover 2018 (CLC 2018) dataset, developed under the Copernicus program. This standardized European classification system, mapped at 1:100,000, provided surface typologies such as urban, agricultural, and forested areas, each influencing storm impact and shelter feasibility (Popescu et al., 2024). Demographic layers, including population density and hospital proximity, were generated from Romanian government portals, producing rasters of population distribution and healthcare accessibility.

Hydrographic and transportation data were obtained as open-access shapefiles from national and EU platforms, then converted into continuous distance rasters representing proximity to rivers and roads, vital for minimizing flood exposure and ensuring emergency mobility. All raster layers were standardized in resolution, reclassified into five suitability classes, and structured for weighted overlay analysis. This spatial database forms the analytical core of the study, enabling a scientifically sound model for identifying suitable storm refuge zones amid increasing climate-related hazards.

RESULTS AND DISCUSSIONS

Spatial Distribution of Suitability Factors and Final Refuge Suitability Map

Elevation is a key factor in storm refuge planning, influencing both hazard exposure and accessibility. The Elevation Map of Cluj County (Figure 4), derived from 25-meter resolution SRTM data using ArcGIS 10.8, illustrates the county's varied terrain. Elevation was classified into five ranges, from 214 meters (lowest) to 1827 meters (highest), reflecting the topographic gradient from lowland basins and rolling hills in the east and northeast to rugged mountain zones in the south and southwest, notably the Apuseni Mountains.

Lower elevation zones (214-439 m), shown in dark green, are concentrated in the Someșul Mic valley and adjacent plains. These areas typically offer better infrastructure, higher population density, and easier evacuation, making them more suitable for storm refuges. In contrast, zones above 916 meters, marked in brown and orange, are less accessible and prone to hazards such as landslides or snow, making them unsuitable for rapid response or shelter deployment.

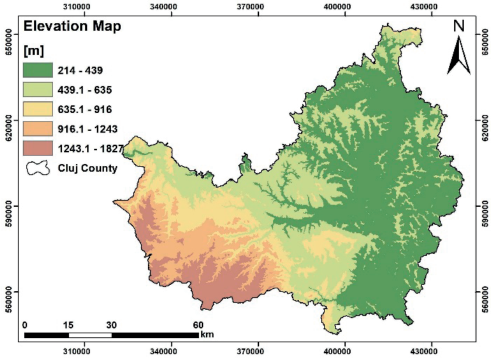

Figure 4. Elevation map of Cluj County derived from SRTM data, reclassified into five elevation ranges to support refuge suitability analysis based on terrain accessibility and storm-related exposure

In cyclone-prone areas, shelters are often built on elevated ground to avoid flooding. While Cluj County doesn't face storm surges, flash floods and heavy rainfall, intensified by climate change, pose serious risks. Thus, elevation must strike a balance: avoiding low-lying flood zones while remaining accessible. The 439-635 meter range was deemed optimal, minimizing flood risk without compromising access for emergency services.

Elevation also influences drainage, infrastructure stability, and emergency logistics. Moderately elevated areas with gentle slopes offer safer, more stable ground. The elevation layer was therefore reclassified to reflect these criteria, increasing the model's relevance for shelter site selection.

By aligning international shelter planning practices (Hasan et al., 2024) with local terrain, the elevation variable strengthens the model's utility for climate-resilient planning in Cluj.

Slope is another critical factor, affecting land use, construction feasibility, and resilience to storms. Derived from the 25-meter SRTM DEM, the slope map (Figure 5) classifies terrain into five categories, from gentle (0-9%) to very steep (49.1-87%). Low-gradient areas in the north and east are ideal for shelter siting due to ease of construction and accessibility, especially for vulnerable groups.

Steeper slopes, concentrated in the southern Apuseni foothills, are unsuitable because of erosion risks, poor access, and construction difficulty (Sestras et al., 2023). Slope also affects runoff, erosion, and infiltration (Costea et al., 2022). Research suggests ideal shelter sites lie on 2-5% slopes, not exceeding 7%, to support safe evacuation and emergency response. Steep areas exceed this threshold, reducing safety and logistics efficiency.

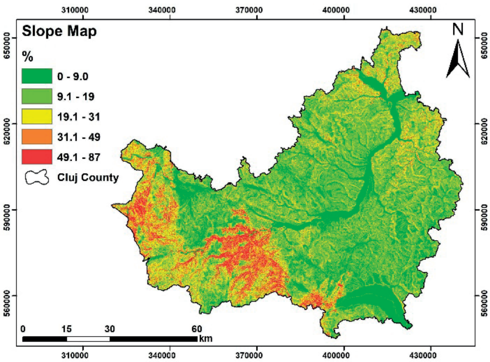

Figure 5. Slope classification map of Cluj County, derived from SRTM data, used to assess terrain suitability for storm refuges based on five slope categories ranging from flat to very steep

In this study, slope is used as a restrictive criterion, assigning higher suitability scores to flatter areas in the AHP model. This approach excludes high-risk or inaccessible terrain, aligning with international best practices, such as those from the IFRC, for emergency shelter siting. Including slope as a core biophysical factor enhances the model's ability to identify stable, accessible refuge zones and supports storm preparedness in diverse topographies.

Land Use and Land Cover (LULC) is another critical spatial variable influencing refuge suitability by affecting environmental stability, functionality, and site accessibility. The LULC map of Cluj County (Figure 6), developed from the Corine Land Cover 2018 dataset using ArcGIS 10.8, reflects five primary land types: agricultural land, vegetation (mainly forests), built-up areas, barren land, and water bodies (Bilașco et al., 2016).

Vegetation-dominated zones, especially in the west and south, overlap with hilly and mountainous terrain. While forests serve as natural buffers during storms and offer protection in rural or peripheral settings, they are generally rated as moderately suitable due to access limitations, rough terrain, and environmental restrictions (Curovic et al., 2020).

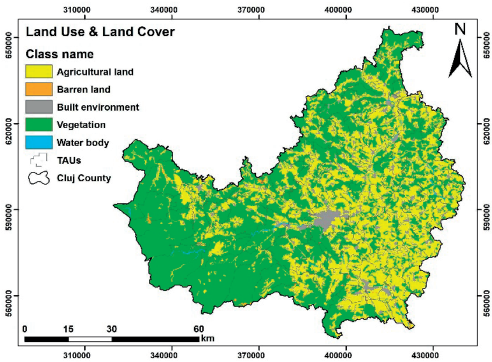

Figure 6. Land Use and Land Cover (LULC) map of Cluj County classified into five categories, supporting the assessment of land suitability for severe storm refuge placement

Agricultural lands, mainly in central and eastern Cluj County, lie on accessible, gently sloped terrain (Chiorean et al., 2024). Though primarily used for farming, they can accommodate storm refuges, especially on less cultivated or public plots. While generally rated as less suitable, with proper land-use planning they can support multipurpose shelter roles.

Built-up areas in cities like Cluj-Napoca, Turda, and Dej include schools and public buildings that are ideal for conversion into storm refuges. Their infrastructure and proximity to dense populations enhance suitability. However, urban congestion and limited space may restrict new shelter construction, reinforcing the need to integrate storm safety into existing urban design.

Barren land, though scarce, is typically open and underused, making it highly suitable for shelter development due to minimal environmental constraints. Conversely, water bodies and floodplains are unsuitable, being prone to flooding, unstable soils, and high exposure during extreme weather.

Including LULC in the multicriteria analysis offers a land-based understanding of site suitability, considering functional roles, adaptability, and environmental priorities (Chiorean et al., 2024). This helps balance refuge placement with ecological and development needs, supporting a more resilient storm preparedness strategy in Romania.

Population density is another crucial factor, indicating human exposure and emergency logistics needs. The Population Density Map (Figure 8), based on TAU-level data, categorizes values from 702 to 286,598 residents into five classes, from dark green (low) to red (high). This enables targeted refuge planning in high-risk, densely populated zones, where vulnerability and response demands are highest. The Population Density Map (Figure 7), derived from TAU-level data, classifies population values ranging from 702 to 286,598 residents into five categories, from dark green (low density) to red (high density). This classification supports targeted refuge planning in high-risk, densely populated areas where vulnerability and emergency response needs are highest.

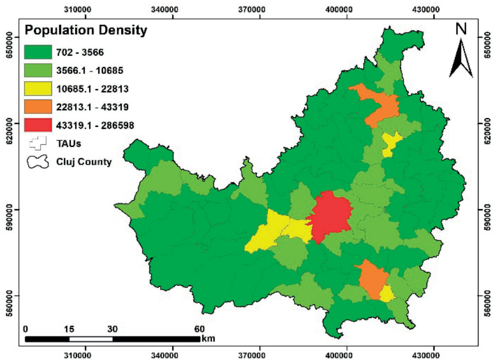

Figure 7. Population density distribution across Cluj County, categorized into five classes, highlighting high-density zones essential for prioritizing storm refuge locations

Cluj-Napoca, marked in red, is the demographic core of Cluj County, with significantly higher population density than surrounding areas. As the administrative and economic hub, it needs a well-distributed shelter network to ensure equitable access. Planning must consider limited space, urban mobility, and integration with existing public buildings, ideally within 1.5 km, following global guidelines for rapid access and minimal evacuation delays.

The orange and yellow zones, representing populations between 10,000 and 43,000 residents, encompass cities such as Turda, Dej, and surrounding peri-urban areas. While these zones are less densely populated, they often lack adequate emergency infrastructure, making them reliant on mobile or temporary shelters. Including these areas in the suitability model ensures that resources are distributed based on both density and spatial coverage.

Rural areas, shown in green, span most of the county but have sparse populations. Despite lower exposure, their isolation, weak healthcare access, and poor transport increase vulnerability. Smaller, strategically placed shelters are essential for timely response.

Population density was weighted in the AHP model to align site prioritization with real-world needs. Dense zones were prioritized for efficiency, while rural communities were considered proportionally to enhance regional resilience. This inclusive, people-centred approach supports equitable storm preparedness.

Access to healthcare is also crucial during and after storms. The Distance from Hospitals Map (Figure 8), created using Euclidean analysis in ArcGIS, divides proximity into five classes from 0 to over 44,000 meters. The most accessible zones, within 9,040 meters, appear in blue to orange and cluster around urban centres like Cluj-Napoca, Turda, Dej, and Huedin. These well-connected areas are ideal for shelters, ensuring rapid medical response during emergencies and improving survival outcomes.

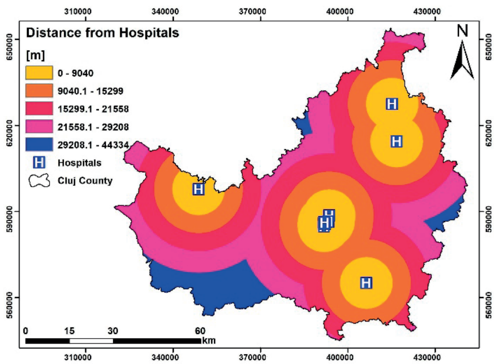

Figure 8. Euclidean distance from hospitals across Cluj County, classified into five distance zones, used to assess healthcare accessibility in emergency refuge site selection

Peripheral and southern rural areas, shown in dark pink and violet, fall into the least accessible zones, often over 29 km from the nearest hospital. These sparsely populated regions face major emergency challenges due to limited infrastructure. Shelters here risk delayed medical response unless supplemented with mobile clinics or stocked supplies. Thus, hospital proximity is a key constraint in determining site suitability.

Including hospital access in the MCDA framework ensures the model supports human-centred planning, not just physical analysis. Globally, co-locating shelters near medical services is best practice, as immediate access to trauma care, maternal support, and mental health services is vital during disasters. This is echoed in the Sendai Framework, which promotes healthcare resilience and coverage.

In Cluj County, where harsh winters and rural health disparities complicate access, hospital distance is crucial. Including it in the AHP model supports socially responsible storm shelter planning, using realistic travel thresholds to ensure emergency accessibility. Proximity to roads is another essential factor for refuge suitability. The Distance from Roads Map (Figure 9), produced via Euclidean analysis in ArcGIS 10.8, classifies areas within 545 meters of roads as highly suitable, while those beyond 5 km are least suitable. This variable has strong operational relevance. In Cluj's mountainous terrain, evacuation success hinges on road access. Studies show people often delay evacuation, so short, reliable access routes are crucial. Shelters near road networks reduce delays and serve vulnerable populations more effectively. In rugged areas, road proximity often determines whether a refuge is functionally viable.

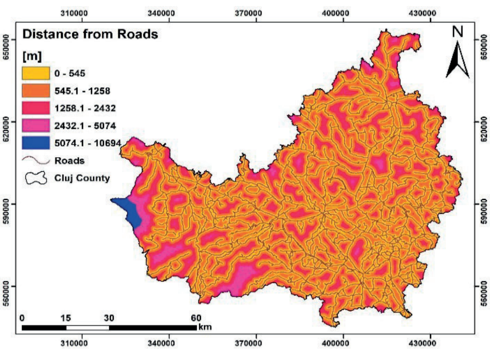

Figure 9. Road distance map of Cluj County showing Euclidean proximity to primary and secondary roads, essential for evaluating emergency accessibility and evacuation efficiency in storm refuge site planning

Most highly accessible zones in Cluj County, shown in yellow and orange, overlap with densely populated, economically active areas, making them ideal for storm refuge placement. In contrast, blue and purple areas in remote and forested regions have limited road access, increasing the risk of evacuation delays, isolation, and restricted emergency response during storms.

Including road proximity in the GIS-based multicriteria model ensures that shelters are not only structurally feasible but also functionally accessible. Prioritizing transport connectivity strengthens an inclusive, resilient shelter network serving both urban and rural communities facing climate-driven storm risks.

Proximity to rivers is equally important in assessing storm refuge suitability, as areas near watercourses are vulnerable to flooding, erosion, and overbank flow during heavy rainfall. Figure 10 shows Euclidean distance from Cluj County's river networks, grouped into five suitability classes, from 0-404 meters (least suitable) to 2073-4480 meters (most suitable). These were derived using hydrological vector data and ArcGIS 10.8 spatial analysis, clearly outlining flood-sensitive zones.

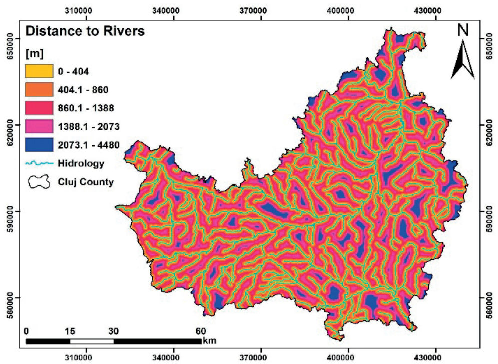

Figure 10. River distance map of Cluj County derived through Euclidean analysis, used to assess flood exposure and prioritize storm refuge sites located at safer distances from hydrological networks

Shelters near rivers face increased risks during storms due to overflow, runoff, and saturated soils. Evacuation delays or structural failures in these areas can threaten safety. Greater distances from rivers often align with higher elevation and slope, reducing flood exposure and improving shelter performance (Yang et al., 2022). This highlights the need to balance accessibility with environmental resilience.

Standard practice considers locations over 2 km from rivers as highly suitable, minimizing flood risk and supporting evacuation. In Cluj County, these zones, marked in blue, lie on interfluves and plateaus, offering secure and practical options. Areas within 860 meters of rivers (yellow to red) are less suitable and should be avoided.

Incorporating Distance to Rivers into the multicriteria analysis improves the overall resilience of the shelter network. It ensures sites are outside flood zones, helping to safeguard infrastructure, maintain emergency access, and enhance public safety.

The final Severe Storm Refuge Suitability Map for Cluj County (Figure 11) represents the output of a GIS-based multicriteria analysis (MCA) using the Analytic Hierarchy Process (AHP). It combines seven key spatial factors, elevation, slope, land use/land cover, population density, and proximity to rivers, roads, and hospitals, each contributing to the safe and accessible placement of storm refuges.

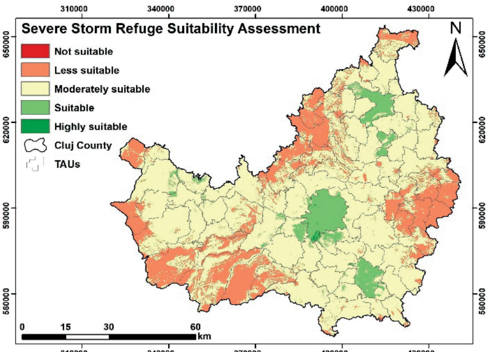

Figure 11. Final storm refuge suitability map for Cluj County, illustrating five suitability classes derived from weighted overlay analysis, integrating elevation, slope, land use, population density, and proximity to infrastructure and rivers

The process began with reclassifying each spatial factor into five standardized suitability classes, followed by a pairwise comparison matrix based on Saaty's (1987) AHP method, informed by expert input and field knowledge. The normalized weights prioritized healthcare proximity (25%) and population density (22%) due to their role in protecting vulnerable, high-density zones. These were followed by proximity to roads (18%) and elevation (16%) for access and hazard mitigation. Slope (7%), LULC (6%), and river distance (6%) had lesser weights due to localized variation.

A weighted overlay in ArcGIS 10.8 then generated a composite map categorizing Cluj County into five refuge suitability levels: Highly Suitable, Suitable, Moderately Suitable, Less Suitable, and Not Suitable. This serves as a clear decision-making tool for emergency planners and local authorities.

The results show that moderately suitable areas dominate the county's central region, with stable terrain and moderate access. Highly suitable zones are located around Cluj-Napoca and peri-urban areas, while mountainous and remote regions, particularly in the southwest and northeast, are largely unsuitable due to steep slopes and limited infrastructure.

Overall, the map offers a reliable, integrated planning tool, combining topographic, infrastructural, and demographic data to support informed storm preparedness and climate resilience strategies.

Interpretation of Suitable Refuge Zones: Spatial Insights and Planning Implications

The final composite figure presents the GIS-based multi-criteria analysis results, showing storm refuge suitability across Cluj County. Generated through an AHP-guided weighted overlay, the map categorizes the area into five classes: not suitable, less suitable, moderately suitable, suitable, and highly suitable. Supporting charts indicate that 68.67% of the region is moderately suitable, while only 0.07% (4.308 km²) qualifies as highly suitable, reflecting the stringent conditions for optimal shelter placement.

A notable highly suitable area is the Făget neighbourhood in southern Cluj-Napoca, characterized by moderate elevation, low slopes (<5%), and a mix of built-up and vegetated land, enhancing accessibility and natural buffering. Its proximity to roads and hospitals and distance from rivers further improve suitability, as assessed through Euclidean distance metrics.

A detailed zoom-in, overlaid with orthophoto imagery, validates the GIS outputs and supports local-scale planning. This visualization serves as a tool for municipal authorities to prioritize interventions and guide resource distribution.

The study aligns with global emergency planning standards, where factors like elevation, slope, and infrastructure access are central to GIS-AHP approaches. Its successful adaptation to Romania's varied terrain demonstrates the method's versatility. By combining spatial analysis with policy-relevant insights, the study offers a transferable model for disaster preparedness in Eastern Europe and similar regions.

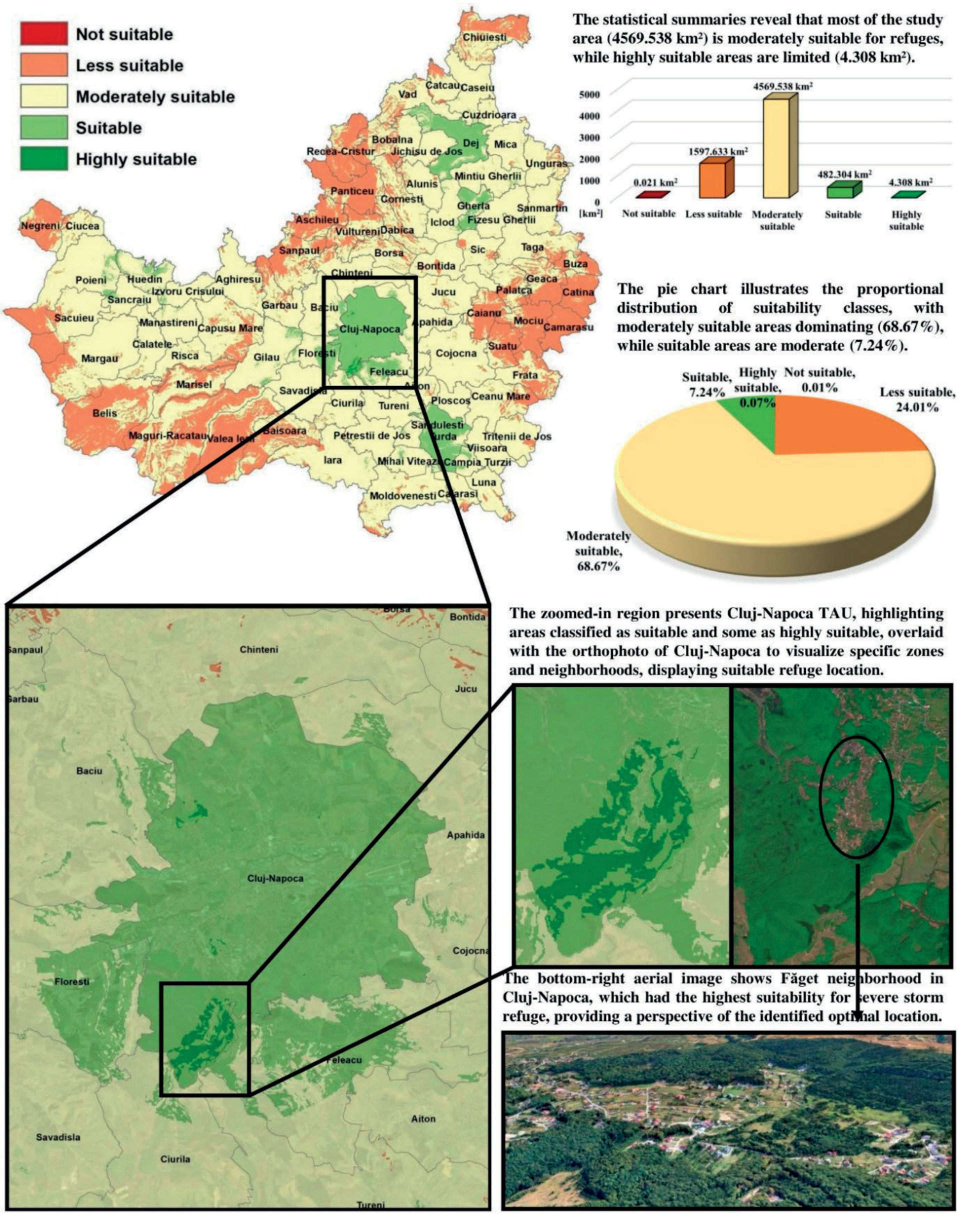

Figure 12. Spatial and statistical synthesis of the final storm refuge suitability analysis in Cluj County, highlighting highly suitable zones around Cluj-Napoca. Includes area statistics, proportional class distribution, orthophoto overlays, and aerial imagery of Făget neighbourhood, identified as the optimal refuge location

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CONCLUSIONS

This study employed a GIS-based multicriteria approach to identify optimal storm refuge locations in Cluj County, Romania, an area increasingly exposed to extreme weather due to climate change. Using the Analytic Hierarchy Process, seven critical factors were weighted: elevation, slope, population density, land use/land cover, and proximity to rivers, roads, and healthcare facilities.

The final suitability map, validated through orthophoto overlays and field verification, showed that most of the county (68.67%) is moderately suitable, while only 0.07% is highly suitable. The Făget neighbourhood in Cluj-Napoca stood out as an ideal refuge site due to its balanced elevation, low slopes, strong infrastructure access, and diverse land cover.

These results demonstrate the value of GIS-AHP models for disaster risk reduction and spatial planning. The methodology offers a replicable, objective framework for shelter site selection, providing a model for climate resilience strategies not only in Romania but across other vulnerable regions in Eastern Europe.

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REFERENCES

Antonescu, B., & Bell, A. (2015). Tornadoes in Romania. *Monthly Weather Review*, 143(3), 689-701.

Bammou, Y., Benzougagh, B., Igmoullan, B., Kader, S., Ouallali, A., Spalevic, V., ... & Kuriqi, A. (2024). Spatial mapping for multi-hazard land management in sparsely vegetated watersheds using machine learning algorithms. *Environmental Earth Sciences*, 83(15), 447.

Bammou, Y., Benzougagh, B., Igmoullan, B., Ouallali, A., Kader, S., Spalevic, V., ... & Marković, S. B. (2024). Optimizing flood susceptibility assessment in semi-arid regions using ensemble algorithms: a case study of Moroccan High Atlas. *Natural Hazards*, 120(8), 7787-7816.

Bilaşco, Ş., Roşca, S., Păcurar, I., Moldovan, N., Boţ, A., Negrușier, C., ... & Naș, S. (2016). Identification of land suitability for agricultural use by applying morphometric and risk parameters based on GIS spatial analysis. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 44(1), 302-312.

Bilașco, Ș., Roșca, S., Vescan, I., Fodorean, I., Dohotar, V., & Sestras, P. (2021). A GIS-based spatial analysis model approach for identification of optimal hydrotechnical solutions for gully erosion stabilization. Case Study. *Applied Sciences*, 11(11), 4847.

Calotescu, I., Chitez, A. S., Birsan, M. V., Micu, D., & Dumitrescu, A. (2024). Assessment of thunderstorm-prone areas in Romania based on wind damage occurrence and surface observation data. *Journal of Wind Engineering and Industrial Aerodynamics*, 250, 105765.

Chiorean, S., Arion, I. D., Sălăgean, T., Nap, M. E., Șuba, E. E., & Colișar, A. (2024). The Impact of Market Analysis in Determining the Market Value of Agricultural Land in Romania. *Scientific Papers Series Management, Economic Engineering in Agriculture & Rural Development*, 24(1).

Chiorean, S., Coroian, I., Sălăgean, T., Nap, M. E., Deak, J., & Luput, I. (2024). Global Trends on Research Towards the Valuation Process of an Agriculture Land. *Scientific Papers Series Management, Economic Engineering in Agriculture & Rural Development*, 24(2).

Costea, A., Bilasco, S., Irimus, I. A., Rosca, S., Vescan, I., Fodorean, I., & Sestras, P. (2022). Evaluation of the risk induced by soil Erosion on land use. Case study: Guruslău depression. *Sustainability*, 14(2), 652.

Cristian, A., Zuzeac, M., Ciocan, G., Iorga, G., & Antonescu, B. (2024). A Thunderstorm Climatology of Romania (1941–2022). *Romanian Reports in Physics*, 76, 710.

Curovic, M., Spalevic, V., Sestras, P., Motta, R., Dan, C., Garbarino, M., ... & Urbinati, C. (2020). Structural and ecological characteristics of mixed broadleaved old-growth forest (Biogradska Gora-Montenegro). *Turkish journal of Agriculture and Forestry*, 44(4), 428-438.

Das, T., Talukdar, S., Naikoo, M. W., Ahmed, I. A., Rahman, A., Islam, M. K., & Alam, E. (2024). Integration of fuzzy AHP and explainable AI for effective coastal risk management: A micro-scale risk analysis of tropical cyclones. *Progress in Disaster Science*, 23, 100357.

Hasan, I., Faruk, M. O., Katha, Z. T., Goni, M. O., Islam, M. S., Chakraborty, T. R., ... & Hossain, M. S. (2024). Geo-spatial based cyclone shelter suitability assessment using analytical hierarchy process (AHP) in the coastal region of Bangladesh. *Heliyon*, 10(21).

Hussainzad, E. A., & Gou, Z. (2024). Climate Risk and Vulnerability Assessment in Informal Settlements of the Global South: A Critical Review. *Land*, 13(9), 1357.

Khalaj, M. R., Noor, H., & Dastranj, A. (2021). Investigation and simulation of flood inundation hazard in urban areas in Iran. *Geoenvironmental Disasters*, 8, 1-13.

Mamun, M. A. A., Zhang, L., Chen, B., Rahman, Z. U., Mahzabin, T., Zuo, J., ... & Reza, S. A. (2024). Assessment of spatial cyclone surge susceptibility through GIS-based AHP multi-criteria analysis and frequency ratio: a case study from the Bangladesh coast. *Geomatics, Natural Hazards and Risk*, 15(1), 2368071.

Mourato, S., Fernandez, P., Pereira, L. G., & Moreira, M. (2023). Assessing vulnerability in flood prone areas using analytic hierarchy process - group decision making and geographic information system: a case study in Portugal. Applied Sciences, 13(8), 4915.

Nap, M. E., Ficior, D., Sălăgean, T., Pop, I. D., Matei, F., Coroian, I., ... & Şuba, E. E. (2022). A GIS study about forest management in Strâmbu Baiut. *Bulletin of University of agricultural sciences and veterinary medicine Cluj-Napoca. Horticulture,* 79(1), https://doi.org/10.15835/buasvmcn-hort:2021.0025

Oprea, C. I. (2009). A torrential precipitation event in the eastern part of Romania–a case study. *Romanian reports in physics*, 61(1), 139-150.

Parajuli, G., Neupane, S., Kunwar, S., Adhikari, R., & Acharya, T. D. (2023). A GIS-based evacuation route planning in flood-susceptible area of Siraha municipality, Nepal. *ISPRS International Journal of Geo-Information*, 12(7), 286.

Popescu, G., Popescu, C. A., Dragomir, L. O., Herbei, M. V., Horablaga, A., Ţenche-Constantinescu, A. M., ... & Sestras, P. (2024). Utilizing UAV technology and GIS analysis for ecological restoration: A case study on Robinia pseudoacacia L. in a mine waste dump landscape rehabilitation. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 52(4), 13937-13937.

Saaty, R. W. (1987). The analytic hierarchy process - what it is and how it is used. *Mathematical modelling*, 9(3-5), 161-176.

Sbihi, A., Mastere, M., Benzougagh, B., Spalevic, V., Sestras, P., Radovic, M., ... & Kader, S. (2024). Assessing landslide susceptibility in northern Morocco: A geostatistical mapping approach in Al Hoceima-Ajdir. *Journal of African Earth Sciences*, 218, 105361.

Sestras, P., Mircea, S., Cîmpeanu, S. M., Teodorescu, R., Roșca, S., Bilașco, Ș., ... & Spalević, V. (2023). Soil erosion assessment using the intensity of erosion and outflow model by estimating sediment yield: Case study in river basins with different characteristics from Cluj County, Romania. *Applied Sciences*, 13(16), 9481.

Sestras, P., Mircea, S., Roșca, S., Bilașco, Ș., Sălăgean, T., Dragomir, L. O., & Kader, S. (2023). GIS based soil erosion assessment using the USLE model for efficient land management: a case study in an area with diverse pedo-geomorphological and bioclimatic characteristics. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 51 (3): 13263-13263.

Sestraș, P., Sălăgean, T., Bilașco, S., Bondrea, M. V., Naș, S., Fountas, S., & Cîmpeanu, S. M. (2019). Prospect of a GIS based digitization and 3D model for a better management and land use in a specific micro-areal for crop trees. *Environmental Engineering and Management Journal*, 18(6), 1269-1277.

Stan-Sion, A., & Antonescu, B. (2006, November). Mesocyclones in Romania–characteristics and environments. In *Preprints of the 23rd Conference on Severe Local Storms. St. Louis, MO*.

Swain, K. C., Singha, C., & Nayak, L. (2020). Flood susceptibility mapping through the GIS-AHP technique using the cloud. *ISPRS International Journal of Geo-Information*, 9(12), 720.

Yang, F., Xiong, S., Ou, J., Zhao, Z., & Lei, T. (2022). Human settlement resilience zoning and optimizing strategies for river-network cities under flood risk management objectives: taking Yueyang City as an example. *Sustainability*, 14(15), 9595.