 e-ISSN 2682-7727 https://doi.org/10.17576/geo-2026-2203-02

Beyond spatial coverage: Analysing capacity deficits and population pressure in Kuantan's flood evacuation network using GIS-Kriging

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Received: 18 February 2026; Accepted: 15 May 2026; Published: 26 August 2026

Abstract

This study examines the spatial and capacity deficiencies of the evacuation centre (EC) network in Kuantan, Pahang, highlighting critical implications for flood risk management and urban resilience. Despite residential land use occupying only 2% of the total area, approximately 71% of residential zones are located within designated flood-prone areas, exposing many residents to significant flood risks. Service area analysis indicates that only 35% of residential land falls within a 1-km travel distance of existing ECs, revealing inadequate accessibility. Capacity analysis further uncovers spatial inequities, with a projected population of 548,000 in 2025 being able to be accommodated by only 6% of the current EC capacity. This gap raises concerns about emergency planning effectiveness during large-scale flood events, potentially leading to overcrowding and increased reliance on informal shelters. The study emphasizes the need for targeted interventions to enhance EC capacity and accessibility, particularly in flood-prone zones and densely populated urban areas. By integrating site suitability assessments with capacity and service area analyses, the research provides a comprehensive framework for optimizing evacuation infrastructure, ultimately fostering a more equitable and resilient community prepared for flood-related risks in Kuantan.

Keywords: Capacity, evacuation centre, flood risk management, GIS, population, Urban resilience

Introduction

Flooding is one of the most recurrent and destructive climate-related hazards in Southeast Asia, with its severity intensified by climate change and increasingly extreme monsoonal rainfall patterns. Across the region, shifts in precipitation have led to prolonged and intense rainfall events, significantly elevating flood risk in countries like Malaysia, which is situated within the tropical monsoon climate zone (Chan, 1997; Rosmadi et al., 2023). Seasonal monsoons affecting Malaysia's East Coast, particularly in Kelantan, Terengganu, and Pahang, frequently result in severe flooding episodes that cause extensive infrastructure damage, disrupt economic activities, increase public recovery expenditures, and impose long-term socio-economic impacts on local communities.

Kuantan, the capital city of Pahang, is particularly vulnerable to flooding due to its proximity to major river systems, low-lying coastal topography, rapid urban expansion, and limited flood management capacity (Isahak et al., 2018; Mabahwi & Nakamura, 2024). These factors often necessitate large-scale evacuations during flood events, highlighting the critical role of well-planned evacuation centres (ECs) in providing temporary shelter and essential services. Poorly located ECs can exacerbate evacuation challenges, leading to issues such as accessibility problems, overcrowding, and increased vulnerability among displaced populations (Papilloud et al., 2024).

Geographic Information Systems (GIS) offer a powerful framework for evaluating the spatial distribution, accessibility, and adequacy of evacuation centres. This study employs GIS-based spatial analysis to examine the alignment of EC locations with residential areas, flood-prone zones, and population distribution in Kuantan. By integrating service area analysis, site suitability assessment, and population density data, the research identifies spatial deficiencies and coverage gaps within the existing evacuation infrastructure (Mabahwi et al., 2025).

While previous studies have established the physical suitability of shelter sites (Mabahwi & Nakamura, 2024) and highlighted spatial coverage limitations (Mabahwi et al., 2025), a critical research gap remains regarding the adequacy of EC operational capacity relative to population densities during flood events. This study aims to address this gap by providing evidence-based recommendations for optimizing EC placement, strengthening disaster preparedness, and enhancing community resilience. Through the effective application of GIS technology, this research contributes to improved evacuation planning and more equitable protection of vulnerable populations in flood-prone urban areas.

Literature review

Flooding poses a significant threat to urban transport networks, often resulting in severe and disproportionate disruptions to accessibility. Empirical and modeling studies consistently demonstrate that flood-induced road network failures exhibit nonlinear behaviour, where relatively small disruptions can trigger extensive accessibility losses. For instance, probabilistic percolation modeling reveals that the inundation or failure of just 2% of critical road segments near floodway may cause approximately a 20% reduction in access to healthcare facilities, with cascading effects extending up to 9 miles beyond the flooded area (Dong et al., 2020). These findings underscore the sensitivity of urban transport networks to flooding and highlight the importance of network robustness over assessments based solely on direct flood exposure.

Hydrological and hydrodynamic flood models integrated with GIS-based network analysis further reveal that flood depth and duration are key determinants of mobility degradation. Depth-disruption functions, which quantify speed reductions or complete road closures based on inundation depth, are widely used to assess flood impacts on vehicle movement. Studies indicate that EC are particularly vulnerable, with 23%-47% of residential and working populations losing access during flood events, compared to relatively lower impacts on fire and police services (Tsang & Scott, 2020). This shows that flood impacts on accessibility are both service-specific and highly dependent on network topology and flood characteristics.

Traditional accessibility assessments typically rely on static assumptions regarding travel speed, population distribution, and network conditions. However, recent research increasingly adopts dynamic and spatiotemporal approaches, integrating flood simulations with time-varying network analysis. These studies demonstrate that accessibility losses vary substantially over time and space: areas near flood sources may experience complete isolation, while peripheral areas may temporarily benefit from rerouting effects (Papilloud et al., 2024). Importantly, accessibility recovery is often slow and uneven, with certain communities remaining underserved long after floodwaters recede (Papilloud & Keiler, 2021), a temporal vulnerability often overlooked in static planning models.

Service area analysis is a core method for evaluating the spatial reach of emergency services and evacuation facilities under both normal and disrupted conditions. Common approaches define coverage using distance- or time-based thresholds, typically ranging from 10 to 60 minutes. Floating Catchment Area (FCA) methods, including the Two-Step FCA (2SFCA), Enhanced 2SFCA (E2SFCA), and Three-Step FCA (3SFCA), have been widely used to measure EC accessibility, explicitly incorporating service capacity, distance decay, and travel time constraints (Li et al., 2021; Zheng et al., 2024).

Recent methodological advances integrate real-time or navigation-grade network data through routing engines such as the Open-Source Routing Machine (OSRM), significantly improving the realism of travel time estimation under flood-disrupted conditions (Papilloud et al., 2024). These studies consistently show that flooding dramatically contracts service areas, particularly during extreme events. While frequent (5-year) and moderate (20-year) pluvial floods tend to have minor impacts on overall Fire and Rescue Service (FRS) coverage, extreme (100-year) surface water flooding can reduce FRS service areas by up to 13% and EC coverage by up to 19% at the city scale. Under congested traffic conditions, response delays may exceed 30 minutes for over 40% of critical facilities (Yin et al., 2021).

Time-distance evacuation mapping that incorporates elevation and flood depth further demonstrates that flood conditions significantly narrow evacuation service areas by increasing travel impedance or eliminating viable routes (Kim & Park, 2019). Models accounting for road cuts and capacity loss show that evacuation performance remains acceptable only when alternative routes and safety points are strategically planned, reinforcing the need for flood-aware and capacity-sensitive service area analysis (Irsyad & Nakamura, 2022).

Beyond spatial accessibility, shelter capacity constraints and overcrowding play a decisive role in evacuation effectiveness. Multiple studies reveal that evacuation efficiency is more sensitive to the distribution of shelter capacity than to total capacity alone (Sritart et al., 2020). Nonuniform capacity distributions lead to rapid saturation of smaller shelters, forcing evacuees to travel longer distances and substantially increasing overall evacuation duration.

Flooding exacerbates capacity constraints by physically disabling shelters. Empirical evidence shows that more than half of designated evacuation shelters in some cities are themselves vulnerable to flooding, resulting in drastic reductions in effective capacity (e.g., from over 3,000 to approximately 1,300 places) (Sritart et al., 2020). Consequently, only a small fraction of the total population, often far below technical planning standards, can realistically access shelters, with elderly and other vulnerable groups disproportionately affected.

Location-allocation studies using models such as the Location Set Covering Problem (LSCP), p-median, and Maximal Covering Location Problem (MCLP) demonstrate that increasing allowable travel distance (e.g., from 3 km to 10 km) and permitting split allocation of households can significantly improve coverage (Rahman et al., 2021). However, even under these relaxed assumptions, existing shelter capacity remains insufficient to accommodate all evacuees. Moreover, increasing the number of shelters without strategic siting may not alleviate overcrowding and can even degrade system-wide performance, consistent with the Braess paradox (Du et al., 2023).

Capacity constraints extend beyond shelters to the transportation system itself. Studies consistently show that evacuation performance deteriorates sharply as traffic conditions shift from free flow to congestion. Under worst-case traffic scenarios combined with extreme flooding, response delays of up to 6 minutes for emergency services and over 30 minutes for evacuation routes have been observed (Yin et al., 2021).

Evacuee behaviour further amplifies congestion effects. While most evacuees tend to follow the most direct routes, often aligned with high normalized angular choice (NACH) in space syntax analyses, vulnerable groups such as women and the elderly are more likely to detour toward perceived safer paths, increasing travel time and unevenly redistributing demand across the network (Irsyad & Hitoshi, 2022). Low heterogeneity in departure times and uncoordinated route choices can intensify congestion, significantly reducing system-level evacuation efficiency.

Strategic interventions, such as restricting access to high-risk flooded roads, promoting vertical evacuation shelters, optimizing vehicle deployment through split delivery and multi-trip strategies, and increasing the number of safety points, have been shown to partially mitigate these capacity-related challenges (Coles et al., 2017).

An emerging body of literature emphasizes that physical accessibility alone is insufficient to capture flood-related service vulnerability (Dong et al., 2020). Studies integrating sociodemographic indicators, such as income, age, vehicle ownership, and household composition, demonstrate that communities with lower socio-economic status often exhibit lower tolerance to service disruptions, even when nominal accessibility appears adequate. Advanced metrics, including the Disruption Tolerance Index (DTI), Gini coefficients, Lorenz curves, and regression-based methods (OLS and GWR), reveal spatial clusters where high physical exposure coincides with low social resilience. These findings indicate that capacity constraints and overcrowding disproportionately affect socially vulnerable populations, reinforcing inequities during flood events.

Optimization modeling has been widely applied to improve the spatial efficiency and equity of emergency service provision. Approaches such as MCLP, quadratic programming, greedy algorithms, and multi-objective optimization show that two-step models combining location and capacity allocation generally outperform single-objective methods. Scenario-based models incorporating flood-induced travel cost changes further demonstrate that accessibility is highly sensitive to road connectivity during disasters (Li et al., 2022).

Despite these advances, most optimization studies focus on response-oriented services, while ECs receive comparatively limited attention, particularly in flood-prone cities in Malaysia. Furthermore, evacuation centre planning is often conducted under static assumptions, with insufficient consideration of flood exposure, dynamic accessibility degradation, and shelter capacity loss.

To address these gaps, this study proposes a GIS-based integrated framework that combines site suitability analysis, shelter capacity assessment, and flood-aware service area analysis to evaluate and optimize the spatial distribution of evacuation centres in Kuantan, Pahang. By explicitly incorporating flood risk, population distribution, and accessibility degradation, the study aims to contribute to more resilient, efficient, and equitable flood evacuation planning in Malaysia.

Method and study area

As the most densely populated urban centre on Malaysia's East Coast, Kuantan faces a unique "evacuation bottleneck" during flood events, where high population concentration places substantial pressure on limited evacuation infrastructure. While previous studies have extensively documented Kuantan's susceptibility to flooding (Mabahwi, 2024; 2025), these assessments have largely focused on hazard exposure and flood characteristics. In contrast, this study shifts attention toward the demographic pressure exerted on existing evacuation infrastructure, particularly ECs, during emergency situations.

Kuantan's flood vulnerability is further compounded by its geographical and environmental context. The city is located in close proximity to major river systems, including the Kuantan River Basin, and is characterised by low-lying coastal terrain, which increases exposure to fluvial and coastal flooding. Rapid urban development and ongoing land-use changes, such as the expansion of residential areas into flood-prone zones, have altered natural drainage patterns and increased surface runoff, thereby intensifying flood impacts. These interacting factors not only elevate flood risk but also constrain evacuation routes and access to safe shelters, heightening the likelihood of congestion and delayed evacuation during extreme events.

Under such conditions, the effectiveness of flood risk management depends not only on hazard mitigation but also on the spatial adequacy, accessibility, and capacity of evacuation centres relative to population distribution. In densely populated areas like Kuantan, mismatches between population demand and evacuation infrastructure can significantly undermine emergency response efforts. Therefore, Kuantan represents a particularly suitable and policy-relevant case study for evaluating the spatial distribution and adequacy of flood evacuation centres within a Malaysian urban context, offering insights into how demographic pressures interact with urban form and infrastructure during flood emergencies.

Field surveys were conducted to validate and complement GIS-based spatial data on EC locations obtained from PLANMalaysia, and Social Welfare Department ensuring positional accuracy and consistency with on-the-ground conditions. Population data were sourced from the WorldPop platform in raster (TIFF) format and cross-referenced with official statistics from the Department of Statistics Malaysia (DOSM) to provide high-resolution estimates of population distribution across the study area. EC capacity data were obtained from the Civil Defence Department to assess shelter adequacy relative to the population at risk. The flood map was sourced directly from the Department of Irrigation and Drainage Pahang. This official mapping was provided in a GIS shapefile format, which delineates all regions officially categorised as flood-prone areas within the state. The integration of field-verified data, official spatial datasets, and population information enhanced the reliability and robustness of subsequent geospatial analyses.

GIS analyses were conducted using ArcGIS software to examine the spatial distribution, accessibility, and adequacy of ECs in relation to flood-prone residential areas. The workflow included spatial data integration, overlay analysis, network-based service area analysis, zonal statistics, and site suitability assessment. Initially, EC locations were geocoded and mapped to generate a point feature layer, serving as the foundational dataset for all subsequent analyses.

Service area analysis was performed to evaluate the spatial coverage of ECs, applying a 1-kilometre travelled distance around each centre to represent the standard acceptable walking distance for residents during emergencies. While flood propagation is dynamic, a static 1-km network-based service area was selected to establish a baseline for pedestrian accessibility. This threshold accounts for the worst-case mobility scenario where vehicular transport is rendered unviable by floodwaters, necessitating walkable access to safety. The service area polygons were generated using ArcGIS network analysis tools. These polygons were intersected with the residential land-use layer to quantify the extent of residential land within and beyond the 1-kilometre threshold. Further intersection with the site suitability map, flood-prone areas, and population grid data allowed for the estimation of both the spatial extent and population effectively served by existing ECs, highlighting areas of insufficient shelter coverage.

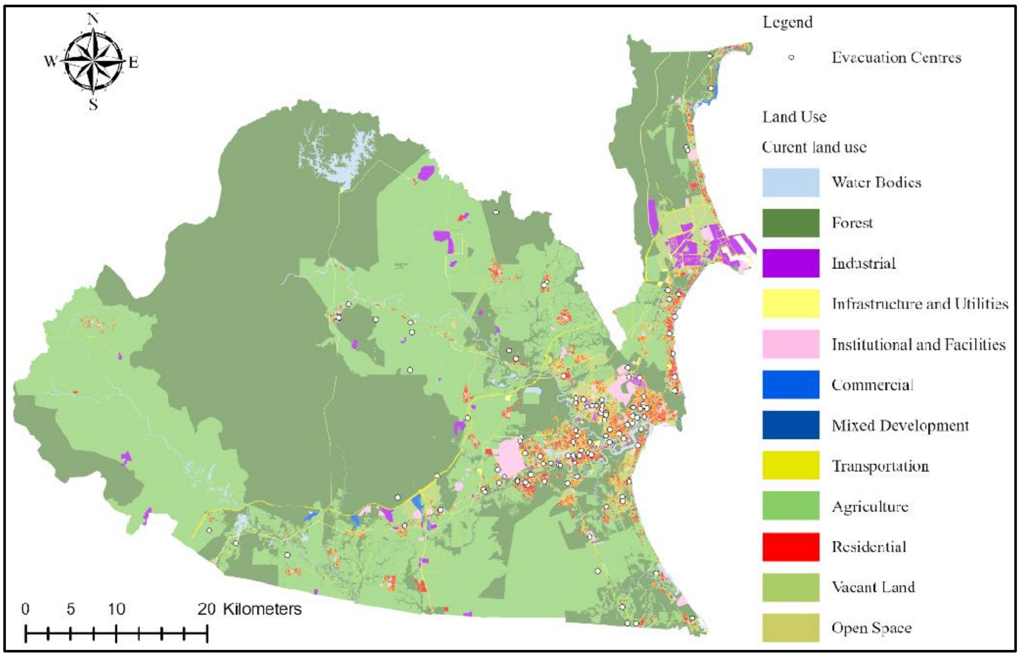
Population data from WorldPop were georeferenced and clipped to the Kuantan District boundary. To ensure consistency with official statistics, the raster dataset was normalized using the DOSM total population. A scaling factor was calculated as the ratio of the DOSM population to the total WorldPop population, and each raster cell was multiplied by this factor. The resulting normalized population raster was applied in all GIS analyses, including service area evaluation, overlay with flood-prone residential zones, and assessment of EC capacity, thereby improving the accuracy of accessibility and demand estimates.

Residential exposure to flooding was assessed through an intersect overlay of flood-prone area layers with residential land-use polygons. This process involved preparing and validating flood-prone layers, spatially referencing residential polygons, and merging the layers using ArcGIS's Intersect tool. Subsequently, the 1-kilometre EC service area polygons were overlaid onto the intersected flood-prone residential layer, allowing quantification of the proportion of flood-exposed residential areas covered by ECs and identification of spatial gaps in shelter provision.

To evaluate the adequacy of ECs relative to population distribution, Ordinary Kriging was applied to EC point data with associated capacity attributes to generate a continuous raster surface representing the spatial variation of EC capacity across the district. Although EC capacity is inherently a discrete point-based attribute, this geostatistical interpolation explicitly accounts for spatial autocorrelation among EC locations. This generates a 'service availability surface' that visualizes the spatial gradient of shelter provision, allowing for the identification of regional capacity deficits that extend beyond the immediate vicinity of a single facility.

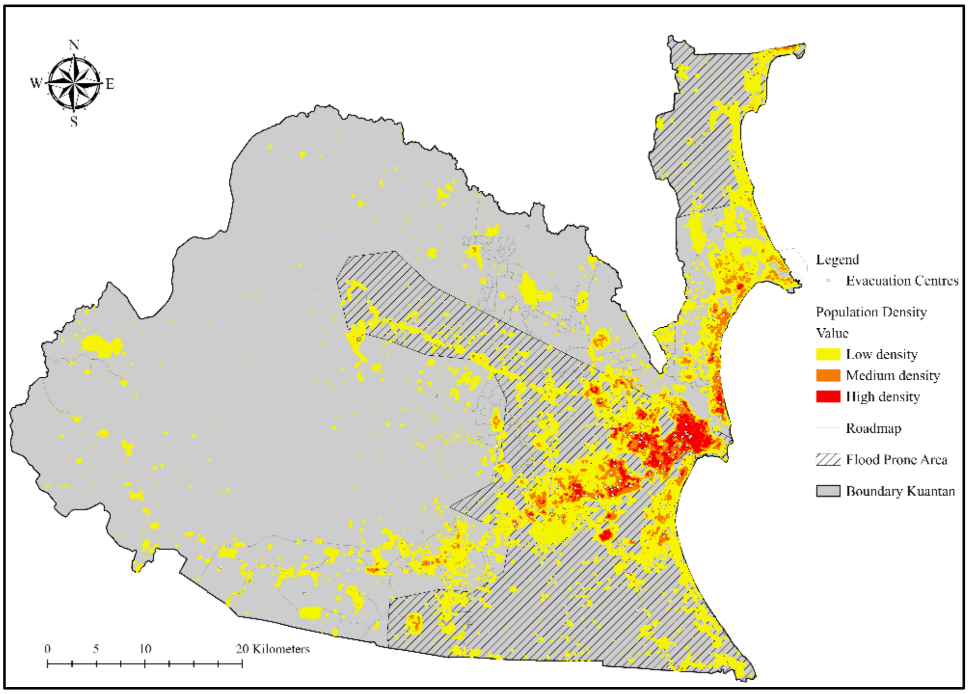
Unlike previous assessments by Mabahwi et al. (2025) that relied on static point-based capacity summation or simple buffering techniques, this study adopts Ordinary Kriging to capture the spatial continuity of service influence. The interpolated EC capacity raster was subsequently overlaid with a normalized population density raster to conduct a spatial demand analysis. Through the application of raster algebra and zonal statistics, the ratio of population demand to available EC capacity was calculated across the district. This process enabled the identification of under-served and overburdened zones, where population concentrations exceed accessible shelter capacity.

By integrating GIS-based service area analysis, flood exposure overlay, population normalization, and kriging-based EC capacity interpolation, the study provides a comprehensive assessment of the spatial adequacy of evacuation centres in Kuantan. The methodology facilitates evidence-based decision-making for improving flood evacuation planning and enhancing community resilience.



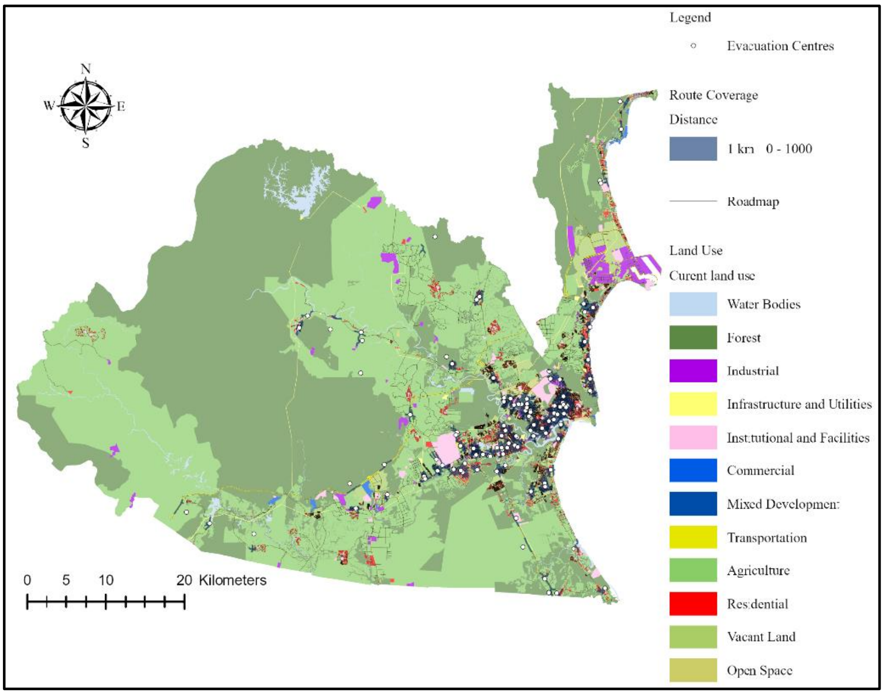
Source: Author, 2026

Figure 1. Spatial distribution of evacuation centres



Source: Author, 2026

Figure 2. GIS-based overlay population distribution and flood-prone



Source: Author, 2026

Figure 3. Evacuation centres service area map

Results and discussion

The results of the spatial and capacity analyses reveal critical structural deficiencies in the existing EC network in Kuantan, with important implications for flood risk management and urban resilience. Although residential land use in Kuantan District (Figure 1) occupies a relatively small proportion of the total land area, approximately 5,919 ha, or 2%, its spatial exposure to flooding is disproportionately high. The analysis reveals that 4,214 hectares of residential land, approximately 71% of all residential areas, are situated within designated flood-prone zones. This is further supported by overlaying population distribution with flood-prone areas (Figure 2), indicating that many residents are exposed to risk. The significant overlap between residential land use and flood risk underscores the serious threat flooding poses to human safety and livelihoods in Kuantan. It also highlights the essential role of ECs as a crucial component of disaster preparedness infrastructure.

Despite the high level of residential exposure, the spatial accessibility of evacuation centres is notably limited. Service area analysis (Figure 3) indicates that only 2,059 ha of residential land, or approximately 35%, falls within a 1 km travel distance of existing ECs. This finding suggests that the majority of residential areas, particularly those situated in flood-prone zones, lack adequate proximity to evacuation facilities. Given that flood events often disrupt transportation networks and restrict vehicular movement, reliance on walkable access becomes critical. Insufficient service coverage therefore represents a significant barrier to timely and safe evacuation.

The spatial capacity analysis (Figure 4) reveals pronounced spatial inequities in the provision of evacuation shelters across the study area. Higher EC capacity coverage is predominantly observed in areas characterised by low population density or mountainous terrain, which generally correspond to lower flood exposure and reduced evacuation demand. In contrast, Kuantan City, where flood exposure and population density are highest, exhibits consistently low EC capacity coverage, indicating a critical mismatch between shelter provision and actual evacuation needs.

By transforming discrete EC capacity points into a continuous spatial representation, the interpolation highlights zones with persistently low effective shelter coverage, particularly in areas with high population density and flood vulnerability. While models in the 2SFCA family are constrained by predefined catchment zones and assumed distance-decay functions, Kriging utilizes real-world spatial autocorrelation to create a seamless gradient of coverage that eliminates unnatural "edge effects", while simultaneously generating standard error maps, equipping disaster planners with a highly realistic, data-driven assessment of both capacity distribution and statistical uncertainty. These zones represent priority intervention areas where new ECs should be established, existing facilities expanded, or alternative shelter strategies introduced.

Overlay analysis of EC capacity and flood vulnerability further highlights this imbalance. Areas classified under very low (12%), and low (30%) EC capacity categories dominate, while zones with high and very high EC capacity collectively account for only 25% of the total area. This spatial pattern demonstrates that the current allocation of evacuation centres does not adequately reflect the distribution of flood risk or population concentration, resulting in an imbalanced shelter network that under-serves the most vulnerable communities.

The inadequacy of the existing EC system is further substantiated through aggregate capacity-demand comparisons. Assuming a full evacuation scenario, Kuantan’s projected population of approximately 548,000 in 2025, compared with a total EC capacity of 32,730 persons across 127 centres, indicates that the current shelter network can accommodate only about 6% of the total population. When considering that approximately 71% of residential zones are located within flood-prone areas, the potentially affected population is estimated at around 389,000 persons, of whom only about 8% can be accommodated by existing ECs.

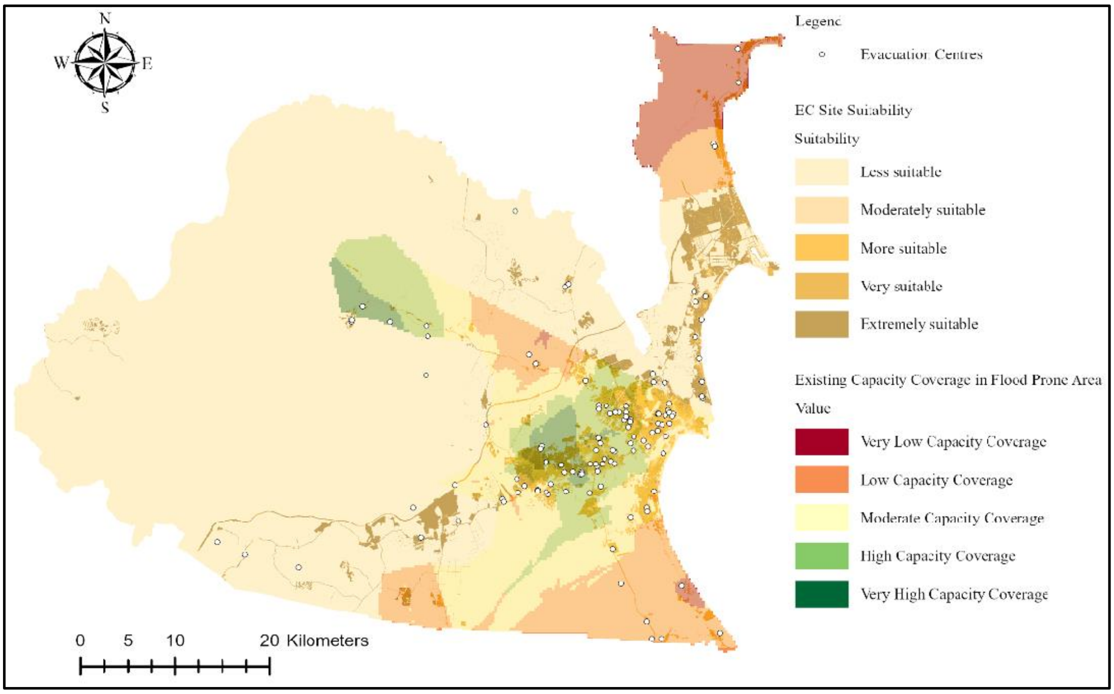
While this study's capacity coverage estimate (6%) differs from previous findings (25%; Mabahwi et al., 2025), both consistently highlight a significant shortfall between evacuation demand and available shelter capacity. This discrepancy stems from replacing 1-km circular buffers with static network distances. Unlike Euclidean 'as-the-crow-flies' measurements, a network-based approach accounts for physical barriers and infrastructure limitations, preventing the overestimation of accessibility. Additionally, previous research focused on populations historically affected within flood-prone regions, the current study utilizes the general population. This approach was adopted due to the dynamic nature of flood-affected demographic. This persistent capacity gap raises serious concerns regarding the effectiveness of current emergency planning arrangements. In the event of large-scale flooding, such limited shelter capacity is likely to result in overcrowding, exclusion of at-risk populations, and increased reliance on informal or unsafe sheltering options, thereby exacerbating disaster-related vulnerabilities and undermining evacuation effectiveness.

The EC capacity coverage map and service area map (Figure 5) were overlaid with the site suitability map from previous research to support evidence-based planning recommendations. This integrated analysis offers a comprehensive understanding of how existing EC provision aligns with flood risk, population distribution, and spatial suitability, enabling targeted interventions.

Additionally, priority should be given to improving EC capacity coverage and service area accessibility within flood-prone zones, especially in areas identified as highly suitable for EC development. Strengthening EC provision in these locations is essential to enhance the resilience of vulnerable, high-risk communities most exposed to flood hazards. By focusing on flood-affected residential areas with limited accessibility and insufficient shelter capacity, planners can reduce evacuation distances, alleviate overcrowding, and improve the effectiveness of emergency response during flood events.

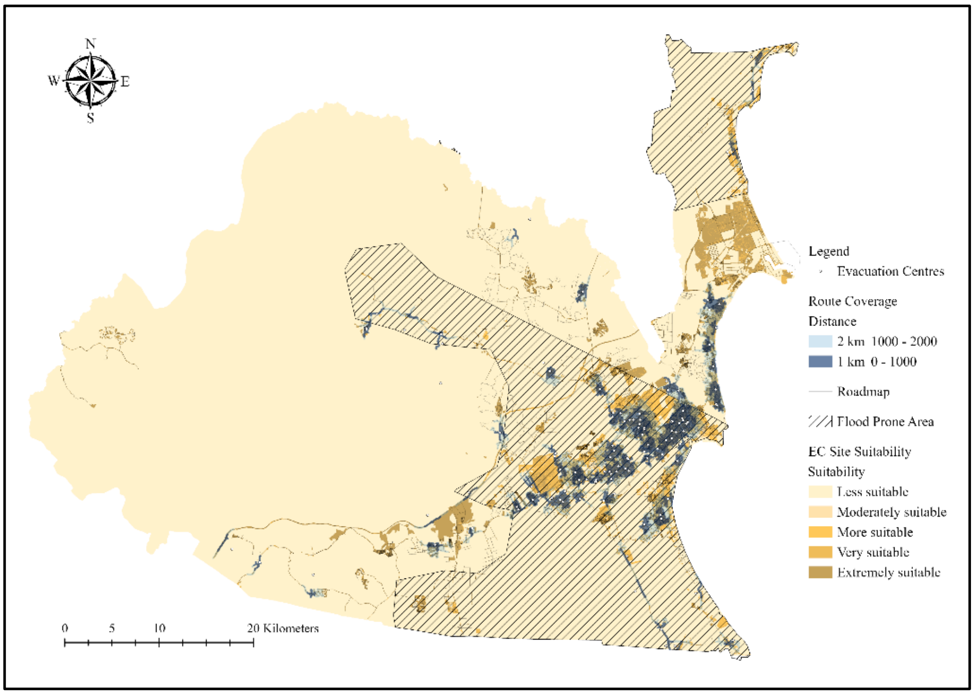
Furthermore, expanding EC capacity in densely populated urban areas, particularly in Kuantan City, should be emphasized, as these areas exhibit both high flood vulnerability and significant deficits in shelter provision. Locating new ECs or upgrading existing facilities in highly suitable sites can help address spatial imbalances and ensure that shelter capacity aligns more closely with potential evacuation demand.

Overall, integrating EC capacity and service area analyses with site suitability assessments provides a robust spatial framework for prioritizing investments in evacuation infrastructure. This approach fosters the development of a more equitable, accessible, and resilient EC network, ultimately enhancing community preparedness and reducing flood-related risks in Kuantan.



Source: Author, 2026

Figure 4. GIS-based overlay of suitability map and EC capacity coverage



Source: Author, 2026

Figure 5. GIS-based overlay of suitability map and service area map

Conclusion

The comprehensive spatial and capacity analyses of Kuantan's EC network reveal critical shortcomings that undermine the city's flood resilience and disaster preparedness. A significant portion of residential land, particularly in flood-prone zones, faces high exposure to flood hazards; however, the current EC system is hindered by limited accessibility, pronounced spatial inequities, and insufficient overall capacity. With only 6% of the projected 2025 population able to be accommodated in existing shelters, there is a substantial gap between potential evacuation demand and available resources, especially in densely populated and highly vulnerable urban areas.

These findings highlight the urgent need for evidence-based interventions to address both the spatial and capacity deficiencies of Kuantan's EC network. Prioritizing the expansion and upgrading of ECs in flood-prone and densely populated areas, along with targeted improvements in shelter accessibility and suitability, is essential for safeguarding at-risk populations. Integrating EC planning with site suitability assessments provides a robust framework for optimizing resource allocation, reducing evacuation distances, and ensuring equitable shelter provision.

Importantly, these recommendations align directly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). By advocating for a more resilient and inclusive EC network, this analysis supports the development of safer urban environments and proactive disaster risk management. Enhancing evacuation infrastructure in flood-prone and socially vulnerable areas not only improves preparedness and response to climate-related disasters but also advances social equity, protecting marginalized groups.

Integrating EC capacity and service area analyses with site suitability assessments embodies the SDG commitment to building sustainable, resilient cities and reducing the adverse impacts of natural hazards. This holistic approach enables local planners and decision-makers to prioritize investments in evacuation infrastructure, ultimately fostering a more equitable, accessible, and resilient Kuantan. By strengthening community preparedness and reducing flood-related risks, these efforts contribute to a safer and more sustainable future for all residents, fully supporting the global vision for sustainable development.

Acknowledgement

This research was supported by a Universiti Sains Malaysia, Short-Term Grant with Project No: R501-LR-RND002-0000 0007 29-0000.

References

Albuquerque, N. L. B., Silva, L. B. L., Alencar, M. H., & de Almeida, A. T. (2024). A multicriteria decision model to improve emergency preparedness: Locating-allocating urban shelters against floods. *International Journal of Disaster Risk Reduction, 111*, 104695.

Bhatta, N., Tanim, S. H., & Murray-Tuite, P. (2024). Dynamics of link importance through normal conditions, flood response, and recovery. *Sustainability, 16*(2), 819.

Chan, N. W. (1997). Increasing flood risk in Malaysia: Causes and solutions. *Disaster Prevention and Management: An International Journal, 6*(2), 72-86.

Coles, D., Yu, D., Wilby, R. L., Green, D., & Herring, Z. (2017). Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK. *Journal of Hydrology, 546*, 419–436.

Dong, S., Esmalian, A., Farahmand, H., & Mostafavi, A. (2020). An integrated physical-social analysis of disrupted access to critical facilities and community service-loss tolerance in urban flooding. *Computers, Environment and Urban Systems, 80*, 101443.

Du, E., Wu, F., Jiang, H., Guo, N., Tian, Y., & Zheng, C. (2023). Development of an integrated socio-hydrological modeling framework for assessing the impacts of shelter location arrangement and human behaviours on flood evacuation processes. *Hydrology and Earth System Sciences, 27*(7), 1607–1626.

Irsyad, H. A. W., & Nakamura, H. (2022). Flood disaster evacuation route choice in Indonesian urban riverbank kampong: Exploring the role of individual characteristics, path risk elements, and path network configuration. *International Journal of Disaster Risk Reduction, 81*, 103275.

Isahak, A., Reza, M. I. H., Siwar, C., Ismail, S. M., Sulaiman, N., Hanafi, Z., Zainuddin, M. S., & Taha, M. R. (2018). Delineating risk zones and evaluation of shelter centres for flood disaster management along the Pahang River Basin, Malaysia. *Jamba: Journal of Disaster Risk Studies, 10*(1), 501.

Kim, J. O., & Park, S. (2019). Constructing the flood evacuation zones based on user-centric time-distance representation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42*(3/W8), 203–204.

Li, M., Kwan, M. P., Chen, J., Wang, J., Yin, J., & Yu, D. (2021). Measuring emergency medical service (EMS) accessibility with the effect of city dynamics in a 100-year pluvial flood scenario. *Cities, 117*, 103314.

Li, M., Wang, F., Kwan, M. P., Chen, J., & Wang, J. (2022). Equalizing the spatial accessibility of emergency medical services in Shanghai: A trade-off perspective. *Computers, Environment and Urban Systems, 92*(2), 101745.

Mabahwi, N. A., & Nakamura, H. (2024). Enhanced GIS-Based multi-criteria decision analysis for optimal flood shelter site selection: A case study of Kuantan, Malaysia. *PLANNING MALAYSIA, 22*(5), 248-262.

Mabahwi, N.A, Cheah, W.C., Rahman, S., & Yin, I. (2025). GIS analysis of flood evacuation centre placement: Identifying spatial gaps in Kuantan, Malaysia. *PLANNING MALAYSIA, 23*(38).

Nurul Ashikin, A., Nor Diana, M. I., Siwar, C., Alam, M. M., & Yasar, M. (2021). Community preparation and vulnerability indices for floods in Pahang State of Malaysia. *Land, 10*(2), 1–23.

Papilloud, T., & Keiler, M. (2021). Vulnerability patterns of road network to extreme floods based on accessibility measures. *Transportation Research Part D: Transport and Environment, 100*, 103045.

Papilloud, T., Steiner, A., Zischg, A., & Keiler, M. (2024). Road network disruptions during extreme flooding events and their impact on the access to emergency medical services: A spatiotemporal vulnerability analysis. *Science of the Total Environment, 956*, 177140.

Rahman, M., Chen, N., Islam, M. M., Dewan, A., Pourghasemi, H. R., Washakh, R. M. A., Nepal, N., Tian, S., Faiz, H., Alam, M., & Ahmed, N. (2021). Location-allocation modeling for emergency evacuation planning with GIS and remote sensing: A case study of Northeast Bangladesh. *Geoscience Frontiers, 12*(3), 101095.

Rosmadi, H. S., Ahmed, M. F., Mokhtar, M. Bin, & Lim, C. K. (2023). Reviewing challenges of flood risk management in Malaysia. *Water, 5*(13), 2390.

Sritart, H., Miyazaki, H., Kanbara, S., & Hara, T. (2020). Methodology and application of spatial vulnerability assessment for evacuation shelters in disaster planning. *Sustainability, 12*(18), 7355.

Tsang, M., & Scott, D. M. (2020). An integrated approach to modeling the impact of floods on emergency services: A case study of Calgary, Alberta. *Journal of Transport Geography, 86*, 102774.

Yin, J., Yu, D., & Liao, B. (2021). A city-scale assessment of emergency response accessibility to vulnerable populations and facilities under normal and pluvial flood conditions for Shanghai, China. *Environment and Planning B: Urban Analytics and City Science, 48*(8), 2239–2253.

Zheng, M., Liu, J., Gao, J., Zhou, N., & Jiang, S. (2024). Navigating urban challenges: Quantifying emergency service accessibility and robustness amid meteorological disasters. *International Journal of Disaster Risk Reduction, 110*, 104655.

Zhou, X., Wang, S., Yao, S., & Fang, L. (2025). Influence of urban flooding on the spatial equity of access to emergency medical services among nursing homes in Shanghai. *Land*, *14*(2), 309.