The International Journal of Health Planning and Management

WILEY

RESEARCH ARTICLE OPEN ACCESS

A Hybrid Fuzzy AHP–Fuzzy TOPSIS and GIS-Based Framework for Mobile Clinic Location Selection in Conflict Zones: A Case Study From Northern Syria

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Received: 27 October 2024 | **Revised:** 2 September 2026 | **Accepted:** 11 September 2026

Keywords: conflict-affected regions | fuzzy analytic hierarchy process (F-AHP) | geographic information systems (GIS) | healthcare delivery | humanitarian logistics | mobile clinics | multi-scenario planning | northern syria

ABSTRACT

Providing healthcare services in conflict-affected regions like northern Syria is a significant challenge due to ongoing conflict and massive displacement. Mobile clinics offer a flexible solution to meet the urgent healthcare needs of displaced communities. This study aims to develop a comprehensive evaluation framework for the optimal location selection of mobile clinics, integrating fuzzy multi-criteria decision-making approaches, Geographic Information Systems (GIS), and multi-scenario planning. We conducted surveys with 37 medical NGOs actively engaged in the Syrian health sector to identify key criteria for mobile clinic locations. Using the Fuzzy Analytic Hierarchy Process (F-AHP), we weighted these criteria based on their importance. Spatial analysis with GIS provided a visual assessment of each potential location against these criteria, creating risk maps to guide decision-making. We applied the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to evaluate and rank 51 candidate locations. Additionally, multi-scenario planning was employed to assess the performance of these locations under four potential conditions: current/continued instability (S1), conflict escalation (S2), flood risk (S3), and post-conflict recovery (S4). The results highlight strategic locations for mobile clinics, providing actionable insights for health authorities, NGOs, and donors. This framework offers a data-driven, adaptable solution for healthcare delivery in crisis zones, enhancing the strategic planning capabilities of humanitarian organisations.

1 | Introduction

Providing healthcare services in conflict-affected regions like northern Syria remains a significant challenge due to infrastructural devastation, ongoing conflict, and large-scale displaced populations. Mobile clinics have increasingly been recognized as a vital means of delivering health services in such settings, offering a flexible and adaptable solution to meet the urgent healthcare needs of displaced communities [1]. As humanitarian needs rose by nearly 25% from 2022 to 339 million people, the World Health Organization (WHO) launched a $2.54 billion health emergency appeal in 2023 to support millions facing health crises worldwide. The WHO prioritises deploying mobile clinics to provide basic physical and mental healthcare, strengthen blood transfusion capacity, and provide oxygen for malnourished children. These efforts also aim to vaccinate internally displaced persons and host communities against preventable diseases (e.g., cholera, COVID-19, gender-based violence, trauma) and to distribute emergency health kits [2, 3].

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Highlights

- Introduces a hybrid fuzzy AHP, fuzzy TOPSIS and GIS-based framework for mobile clinic location selection in conflict zones.
- Combines expert-based fuzzy weighting with GIS health, risk and accessibility layers to evaluate 51 candidate locations in northern Syria.
- Implements multi-scenario planning that reflects different configurations of security conditions, displacement patterns and flood-related risks.
- Provides a practical decision-support tool tailored to humanitarian health actors operating in unstable environments.

However, the strategic selection of mobile clinic locations is critical for maximising their effectiveness and reach. Studies have demonstrated that successful placement of healthcare services can significantly enhance access to essential medical care in disaster and conflict zones [4, 5]. Geographical Information Systems (GIS) have been effectively utilised to analyse spatial data, determining optimal locations for healthcare facilities that ensure broad coverage and accessibility while also considering the safety and demographic needs of target population [6]. Mobile clinics are widely used by humanitarian organisations to bridge gaps in access to medical care during humanitarian emergencies [7]. Yet, despite the recognized usefulness of mobile clinics, frameworks for evaluating and selecting their locations remain underdeveloped, especially in conflict or mass-displacement contexts. Integrating these services into broader health system planning is often sporadic and inadequately informed by empirical research [8]. This gap limits the potential impact of mobile clinics in areas most in need [9].

Against this backdrop, this study aims to develop a hybrid evaluation framework using fuzzy multi-criteria decision-making approaches to optimise the mobile clinic location selection. Based on a survey of healthcare professionals in northern Syria, this framework captures the contextual realities and criteria that influence operational and strategic decisions in healthcare delivery in crisis areas. The study evaluates the critical factors for the successful placement of mobile clinics, assess how GIS can enhance risk assessment, and explores how the integration of Fuzzy Analytic Hierarchy Process (F-AHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS) can improve decision-making. By addressing these issues, the study aims to provide evidence-based policy recommendations for identifying and prioritising location selection criteria for mobile clinics in northern Syria, helping humanitarian organisations deliver their services more effectively under various scenarios.

2 | Literature Review

Prolonged violent conflicts often have devastating effects on populations, impacting economic, social, ecological, psychological, health, and nutritional aspects [10]. The ongoing conflicts in Syria have resulted in massive displacement and widespread destruction, especially in northern Syria, which has been severely affected. Providing healthcare services in conflict-affected regions like northern Syria is particularly challenging due to infrastructural devastation, ongoing conflict, and large-scale displacement. Despite major challenges in delivering essential healthcare support to these vulnerable populations, one approach considered more effective is deploying mobile clinics. Mobile clinics have increasingly been recognized as a vital means of delivering health services in conflict settings, offering a flexible and adaptable solution to meet the urgent healthcare needs of displaced communities [2, 11]. These clinics are specialised motor vehicles designed to provide general healthcare services to those affected populations. They efficiently use local resources to address health issues in the area [11]. The main benefit of mobile clinics is their ability to move to areas with high demand, such as those with highly vulnerable populations [12]. By addressing the healthcare needs of underserved communities, mobile clinics play a crucial role in reducing unmet healthcare demands. Additionally, their proximity to existing health facilities enhances their complementary role, reducing the unmet healthcare needs of vulnerable populations.

Despite the recognized advantage of mobile clinics, systematic frameworks for selecting their locations remain underdeveloped. Integrating these services into broader health system planning is often sporadic and poorly informed by empirical research [13]. This may be due to the ad hoc nature of humanitarian support and limited time available for thorough planning. The absence of comprehensive strategies for mobile clinic deployment often leads to suboptimal resource utilization and reduced impact on target populations [9]. As stated above that this study aims to develop a hybrid evaluation framework for optimising the selection of mobile clinic location to maximise healthcare impact within limited resources in conflict-affected areas (see section1). In doing so, this section reviews several existing approaches, such as Fuzzy Logic, Multi-Scenario Planning, Multi-Criteria Integration, and Geographic Information Systems (GIS). These methods are often used independently. To provide a broader context, a comparative analysis of studies on mobile clinic location selection follows the review of existing approaches.

2.1 | Fuzzy Logic

Fuzzy logic represents imprecise and linguistic information by assigning degrees of membership rather than relying only on well-defined classifications. This is particularly useful in decision-making problems where many criteria cannot be measured exactly, and expert judgements are expressed in qualitative terms. In multi-criteria decision-making (MCDM), fuzzy logic has been widely integrated with methods such as AHP, the Best–Worst Method and TOPSIS to capture uncertainty and subjectivity in the evaluation process [14–16].

Several spatial decision-making studies have combined fuzzy logic with advanced AHP-type approaches to build risk or suitability maps. For example, interval rough AHP and fuzzy logic have been integrated to assess flood-prone areas at the regional scale, modelling uncertainty in expert preferences and hydrological and topographical factors within a unified framework [17]. Similarly, national-scale landslide susceptibility mapping in Austria used a fuzzy Best–Worst MCDM approach, where fuzzy sets were employed to represent the relative importance and

contribution of conditioning factors across space [18]. These studies show that fuzzy logic can enhance MCDM models when both criterion weights and performances are affected by ambiguity and gradual spatial transitions rather than sharp thresholds.

The mobile clinic location problem studied in this paper shares these characteristics. Many criteria that determine the suitability of a location such as security risk, accessibility, population need and flood exposure are not precisely known and change gradually across neighbouring areas. By representing expert judgements and spatial attributes through fuzzy sets and integrating them into fuzzy AHP and fuzzy TOPSIS, the proposed framework reflects these nuances when ranking candidate locations. In this way, fuzzy logic helps modelling spatial variability and uncertainty that are inherent in mobile clinic planning in conflict-affected environments.

2.2 | Multi-Scenario Planning and Multi-Criteria Integration

The existing literature reveals that mobile clinic location selection varies significantly in differing circumstances. Single-scenario models, which address one condition within a target area, often fall short in effectiveness when compared to multi-scenario models. Multi-scenario models consider a range of potential situations on the ground, offering a more comprehensive and adaptable approach that improves the decision-making process. Integrating expert knowledge with Multi-Criteria Decision Analysis (MCDA) strengthens these models, ensuring they more accurately reflect the real-world complexities. Various models and methods have been applied to facilitate location selection problems, including hospitals and mobile clinics [19]. For instance, Grey Relational Analysis (GRA) was utilised in Porter's diamond model to assess competitive advantages in hospital location selection in Taiwan [20]. Similarly, an Analytical Network Process (ANP) model was employed in Istanbul, which considered multiple criteria such as building construction costs, land costs, population density, and income levels [21]. These models provided a holistic view of factors influencing location decisions.

Recent studies refined these approaches. For example, one model optimised mobile clinic distribution to maximise healthcare benefits minimising the number of mobile clinics while predetermining visit points for optimal coverage [22]. Additionally, cost minimisation strategies were explored while simultaneously meeting service demands under limited time and capacity [5] highlighting the importance of balancing cost-efficiency with service effectiveness in challenging environments. Another study focused on maximising the coverage of mobile clinics through multi-criteria modelling [23] emphasising cost-effectiveness in reaching vulnerable populations and providing longer-term healthcare solutions. Similarly, the importance of strategic planning was underscored in mobile clinic deployment to ensure efficient resources use and comprehensive healthcare for underserved communities [24].

2.3 | Geographic Information Systems (GIS)

Geographic Information Systems (GIS) have been widely used to analyse spatial data and determine optimal healthcare facility locations, ensuring coverage and accessibility while considering safety and demographic needs of target population [6]. GIS-based analysis and risk mapping enable visual and data-driven evaluation of candidate sites, ensuring mobile clinics are strategically positioned for maximum impact.

Recent advancements have further enhanced GIS's role in humanitarian healthcare logistics. By integrating GIS with multi-criteria decision-making methods such as the Fuzzy Analytic Hierarchy Process (F-AHP), planners can prioritise factors like accessibility, security, and service demand in mobile clinic placement. This integration allows decision-makers to assess multiple scenarios, such as conflict escalation or natural disasters, ensuring that mobile clinics adapt to changing conditions on the ground [4]. Additionally, GIS supports real-time monitoring of healthcare delivery and dynamic resource reallocation, which is crucial in rapidly evolving conflict zones [25]. These capabilities improve strategic placement of mobile clinics and enhance healthcare system resilience in crisis settings.

2.4 | Comparative Analysis of Relevant Location and Spatial MCDM Studies

Table 1 provides a purposive comparative analysis of selected studies rather than an exhaustive or systematic review of the literature. The studies were selected according to two levels of relevance. First, priority was given to research directly addressing mobile clinic deployment, mobile clinic location or routing, healthcare-facility location, healthcare accessibility, and health-service allocation. Second, studies from other spatial-planning fields were included when they applied methodological components directly transferable to the proposed framework, particularly fuzzy AHP or related fuzzy weighting methods, fuzzy TOPSIS, GIS-based risk and suitability mapping, and spatial multi-criteria decision analysis. Studies were excluded when they did not address a location, allocation, accessibility, risk-mapping, or spatial-suitability problem; did not apply a methodological approach relevant to the proposed framework; or repeated a methodological application already represented in the table without providing a distinct contribution. Accordingly, the studies presented in Table 1 constitute a representative combination of directly relevant healthcare studies and methodologically transferable spatial decision-making applications selected to clarify the foundations of the proposed framework and the research gap addressed in this study.

The directly relevant mobile-clinic studies summarised in Table 1 address deployment challenges, location-routing decisions, healthcare accessibility, and service allocation, while the methodologically transferable studies demonstrate applications of GIS, fuzzy weighting methods, and fuzzy TOPSIS in healthcare location, hazard mapping, and spatial-suitability assessment [4, 17, 18, 22, 23, 25–32]. However, most existing applications either examine mobile clinic operations without explicit spatial multi-criteria evaluation or apply GIS-based fuzzy methods to static facilities and environmental or agricultural problems in relatively stable settings [4, 17, 18, 22, 30–32]. These studies rarely integrate fuzzy criterion weighting, GIS-based risk assessment, fuzzy location ranking, and multi-scenario analysis for mobile healthcare services in conflict-affected areas. To address this gap, the present study develops a hybrid fuzzy AHP–fuzzy TOPSIS and GIS-based framework,

TABLE 1 | Comparison of selected healthcare location and methodologically relevant spatial MCDM studies.

Method(s)	Criteria	Study focus/case study	Key findings
Integrative literature review, instrumental case study, and mixed-method data collection [4]	Healthcare access in conflict zones; conflict-related operational and logistical constraints; mobile clinic deployment decisions; need for decision-support tools	Mobile clinic deployment during and after the Iraq War	Mobile clinics are important for reaching conflict-affected populations who lack access to healthcare. The study identifies major operational and logistical challenges and highlights the scarcity of decision-support tools for mobile clinic deployment in conflict and post-conflict settings.
Multi-period location-routing problem, set-packing formulation, exact optimization, and sensitivity analysis [22]	Population coverage; continuity of care; operational and logistics costs; number of mobile clinics; selected communities; routes and visit schedules	Tactical planning of mobile clinic operations in Iraq	The model selects communities to be served and determines mobile-clinic routes to maximise healthcare benefits over multiple periods under limited resources. The results demonstrate how the number of clinics and the relative importance assigned to coverage and continuity of care affect deployment decisions.
(Fuzzy-logic, interval AHP, GIS) [17]	Distance to discharge channel, Slope (%), elevation, soil texture and land use, topographic Wetness index, check dams	Flood susceptibility in Iran	Demonstrating high predictive accuracy of the model with flood susceptibility map
(Fuzzy best-Worst method) [18]	Elevation, Slope, Slope aspect, lithology, rainfall, land cover, distance to drainage, distance to roads, distance to faults	Landslide in Austria	Slope as the most important factor and distance to roads as the least important
(GIS, AHP) [23]	Area regulations, patient satisfaction	Mobile clinics in Michigan, USA	Improved access to healthcare, affordable patient coverage
(Delphi process, GIS-based multicriteria decision analysis) [25]	COVID-19 active daily cases, distance to existing COVID-19 testing sites, conditions linked to increased risk, etc.	COVID-19 testing centres in South Carolina, USA	Public health emergency response improved during a pandemic, optimised allocation of public health resources in rural settings
(GIS, fuzzy AHP) [26]	Proximity to green space, proximity to the centre of the neighbourhood, proximity to fire-fighting services, etc.	Health centres in kermanshah, Iran	6% land unsuitable, 16% moderately suitable, 78% good or very good for health centre locations
(Discrete event simulation, queuing models, mixed linear integer programming) [27]	Nearest deviation, shorter queue or free beds, quality of service, centrality, etc.	Hospital selection problem	Proximity, hospital care capacities, shortest queue or highest number of empty beds, shortest transportation, and waiting times
(Statistical analysis, GIS) [28]	Predisposing factors, enabling resources, need factors, geographic access, spatial behaviour, five dimensions of access	Mobile medical clinics in Connecticut, USA	Broader dimensions of accessibility in an environment with both mobile and fixed healthcare services
(GIS, multi-criteria decision analysis) [29]	Functional quality, location quality, environmental quality, economic aspects	Health facilities in milan, Italy	Most important criterion: Location quality; Suburban areas most suitable for hospitals

(Continues)

TABLE 1 | (Continued)

Method(s)	Criteria	Study focus/case study	Key findings
(ANP–Fuzzy, traditional parametric methods) [30]	Topography and slope, soil depth, ESP (exchangeable Sodium percentage), gypsum content, pH, soil salinity	Wheat cultivation in northwestern Iran	Identifying the study area as 53.79% highly suitable (S1), 36.45% moderately suitable (S2), 9.69% marginally suitable (S3), and 0.07% currently unsuitable (N1), with slope, soil depth, ESP, gypsum, pH, and salinity as the main limiting factors.
(Fuzzy-set theory, ANP, GIS) [31]	Soil depth, gypsum, $CaCO_3$, pH, electrical conductivity, exchangeable sodium percentage, Slope, climate data	Maize in northwestern Iran	Provided superior suitability classification by integrating diverse soil and climate parameters, and identified slope, ESP, EC, gypsum, soil depth, $CaCO_3$, and pH as the key limiting criteria
(Simple additive weighting, Fuzzy-TOPSIS, Fuzzy-AHP, principal component analysis, multi-dimensional scaling) [32]	Soil depth, Slope, climate, pH, gypsum, $CaCO_3$, electrical conductivity, exchangeable sodium percentage, calcium carbonate	Maize, rape (canola), soybean in northwestern Iran	Fuzzy TOPSIS outperformed SAW and classical TOPSIS in accurately determining cultivation priorities—ranking maize first, followed by rape and soybean.
(Fuzzy-logic theory, GIS, variogram modelling) [33]	Water and nutrient holding capacity, retention of pollutants, root development, soil biodiversity, biogeochemical cycling, infiltration and runoff processes affecting erosion	Spatial variation of soil texture in north of guilan province, southern coast of caspian Sea, northern Iran	Predictive soil texture map accuracy, spatial variability knowledge of soil texture is a valuable tool for land-use planning and reducing potential soil losses during rainy seasons.
(AHP, interval AHP) [34]	Multiple socio-economic and quality-of-life indicators	Analysing health inequalities in quito, Ecuador	Capturing neighbourhood effects on self-reported health, improving health planning in more deprived areas
(SVM, maximum likelihood, minimum distance methods, ANP-WLC) [35]	Soil characteristics, topography, climate factors, crop types (apricot, grape, wheat, forage maize), and phaenological information	Agricultural lands in Iran	The best land-use classification with SVM; wheat covered the largest area
(AHP, interval AHP) [36]	Technical, environmental, and service-related factors for evaluating future urban public transport options	40 public transport users, 40 non-users, and 17 experts in mersin, türkiye	Produced consensus-based ranking for a future public transportation system
Fuzzy AHP, GIS-based risk assessment, fuzzy TOPSIS, multi-scenario planning (our study)	Accessibility, security, demand for services, integration with other services, environmental conditions, community engagement, economic feasibility	Mobile clinics in northern Syria	Developed a comprehensive framework for evaluating and selecting mobile clinic locations in conflict-affected areas using a robust data-driven approach

complemented by multi-scenario analysis, to evaluate and rank potential mobile clinic locations in northern Syria.

3 | Methodology for Selecting Mobile Clinic Locations in Northern Syria

This study followed a sequential framework-development and case-study evaluation process. First, data obtained from humanitarian health organisations were analysed to identify the criteria relevant to mobile clinic location selection. Second, the selected criteria were weighted using Fuzzy AHP. Third, GIS-based spatial analysis was used to evaluate the geographical characteristics and risks associated with the candidate locations. Fourth, Fuzzy TOPSIS was applied to rank the 51 candidate locations. Finally, the rankings were examined under multiple planning scenarios and evaluated through expert review and robustness analysis. Figure 1 summarises the methodological process.

3.1 | Study Area and Candidate Locations

This study examines the situation in northern Syria, focussing mainly on Idleb Governorate, an area that has endured years of conflict and several waves of displacement. The communities here are far from stable; people move from one place to another depending on the security situation, available help, and conditions on the ground. These changes, together with the fragile environment of the region, create serious obstacles to accessing regular health services. Floods are also a recurring problem and often make movement harder.

For analysis, the study uses 51 possible locations across 26 sub-districts in Idleb. These points were identified through discussions with health actors working in the field who know which areas struggle most. The locations differ greatly in terms of accessibility, exposure to conflict, and availability of basic services. To understand them better, several layers were examined, such as distance from frontlines, proximity to recent conflict events, condition and spread of road networks, and risk of natural hazards like flooding.

Health facilities in many of these communities are weak or unavailable. As such, mobile clinics have become one of the main ways humanitarian organizations reach people who would otherwise remain without care. The study area, therefore, reflects a mix of humanitarian demand, security pressure, geographical barriers, and service shortages: all of which shape the evaluation of where mobile clinics should be placed. The 51 candidate locations therefore constitute the empirical case through which the proposed evaluation framework was tested. Figure 2 illustrates the operational context of the case study. A mobile clinic is prepared and equipped at a medical center or depot and then deployed to camps and underserved communities to provide primary healthcare services.

3.2 | Data Collection and Identification of Evaluation Criteria

Data were obtained through collaboration with an NGO conducting a broader study of healthcare services in northern Syria. Through professional contact with the lead author, questions specifically addressing mobile clinic location selection were incorporated into the study instrument. The data were collected between August and December 2023 from professionals representing 37 local and international NGOs providing health services across 26 sub-districts of Idleb Governorate. The responses to the location-related questions were analysed to identify the criteria considered relevant to mobile clinic location decisions.

Respondents were asked: “Which criteria do you think should be taken into consideration when evaluating mobile clinic/health facility locations in crisis areas?” Multiple selections were permitted, and respondents could propose additional criteria. The frequency with which each criterion was selected was calculated, and criteria endorsed by at least 50% of respondents were retained for inclusion in the framework.

The original data collection was conducted by the collaborating NGO in accordance with its established ethical and data-protection procedures. The study protocol and data-collection instrument, including the survey questions, were reviewed and approved by the NGO's ethics committee (approval no. Bon-EC-128). The data-collection process was also subject to the relevant organizational and donor approval procedures. Participation was voluntary, and respondents were informed about the purpose of the study and their right to discontinue participation at any stage. No names or other direct personal identifiers were collected. The authors accessed only de-identified data relevant to the mobile clinic location questions. The data were securely handled and stored in accordance with the applicable data-protection procedures, with access restricted to authorised members of the research team and use limited to the purposes of the approved research.

3.3 | Fuzzy AHP Weighting Procedure

The criteria retained through the procedure described in Section 3.2 were subsequently weighted using Fuzzy AHP. Three decision-makers representing academic health management, local NGO medical services, and donor programme management participated in the weighting process, as shown in Table 2. An Excel-based pairwise comparison questionnaire was used, through which each expert compared every criterion with the remaining criteria using linguistic importance judgements represented by triangular fuzzy numbers. A pairwise comparison matrix was constructed for each expert. The consistency ratio was calculated for each matrix, using $CR < 0.10$ as the acceptance threshold. The individual matrices were subsequently aggregated using the geometric mean of the corresponding elements. Fuzzy and defuzzified weights were then calculated from the aggregated group matrix using the Fuzzy AHP procedure.

Pairwise comparisons were expressed using the nine-point fuzzy linguistic scale shown in Figure 3. Each linguistic judgement was represented by a triangular fuzzy number. The individual expert judgements were aggregated using the geometric mean, and the centre-of-area method was subsequently used to obtain defuzzified criterion weights.

3.4 | GIS-Based Spatial Analysis

We used the Live Universal Awareness Map (Liveuamap), a tool that provides real-time updates on various incidents, to show the volatile nature of conflict regions [37]. Building on these maps, we employed Geographic Information Systems (GIS) for spatial analysis to assess risks at each potential mobile clinic location based on criteria such as proximity to frontlines, main roads, and conflict zones. Details of these risk factors and their maps can be found in Results and Discussion (see Section 4.3). This process involved creating risk maps that visually represented key data, such as accessibility, proximity to conflict zones, and population density, enabling a spatially informed evaluation of each site.

3.5 | Fuzzy TOPSIS Evaluation Procedure

After the criterion weights and GIS-derived values had been established, Fuzzy TOPSIS was used to evaluate the 51 candidate locations. The weighted fuzzy decision matrix was used to determine each alternative's distance from the fuzzy positive

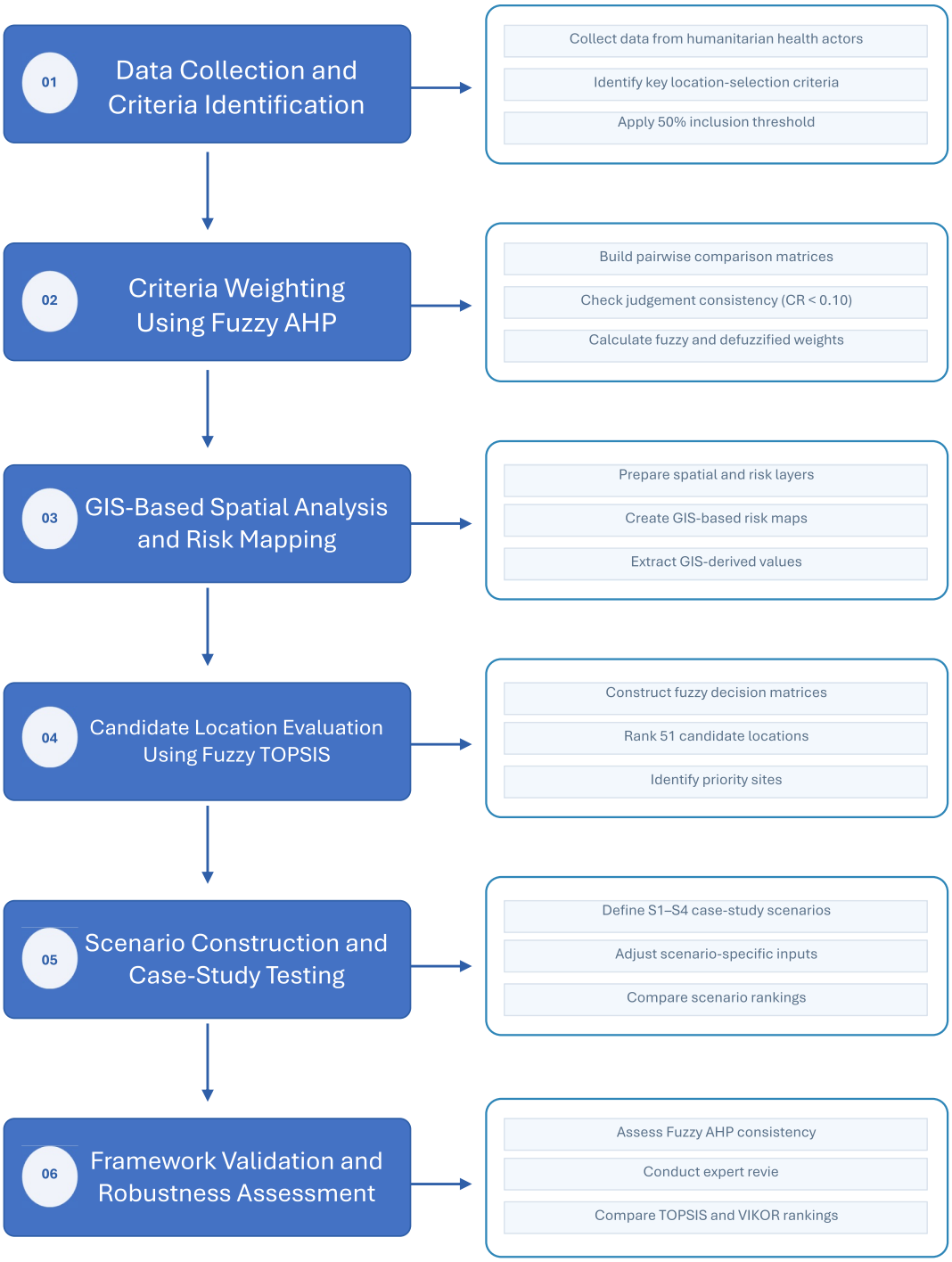

FIGURE 1 | Methodology utilised in evaluation of mobile clinic locations.

ideal solution and the fuzzy negative ideal solution. A closeness coefficient was then calculated for each candidate location, and the locations were ranked from the most to the least suitable.

Each candidate location was evaluated against the 12 criteria using the five-point linguistic scale presented in Figure 4. The linguistic values—Very Low, Low, Average, High, and Very High—were represented by the corresponding triangular fuzzy numbers and incorporated into the Fuzzy TOPSIS decision matrix.

3.6 | Scenario Construction and Case-Study Testing

Scenario-based evaluation is widely used in healthcare planning and humanitarian logistics because it allows researchers to test how location decisions perform under different patterns of uncertainty. Previous studies on mobile clinic operations show that performance, accessibility, and routing needs frequent change across different operational conditions, making multi-scenario analysis valuable for improving the robustness of decisions [2–5]. In operations research, scenario-based planning is well

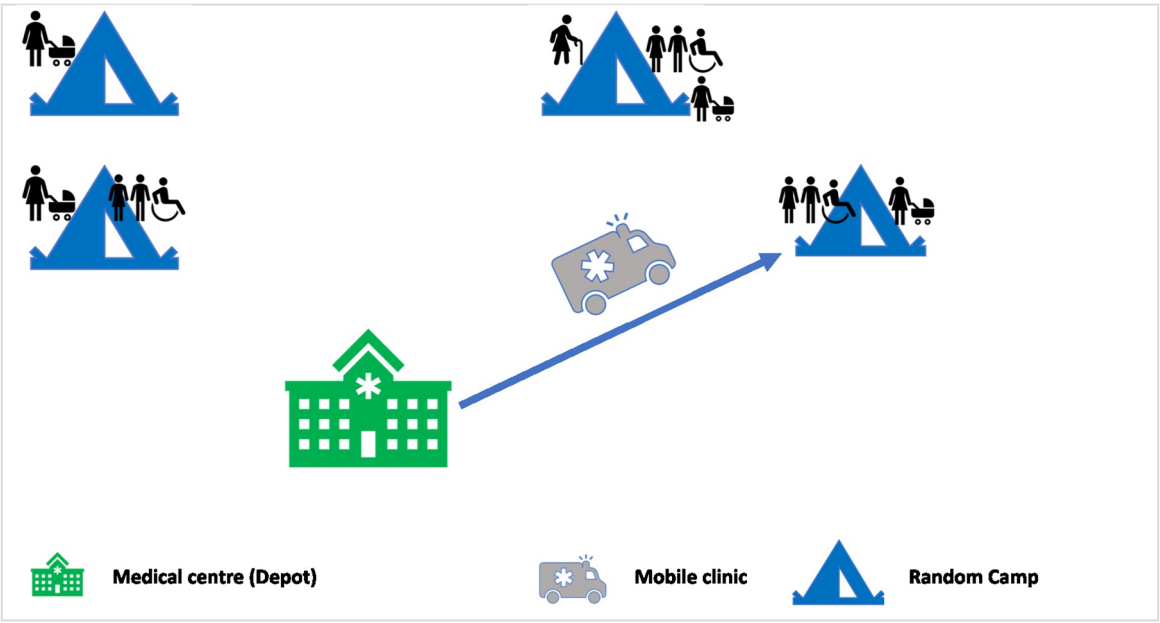

FIGURE 2 | Mobile clinic illustration.

TABLE 2 | The participating experts.

Expert no.	Organisation age (In years)	Type of organisation	Expertise	Experience (In years)	Education level
1	15	Academic	Health management	9	PhD
2	13	Local NGO	Medical services	11	Postgraduate
3	24	Donor	Programme management	8	Postgraduate

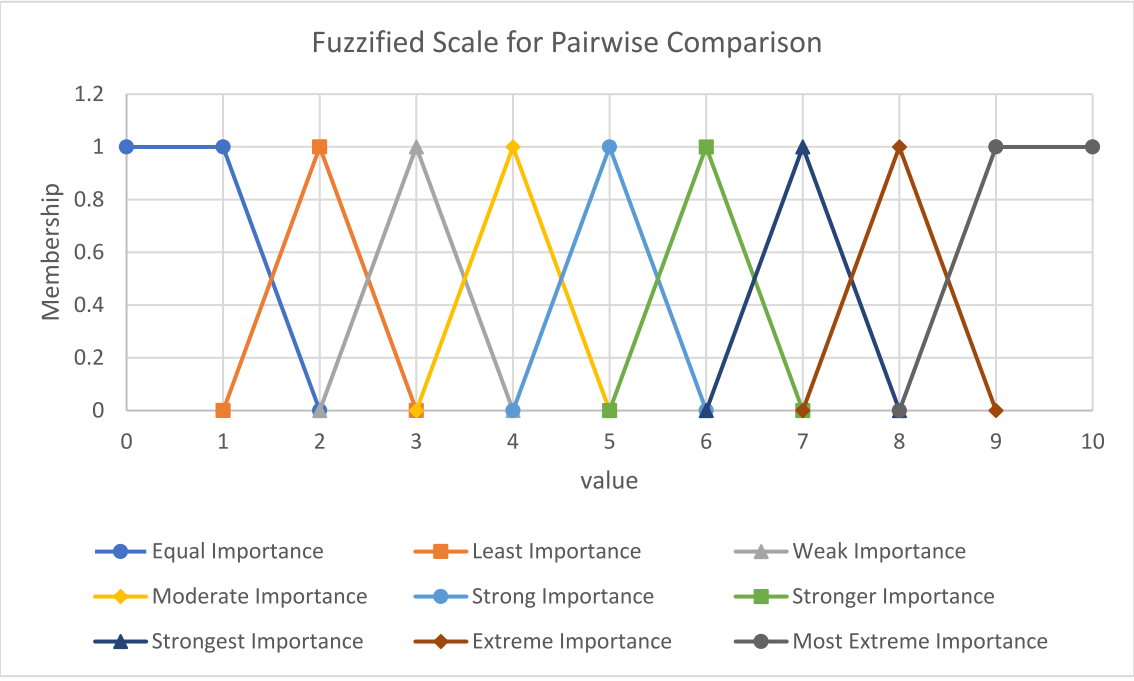

FIGURE 3 | Fuzzy AHP pairwise-comparison scale.

5-based scale	Triangular fuzzy numbers		
Very Low	1	1	3
Low	1	3	5
Average	3	5	7
High	5	7	9
Very High	7	9	9

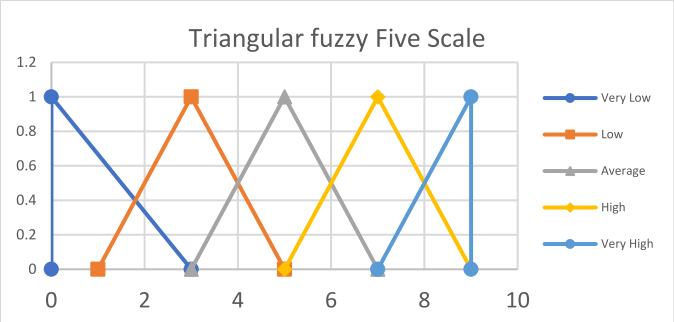

FIGURE 4 | Fuzzy TOPSIS five-point evaluation scale.

established for representing fluctuating demand, varying risk environments, and uncertain future states. Recent work in supply-chain and emergency medical planning demonstrates how scenario variation strengthens model reliability and supports decision-making in unstable contexts [38, 39]. The use of multiple scenarios in this study follows the same logic, enabling evaluation to reflect rapidly shifting security conditions, mobility patterns and environmental risks in northern Syria.

Multi-scenario planning involves developing various scenarios to assess how different mobile clinic location strategies perform under changing conditions. This method ensures flexible and resilient healthcare deployment. In northern Syria, since conflict dynamics shift rapidly, we felt multi-scenario planning would help anticipate and prepare for diverse future scenarios for healthcare support.

3.6.1 | *Primary Steps for Multi-Scenario Planning*

Historical conflict data, displacement patterns, and flood-related information were reviewed in consultation with three health-sector experts to construct four case-study scenarios:

I. Current/Continued Instability Scenario (S1): This scenario represents the prevailing baseline conditions, in which insecurity and displacement continue and conflict intensity changes sporadically, affecting the continuity of healthcare delivery.
II. Conflict Escalation Scenario (S2): This scenario represents an increase in conflict intensity leading to larger population displacement and higher immediate healthcare needs.
III. Flood Scenario (S3): This scenario represents seasonal flooding that may disrupt access routes and reduce the accessibility of potential mobile clinic locations.
IV. Post-Conflict Recovery Scenario (S4): This scenario represents the gradual stabilisation of the region and the return of displaced populations, increasing the need to rebuild and restore healthcare infrastructure.

The scenario definitions were translated into scenario-specific performance values for the 51 candidate locations. For each scenario, the relevant criterion values and GIS-derived inputs were adjusted according to the assumed security, displacement, accessibility, and environmental conditions. The Fuzzy TOPSIS procedure described in Section 3.5 was then repeated using each scenario-specific decision matrix, producing one ranking for each scenario.

Under the conflict-escalation scenario, greater emphasis was placed on security and displacement-related conditions, whereas flood exposure and road accessibility were adjusted under the flood scenario.

3.7 | Framework Validation Procedure

The framework was evaluated using three complementary procedures. First, the consistency ratios of the individual and aggregated Fuzzy AHP matrices were calculated to assess the coherence of the expert judgements. Second, the framework, selected criteria, and resulting location patterns were reviewed by a healthcare professional, an NGO representative, and a local council specialist, each with at least 2 years of experience in the Syrian health sector. Third, the robustness of the location rankings was examined by comparing the Fuzzy TOPSIS rankings with those generated using Fuzzy VIKOR. Pearson correlation was applied to the ranking positions produced by the two methods.

4 | Results and Discussion

This section presents two sets of findings. First, it reports the evaluation framework generated through the survey and Fuzzy AHP procedures, including the selected criteria and their relative weights. Second, it presents the empirical findings obtained by applying the framework to the 51 candidate locations under the four case-study scenarios. The section also examines cross-scenario ranking patterns and the validity and robustness of the proposed framework.

4.1 | Developed Framework and Selected Criteria

Application of the 50% inclusion threshold resulted in the retention of 12 criteria grouped under seven main dimensions: accessibility, security, demand for services, integration with other services, environmental conditions, community engagement, and economic feasibility. Together, these dimensions constitute the evaluation framework developed for mobile clinic location selection in conflict-affected areas. Table 3 presents the selected criteria, their beneficial or non-beneficial orientation, operational definitions, and corresponding evaluation scales.

4.2 | Fuzzy AHP Weighting Results

All three individual pairwise comparison matrices satisfied the consistency requirement of CR < 0.10. The consistency ratio of the aggregated group matrix was 0.07, indicating an acceptable level of judgement consistency. Table 4 presents the fuzzy,

TABLE 3 | Criteria utilised in the process of evaluation of mobile clinic locations.

	Criterion	Type	Description	Scale definitions
Accessibility	C1.1 distance from major roads	Non-beneficial	Measures the distance from major roads, affecting access for mobile clinics and emergency services.	VL: < 1 km, L: 1–2 km, A: 2–5 km, H: 5–10 km, VH: > 10 km
	C1.2 availability of public transportation	Beneficial	Ensures community members without personal transport can access services.	VL: Stops > 2 km away and rare. VH: Stops < 100 m and frequently
	C1.3 distance from supplies	Non-beneficial	Ensures medical and operational supplies can be readily supplied and replenished.	VL: < 5 km, L: 5–10 km, A: 10–20 km, H: 20–50 km, VH: > 50 km
Security	C2.1 distance from conflict zones	Non-beneficial	Minimises risk to staff and patients by avoiding proximity to active conflict areas.	VL: > 20 km, L: 15–20 km, A: 10–15 km, H: 5–10 km, VH: < 5 km
	C2.2 distance from high-crime areas	Non-beneficial	Enhances safety for both staff and patients by avoiding high-crime areas.	VL: > 20 km, L: 15–20 km, A: 10–15 km, H: 5–10 km, VH: < 5 km
	C2.3 distance from frontlines	Non-beneficial	Maintains operational stability and safety by setting up away from active frontlines.	VL: > 20 km, L: 15–20 km, A: 10–15 km, H: 5–10 km, VH: < 5 km
Demand for services	C3.1 population density	Beneficial	Prioritises areas with higher population densities to maximise healthcare impact.	VL: 100–199 people/km^2, L: 200–399, A: 400–599, H: 600–799, VH: 800–1000
	C3.2 presence of vulnerable groups	Beneficial	Focuses services near communities with significant presence of vulnerable populations.	VH: > 40%, H: 30%–40%, A: 20%–30%, L: 10%–20%, VL: < 10%
Integration with other services	C4.1 proximity to existing health facilities	Beneficial	Enhances overall healthcare provision by complementing and integrating with existing health facilities.	VL: > 10 km, L: 5–10 km, A: 2–5 km, H: 1–2 km, VH: < 1 km
Environmental conditions	C5.1 risk of natural disasters	Non-beneficial	Selects locations with a lower risk of natural disasters which could disrupt services and access.	VL: Low risk area, L: Occasionally risky, A: Seasonally risky, H: Frequently risky, VH: High risk area
Community engagement	C6.1 community approval and support	Beneficial	Seeks high levels of local community support and engagement to ensure sustainability and acceptance of the clinic.	VL: Minimal Support, L: Limited Support, A: Moderate Support, H: Strong Support, VH: Widespread support
Economic feasibility	C7.1 installation and operational costs	Non-beneficial	Evaluates financial implications including setup and maintenance costs, affecting long-term sustainability.	VL: Costs significantly low (600 $/week) L: Costs moderately low (700 $/week) A: Costs on average (800 $/week) H: Costs moderately high (900 $/week) VH: Costs significantly high (1000 $/week).

defuzzified, and normalised weights obtained through the Fuzzy AHP analysis.

4.3 | GIS-Based Risk Maps

The GIS-based spatial analysis produced five principal risk maps for evaluating the candidate mobile clinic locations, as presented in Figure 5.

A. Frontline Risk Map: The closer the area to the frontline, the higher the risk.
B. Distance from Main Supplies: The closer the location to the supply market, the lower the risk.
C. Distance from Main Roads: The closer to the main road, the lower the risk.
D. Distance from Crime and Robbery Areas: The closer to these areas, the higher the risk.
E. Distance from Conflict Zones: The farther from conflict zones, the more suitable the location.

4.4 | Scenario-Based Location Rankings

Application of the Fuzzy TOPSIS procedure produced a separate ranking of the 51 candidate locations under each of the four scenarios. The complete rankings are presented in Annex 2,

TABLE 4 | Fuzzy weights of criteria used.

	fuzzy geometric mean value $\tilde{r}_i$			fuzzy weights $\tilde{w}_i$				
Criterion	**a**	**b**	**c**	**a**	**b**	**c**	**Weights w_i**	**Normalised weight**
C1.1	0.736	1.063	1.565	0.022	0.044	0.092	0.053	0.046
C1.2	0.185	0.268	0.375	0.006	0.011	0.022	0.013	0.011
C1.3	0.496	0.695	1.003	0.015	0.029	0.059	0.034	0.030
C2.1	2.192	3.368	4.793	0.067	0.140	0.283	0.163	0.142
C2.2	1.028	1.602	2.367	0.031	0.067	0.140	0.079	0.069
C2.3	3.364	4.823	6.308	0.102	0.200	0.372	0.225	0.195
C3.1	4.861	6.286	7.910	0.148	0.261	0.467	0.292	0.253
C3.2	1.212	1.680	2.393	0.037	0.070	0.141	0.083	0.072
C4.1	0.338	0.485	0.711	0.010	0.020	0.042	0.024	0.021
C5.1	0.780	1.100	1.585	0.024	0.046	0.094	0.054	0.047
C6.1	0.229	0.340	0.520	0.007	0.014	0.031	0.017	0.015
C7.1	1.535	2.355	3.341	0.047	0.098	0.197	0.114	0.099

Note: Population density (C3.1) received the highest normalised weight of 0.253, followed by distance from frontlines (C2.3) at 0.195 and distance from conflict zones (C2.1) at 0.142. Installation and operational costs (C7.1) ranked fourth, with a normalised weight of 0.099. These findings indicate that demand and security considerations exerted the strongest influence on mobile clinic location suitability.

while the ten highest-ranked locations under each scenario are summarised below.

- S1—Current/Continued Instability Scenario: The ten highest-ranked locations under the prevailing baseline conditions are MC24, MC39, MC41, MC44, MC35, MC26, MC42, MC48, MC20, and MC45.
- S2—Conflict Escalation Scenario: Under escalating conflict conditions, the ten highest-ranked locations are MC21, MC30, MC36, MC35, MC24, MC44, MC39, MC43, MC40, and MC25, indicating a shift in location priorities.
- S3—Flood Scenario: The ten highest-ranked locations under flood-risk conditions are MC24, MC39, MC1, MC20, MC26, MC41, MC35, MC36, MC30, and MC22.
- S4—Post-Conflict Recovery Scenario: The ten highest-ranked locations during post-conflict recovery are MC6, MC17, MC47, MC21, MC37, MC44, MC41, MC20, MC46, and MC19.

4.5 | Cross-Scenario Ranking Patterns

Figure 6 compares the ranking positions of the 51 candidate locations across the four scenarios and presents the overall aggregated ranking. For interpretation, the ranking positions were classified into five categories:

— Rank 1–11: Top priority locations for mobile clinics.
— Rank 12–21: Moderately suitable locations.
— Rank 22–31: Less suitable locations.
— Rank 32–41: Lower priority locations.
— Rank 42–51: Least suitable locations.

From the heat map, we can observe:

- Consistency Across Scenarios: Locations like MC21, MC30, MC41, and MC44 consistently rank high across multiple scenarios, indicating their overall strategic importance.
- Scenario-Specific Priorities: Locations such as MC24 and MC6 perform particularly well under S3—Flood and S4—Post-Conflict Recovery, respectively, reflecting their scenario-specific strengths
- Low-Ranking Locations: Consistently low-ranking locations, such as MC9, MC10, and MC11, might be less feasible for mobile clinic deployment due to persistent issues across scenarios.

Figure 7 compares the ranking of each candidate location under S1–S4 with the overall aggregated ranking. In Figure 7E, the blue line represents the overall ranking across all four scenarios. It can be observed that the highest-ranked locations in this aggregated ranking also show high scores in the individual scenarios, validating the model and helping decision-makers understand the robustness and versatility of each site. Locations consistently ranking high, such as MC41, MC30, MC44, and MC21, should be prioritised for mobile clinic deployment due to their overall strategic value. By using this chart, healthcare planners can make informed decisions, ensuring that mobile clinics are suitably placed to maximise their impact and effectiveness in delivering healthcare services in crisis areas.

4.6 | Framework Validation and Robustness

The expert review indicated that the selected criteria, their relative importance, and the resulting location patterns were consistent with the operational conditions experienced by humanitarian health actors in northern Syria. The participating experts considered the framework to provide an appropriate representation of accessibility, security, service demand, environmental risk, community considerations, and operational feasibility within the study area.

The Fuzzy AHP judgements also demonstrated acceptable internal consistency. All individual expert matrices satisfied the

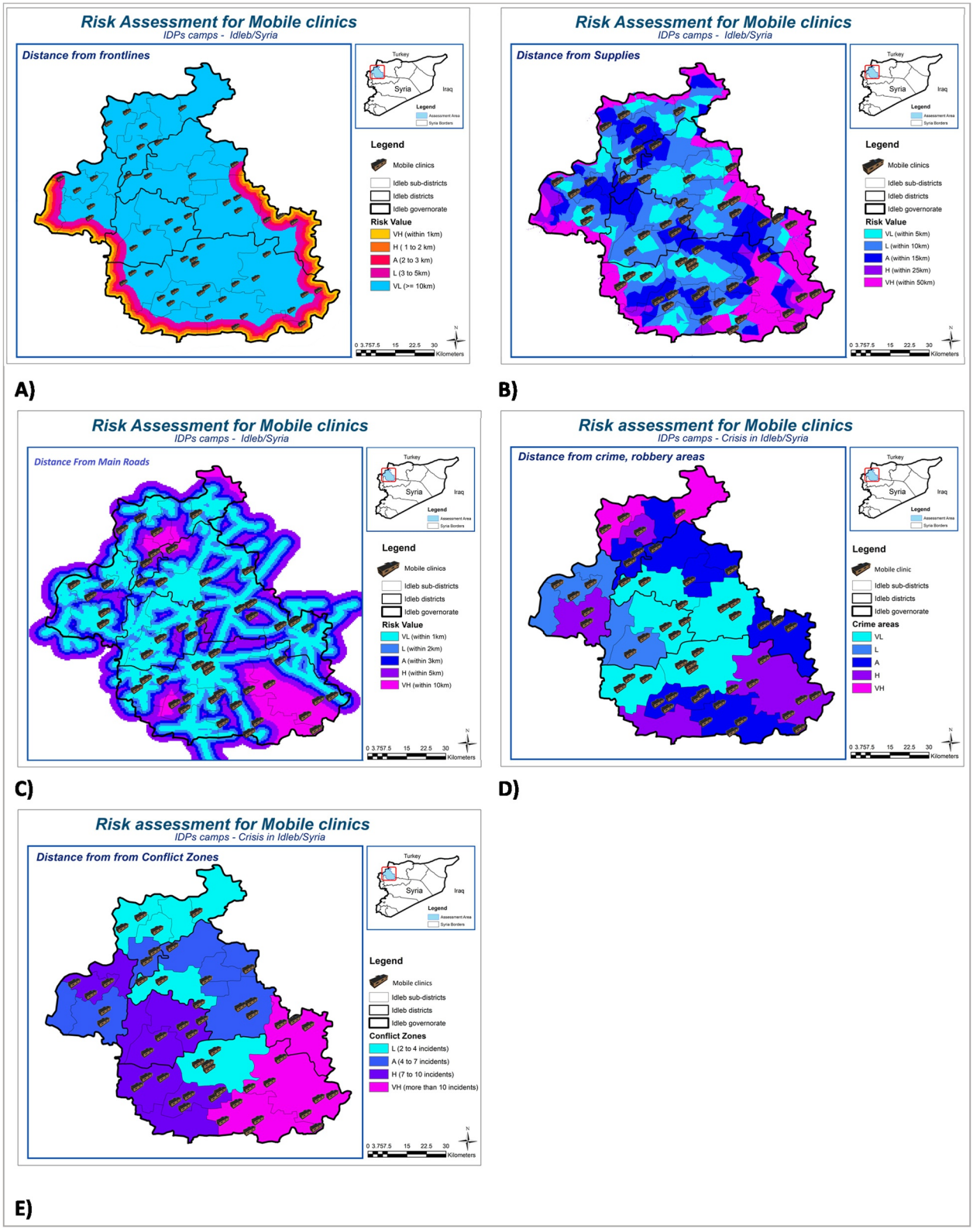

FIGURE 5 | Risk maps created in the target areas (A, B, C, D, E).

standard requirement of CR < 0.10, while the aggregated group matrix produced a consistency ratio of 0.07. These results indicate that the pairwise judgements used to derive the criterion weights were sufficiently coherent.

Because no observed ground-truth ranking of mobile clinic locations was available, the accuracy of the framework could not be assessed through a conventional prediction-error measure. Its reliability was therefore evaluated through the internal

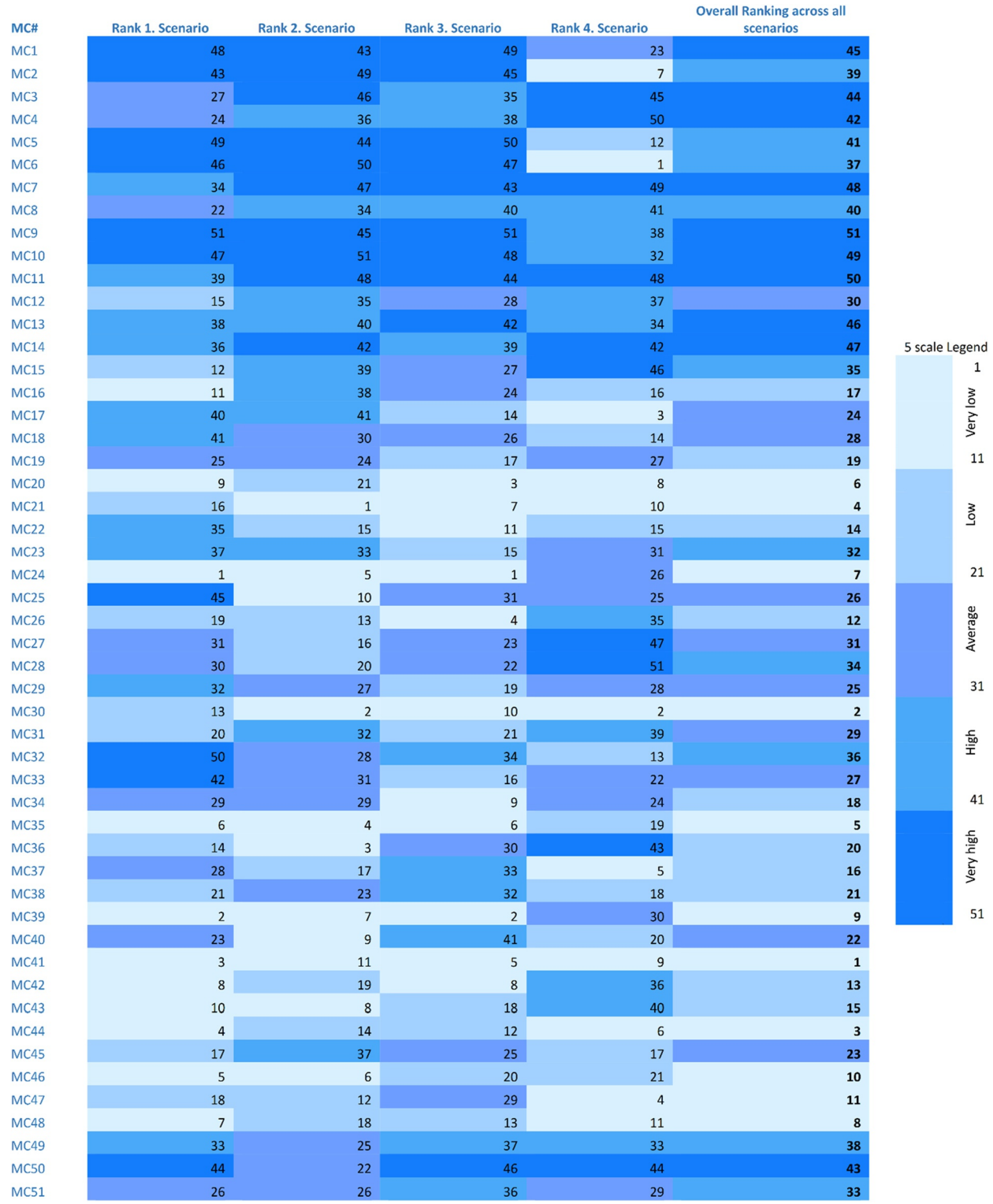

FIGURE 6 | Rankings of the candidate locations under the four scenarios and the overall aggregated ranking.

consistency of the expert judgements, adherence to established Fuzzy AHP and Fuzzy TOPSIS procedures, expert review, and comparison with an alternative fuzzy MCDM method.

To examine methodological robustness, the Fuzzy TOPSIS rankings were compared with rankings generated using Fuzzy VIKOR. Pearson correlation applied to the ranking positions produced a coefficient of 0.99, indicating a very strong association between the two ranking sets. This high level of agreement suggests that the location-priority structure identified through Fuzzy TOPSIS was robust to the application of an alternative fuzzy MCDM method.

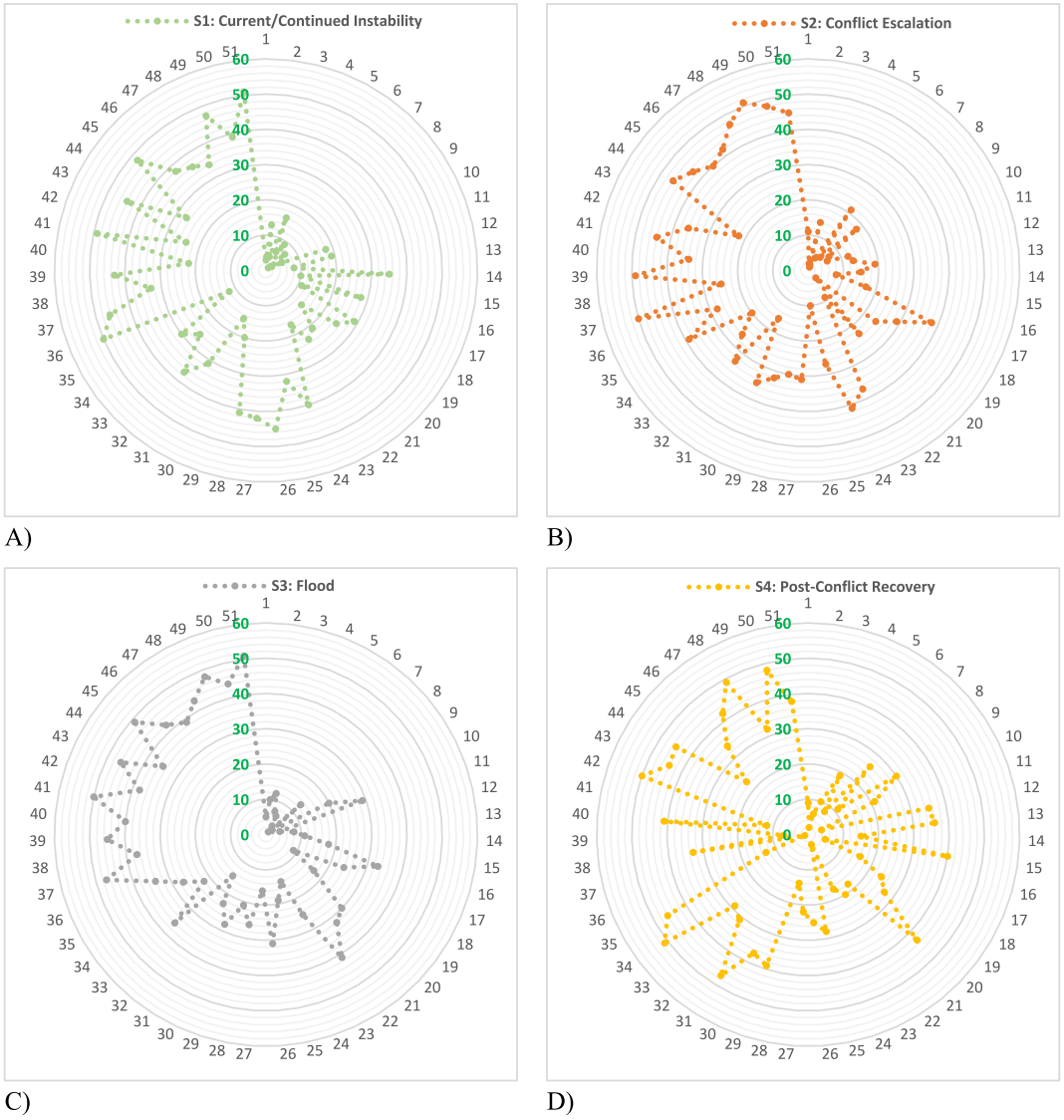

FIGURE 7 | Candidate-location rankings under (A) S1—Current/Continued Instability, (B) S2—Conflict Escalation, (C) S3—Flood, and (D) S4—Post-Conflict Recovery, compared with (E) the overall aggregated ranking.

4.7 | Comparison With Related Studies

In relation to the existing literature, this study sits at the intersection of mobile clinic planning and conflict-sensitive health mapping. Several studies have optimised mobile clinic deployment or evaluated their cost-effectiveness, but usually under a single demand pattern or without explicit multi-scenario health maps [5, 22–24]. GIS-based MCDM has also been widely used to locate static healthcare facilities and assess accessibility in non-conflict or city-scale settings [6, 29]. In north-western Syria, Abujaber et al. proposed an agile framework for mobile health units, yet their focus was on organizational design and implementation rather than multi-scenario spatial prioritisation of service points [7]. On the methodological side, interval and fuzzy extensions of AHP and related weighting schemes have been applied in transport planning, deprivation and health inequalities, and environmental hazard or risk mapping, demonstrating their value for capturing expert uncertainty and differences between stakeholder groups [17, 18, 34, 36, 40]. Similar hybrid frameworks have also been used in land-use and ecological potential studies, where ANP/fuzzy and GIS-based MCDM were integrated to evaluate agricultural land suitability and cultivation priorities under multiple environmental criteria, further illustrating the strength of these approaches for complex spatial planning problems [32, 35]. Building on these strands, our work combines fuzzy AHP weighting and explicit scenario planning and applies this integrated MCDM–GIS framework to the highly volatile context of northern Syria. To our knowledge, there is still very limited work that produces conflict-sensitive health maps for mobile clinics across multiple crisis scenarios in this region. Our study addresses this gap by ranking candidate locations under four distinct planning scenarios tailored to the dynamics of the Syrian conflict.

4.8 | Strengths, Limitations, and Future Research

The study has several methodological and practical strengths. It combines Fuzzy AHP, GIS-based spatial analysis, Fuzzy TOPSIS, and multi-scenario planning within a single decision-support



E)

FIGURE 7 | (Continued)

framework. This integration allows decision-makers to examine the suitability and robustness of mobile clinic locations under changing security and environmental conditions. In addition, the evaluation criteria were derived from responses involving 37 local and international humanitarian organisations, helping the framework reflect priorities identified by practitioners with field experience in crisis settings.

Several limitations should nevertheless be acknowledged. The empirical application is restricted to Idleb Governorate in northern Syria, which limits the direct generalisability of the resulting location rankings. In addition, some spatial data, particularly information concerning security incidents, displacement, and accessibility, may change rapidly. The framework also does not explicitly model mobile-clinic routing, scheduling, service frequency, or vehicle capacity.

These limitations identify several priorities for future research. First, the framework should be tested in other governorates and conflict-affected or humanitarian settings to assess the transferability of both the criteria and their relative weights. Second, future studies could involve a larger and more diverse group of humanitarian organisations and decision-makers to examine whether stakeholder characteristics influence the weighting of location-selection criteria. Third, incorporating dynamic or regularly updated data on displacement, security incidents, road accessibility, and service demand could enable location rankings to be revised as operational conditions change. Further methodological extensions could integrate location-routing, scheduling, service-frequency, and vehicle-capacity decisions with the proposed location-selection framework. Finally, predictive analytics and alternative scenario-generation approaches could be explored to support more systematic anticipation of future healthcare needs and crisis conditions.

4.9 | Contextual and Broader Recommendations

The findings have several context-specific implications for humanitarian health planning in northern Syria. Because the relative suitability of candidate locations changed across the four scenarios, mobile clinic deployment should remain responsive to changes in security, displacement, accessibility,

and environmental conditions rather than relying on a single fixed location strategy. Under conflict-escalation conditions, smaller and highly mobile units may provide greater operational flexibility because they can be relocated as security conditions and population movements change. During post-conflict recovery, larger or semi-stationary mobile clinics may instead support the transition from emergency healthcare delivery towards more sustainable service provision while permanent health infrastructure is restored. Similarly, under flood-risk conditions, locations with more reliable access routes and lower flood exposure may need to be prioritised even when they are moderately farther from major population concentrations. Continued consultation with local communities, healthcare professionals, and humanitarian actors is also important because changing local conditions may alter both healthcare demand and the operational feasibility of specific locations.

Beyond northern Syria, the study provides broader implications for mobile healthcare planning in conflict-affected and disaster-prone settings. Humanitarian organisations should consider incorporating multi-scenario analysis into location-planning processes so that deployment strategies can be evaluated against multiple plausible operational conditions rather than a single expected situation. The integration of expert judgement, spatial risk information, and multi-criteria evaluation also provides a transferable decision-support approach for environments where reliable quantitative data are limited and decisions must account simultaneously for accessibility, security, demand, environmental risk, and operational feasibility. Regular stakeholder feedback and periodic updating of spatial information can further help organisations maintain the relevance of location priorities as conditions evolve.

5 | Conclusion

This study developed a comprehensive framework for evaluating and selecting optimal locations for mobile clinics in conflict-affected areas, focussing on Idleb governorate in northern Syria. By integrating fuzzy multi-criteria decision-making approaches (such as Fuzzy Analytic Hierarchy Process (F-AHP), Geographic Information Systems (GIS), Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and multi-scenario planning) we provided a robust methodology capable of addressing the complex and dynamic conditions inherent in crisis settings. Integration of these tools has been discussed extensively in the literature. Their effectiveness has been highlighted in health logistics and spatial decision-making in both conflict zones and natural disaster scenarios [3, 5]. The data gathered from humanitarian actors in the Syrian health sector were instrumental in identifying and prioritising location selection criteria. These criteria, including accessibility, security, demand for services, integration with other services, environmental conditions, community engagement, and economic feasibility, were weighted using F-AHP, reflecting the complexities and uncertainties of prioritising healthcare needs in conflict zones.

The use of spatial analysis and risk mapping through GIS enabled a visually driven and data-informed evaluation of each candidate site, ensuring that selected mobile clinic locations were strategically positioned to maximise their impact while minimising risk. Similar approaches have been successfully employed in other disaster contexts, such as post-earthquake healthcare facility placement [23], further demonstrating the relevance of this framework across various disaster scenarios. The application of Fuzzy TOPSIS produced a ranked list of 51 candidate locations under four scenarios: current/continued instability (S1), conflict escalation (S2), flood risk (S3), and post-conflict recovery (S4). The multi-scenario planning approach demonstrated the required flexibility and adaptability for effective healthcare service delivery in unpredictable environments. By simulating different future conditions, this study provided valuable insights into how various location strategies for mobile clinics would perform, enabling more resilient and effective planning.

Overall, this framework offers practical, data-driven, and adaptable solutions for health authorities, NGOs, donors and UN organisations involved in humanitarian health logistics. It addresses immediate healthcare delivery needs in crisis zones, including post-earthquake, flood-prone, and other natural disaster areas, while enhancing strategic planning capabilities. This approach can serve as a model for optimising healthcare interventions in other conflict-affected regions, ultimately improving access to critical services for vulnerable populations.

Acknowledgements

The authors have nothing to report.

Funding

The authors have nothing to report.

Ethics Statement

The original data collection was reviewed and approved by the collaborating NGO's ethics committee (approval no. Bon-EC-128) and conducted in accordance with the NGO's ethical and data-protection procedures. Participation was voluntary, and respondents were informed about the purpose of the study and their right to discontinue participation at any stage. The present study used only de-identified secondary data relevant to the mobile clinic location questions, and the authors had no access to names or other direct personal identifiers.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Supporting Information S1: hpm70141-sup-0001-suppl-data.docx.