

Article

A Decision Process for Optimizing Multi-Hazard Shelter Location Using Global Data

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Abstract: Mitigating the effects of natural hazards through infrastructure planning requires integration of diverse types of information from a range of fields, including engineering, geography, social science, and geology. Challenges in data availability and previously siloed data have hindered the ability to obtain the information necessary to support decision making for disaster risk management. This is particularly challenging for areas susceptible to multiple types of natural hazards, especially in low-income communities that lack the resources for data collection. The data revolution is altering this landscape, due to the increased availability of remotely sensed data and global data repositories. This work seeks to leverage these advancements to develop a framework using open global datasets for identifying optimal locations for disaster relief shelters. The goal of this study is to empower low-income regions and make resilience more equitable by providing a multi-hazard shelter planning framework that is accessible to all decision-makers. The tool described integrates spatial multi-criteria decision analysis methods with a network analysis procedure to inform decisions regarding disaster shelter planning and siting.

Keywords: shelter; disaster risk management; multi-hazard; spatial multi-criteria decision analysis

1. Introduction

Disasters can have devastating impacts on societies, resulting in loss of critical infrastructure, loss of economic viability, and above all else, loss of life. Managing disasters is challenging because the types of hazards vary greatly (e.g., natural hazards such as hurricanes, floods, earthquakes, and landslides, or anthropogenic hazards such as terrorism, armed conflict, and oil spills) [1]. Disasters impact communities across a range of sectors at varying levels [2,3], and the magnitude of their impact is determined by a community's social, economic, and environmental capacity to adapt to them [4]. Disaster events are particularly damaging to low-income nations, which do not have adequate resources to withstand the impacts [2,5–7].

Shelter allocation is a critical component of disaster risk management [8] that low-income nations do not have adequate resources to plan effectively [7]. Effective shelter allocation requires integrated assessment of multiple hazards, as well as infrastructural and non-infrastructural elements [9]. Because low-income nations often do not have the resources for information management to make informed shelter planning decisions, shelters may fail to meet the needs of the population [10,11]. The shelter allocation process varies by government policymaker and aid organization [9], but common practices in shelter allocation suffer from several drawbacks that may hinder recovery [8,9]. One drawback is that disaster risk management is often approached through a top-down structure that neglects community participation and local needs [12]. Another is that a segmented approach is often taken to disaster risk

management [13]. This work addresses these two common shortcomings of disaster risk management with respect to shelter site planning for natural hazard events.

1.1. Disaster Risk Management and Resilience

Disaster risk management is the practice of preventing new disaster risks, reducing existing disaster risks, and managing residual risks to strengthen resilience and reduce losses [14]. ‘Resilience’ is the ability of a system or society exposed to hazards to resist, adapt to, and recover from the effects of a hazard [14]. Resilience relies on effective decision-making in all phases of disaster risk management: Mitigation, preparedness, response, and recovery [15,16]. The disaster risk reduction paradigm aims to build community resilience and reduce vulnerabilities in order to better manage disaster risks and impacts [12]. ‘Vulnerability’ is the measure of a community’s susceptibility to the impacts of hazards due to physical, social, economic, and environmental factors [14]. Vulnerability is used in this study as an indicator of a community’s ability to respond to a disaster. It is characterized by a combination of the physical environment, built environment, and social conditions [17]. Hazard exposure is used to represent vulnerability in this study.

A common shortcoming to disaster risk management is a top-down approach, which has been found in historical disasters to not only be ineffective, but undermine the goal of reducing vulnerability to and impacts of disaster in communities. An example of the failures of top-down disaster risk management is the 2009 L’Aquila earthquake in Italy, which was devastating in large part because risk assessment in the area did not consider social factors of risk at the local community level [12]. Project management must consider and engage communities to ensure that their needs are met and specific vulnerabilities are reduced [18]. Participation in disaster risk management, especially the shelter process, has been found in many studies to empower communities to build resilience and improve the community’s likelihood of successful recovery and long-term rehabilitation [9,17,19,20].

1.2. Disaster Shelter Location

A key aspect of disaster risk management is planning shelter locations, made necessary by the displacement of populations as a result of a disaster [21]. In 2019 alone, an estimated 24.9 million people across the world were displaced by disasters with shelter needs [22]. Different types of shelters with different characteristics and requirements are employed for the stages of disaster risk management. A linear, segmented approach is often taken to disaster risk management [13], resulting in emergency shelters that are planned as response preparation without adequate consideration of the potential need for post-disaster shelters during the recovery phase. For example, after the 2010 earthquake in Haiti, the humanitarian emergency shelter response was successful in sheltering the targeted 100,000 families, but the transitional phase towards recovery lasted for years in large part because the emergency shelter plan was not designed to facilitate housing recovery [23]. In many cases, external aid is focused on emergency efforts and does not continue through recovery, leaving communities without resources or guidance to facilitate long-term rehabilitation [9]. Shelter is a process, and continual support is needed to transition from emergency to recovery [24,25].

1.3. SMCDA in Disaster Risk Management

In recent years, the spatial multi-criteria decision analysis (SMCDA) method has been shown to have potential for disaster planning decisions, including shelter site location [26]. SMCDA is a procedure that can be used by a range of stakeholders, including community members, in collaboration to inform a complex decision process such as those associated with shelter site selection [26,27]. The majority of studies utilizing SMCDA for shelter allocation consider a single hazard [28,29] and rely on detailed local data. SMCDA has the capacity to consider criteria for temporary and post-disaster shelter simultaneously, allowing it to harness the complexity of interactions between multiple stages of disaster risk management. It addresses issues in top-down approaches to disaster management by offering a platform for stakeholder collaboration [30]. In SMCDA, alternative solutions, defined in this

case as sites under consideration for shelter allocation, are evaluated by decision makers using weighted criteria [26]. SMCDAs for disaster management are commonly approached through the Analytical Hierarchy Process (AHP) that defines the hierarchy on which criteria are evaluated. This is particularly beneficial to addressing the shelter allocation component of disaster planning, because it can account for input from multiple stakeholders, including government policy makers, aid organizations, impacted communities, technical experts, and involved private sector [4,31]. This procedure allows them to make decisions within their limitations and to set priority between and amongst risks and requirements for a shelter site [27]. This methodology gives the stakeholders the ability to consider both the most likely or frequent natural hazard, as well as the most destructive natural hazard that may affect their community [5]. A limitation of this method is that it is susceptible to uncertainty associated with human decision-making and interpretation [32].

In recent years many studies have utilized SMCDAs for shelter allocation: For example, Kar et al. identified potential emergency shelters for hurricanes in the United States [33]; Alçada-Almeida et al. utilized a multi-objective model to locate emergency shelters in response to major fires in Portugal [34]; and Xu et al. employed a multi-criteria model to allocate urban earthquake emergency shelters in China [35]. However, these are all single-hazard studies, while in reality, disasters are not always isolated incidents. One may occur during the recovery period for another, or a certain hazard event may trigger another [21]. For example, it is common for landslides to occur following large rainfall events, such as in Sierra Leone in August 2017 [36], or to be triggered by earthquakes, such as the 2010 Haiti earthquake that caused landslides that blocked roads, dammed rivers and streams, and threatened infrastructure [37]. Additionally, highly devastating disasters may keep populations displaced for an extended period of time, during which another disaster may occur. In order to address problems associated with a segmented disaster risk management approach and plan emergency shelters that orient long-term recovery, multiple hazards must be considered simultaneously. In the Sendai Framework for Disaster Risk Reduction 2015–2030, the United Nations emphasizes the need for multi-hazard approach for effective disaster risk management [4]. A multi-hazard approach enables shelter infrastructure to be adaptable to the uncertainty associated with disasters and to the complexity of disaster recovery. The interactions between hazards and the entanglement of the stages of disaster risk reduction result in very complex decision-making that SMCDAs have the capacity to tackle, allowing shelters to be planned in a way that facilitates transition from one stage to another and promotes resilience of shelter infrastructure.

Some recent SMCDAs studies consider multiple hazards: Karaman [38] and Skilodimou et al. [39] performed multi-hazard risk assessments in Istanbul, Turkey, and the Peneus river basin, Greece, respectively. These studies, along with the previously cited single-hazard studies, rely on local and private data. Gallina et al. [40] performed a multi-hazard risk assessment at the North Adriatic coast, Italy, using publicly available regional data. Studies which use open data often face challenges in data acquisition that limit the scope of their work, such as the site suitability analysis of emergency earthquake shelters in Japan conducted by Akamatsu and Yamamoto that was restricted to cities which had published their emergency shelter information [41]. Open data has the potential to advance the initiatives contributing to resilience where high costs surveys may not be an option [42].

1.4. Data Driven Approach for Disaster Risk Management and Shelter Location

Integrated assessments of information from a range of scientific and social disciplines are needed to inform disaster risk management [7,29]. Previously, challenges in data acquisition and integration have limited the success of planning for disasters, particularly in low-income nations where the infrastructure for data collection, storage, and integration has not been available [10,43]. The current data revolution is quickly opening doors to potential solutions for disaster risk management in international development through global, open access spatial data that allows for the identification of risk and facilitates planning to reduce it [44]. Global datasets are increasingly made available, making the SMCDAs approach to shelter site selection feasible worldwide, including in low-income, data-sparse communities.

The goal of this study is to leverage the current data revolution to develop a framework for identifying optimal locations for multi-hazard shelters that is accessible to decision makers anywhere using global, publicly available data. This framework addresses the problems associated with a segmented approach to the shelter process and a top-down approach to disaster risk management by integrating information on multiple hazards and creating a platform for stakeholder collaboration that promotes community participation. As a result, this SMCDCA framework promotes more effective disaster risk management. The practice of disaster risk management serves to reduce community vulnerability and strengthen resilience; therefore, the use of global, open data gives this framework the potential to make resilience more equitable by empowering low-resource communities worldwide to make informed shelter allocation decisions.

2. Methods

We propose a multi-hazard SMCDCA approach using global data for shelter allocation to address common failures of top-down, segmented, single-hazard approaches in disaster risk management. To the authors' knowledge, utilizing a multi-hazard SMCDCA for the purpose of shelter site selection is novel, as is relying on global, open data. This project seeks to create a methodology for disaster shelter planning that can be translated and adapted to different regions, countries, hazard scenarios, decision-maker preferences, and optimization goals. We approach shelter as a continuum or a process, as it is required to evolve through multiple phases of disaster risk management [45,46]. While we focus on emergency shelter, our approach has implications for long-term recovery and the inclusion of criteria around livelihood.

Using Haiti as a case study, this paper demonstrates the decision process developed to identify optimal, safe locations for shelters following a disaster event. The study area, shown in Figure 1, was chosen to simulate the framework's applicability in a developing country with high disaster risk whose resilience has been impacted by its lack of resources for effective disaster risk management. High-quality data is typically not available in low-resource communities such as Haiti. Haiti has been continually devastated by multiple types of disasters due to natural hazards throughout history including earthquakes, floods, landslides, and hurricanes [47].



Figure 1. Study area for tool demonstration: The country of Haiti [48].

We utilize a geographic information system (GIS) to process and represent data that support planning recommendations [7,26]. It consists of two stages: Spatially explicit multi-objective decision analysis to identify suitable shelter locations, and a location-allocation algorithm to optimize selection among the suitable locations. The first stage relies on technical intelligence to characterize risk and serviceability of infrastructure at all alternatives, which are defined here as the locations being considered for a shelter site. This involves the integration of relevant datasets from different sources, and provenance through standardization procedures. The process of identifying suitable locations is designed to incorporate, although does not need to rely on, decision-maker preferences.

The second stage utilizes a location-allocation algorithm to optimize selection among the suitable locations, identified in the first step, with respect to vulnerable populations and scenario-specific, user-defined constraints. The location-allocation analysis is executed specific to the problem statement and what the decision-maker defines as “optimal” based on their goals and constraints. The framework is structured by the analytical hierarchy process, which organizes the criteria for site suitability and optimal location into a hierarchy for analysis. Figure 2 shows the hierarchy through which this decision-making process is completed. Attributes measure success of objectives by quantifying criteria for “low hazard risk” and “high serviceability”. The criteria, and how global datasets are transformed to measure them, are detailed in Table 1. Suitable alternatives are selected based on their performance on the objectives. User preferences can be utilized to weight criteria and objectives. The goal is achieved based on the definition of “optimal” through the location-allocation analysis. During this stage, decision rule is executed to select from the suitable alternatives to solve the problem presented. The goal of this hierarchy is open-ended to allow for decision-maker customization based on their limitations.

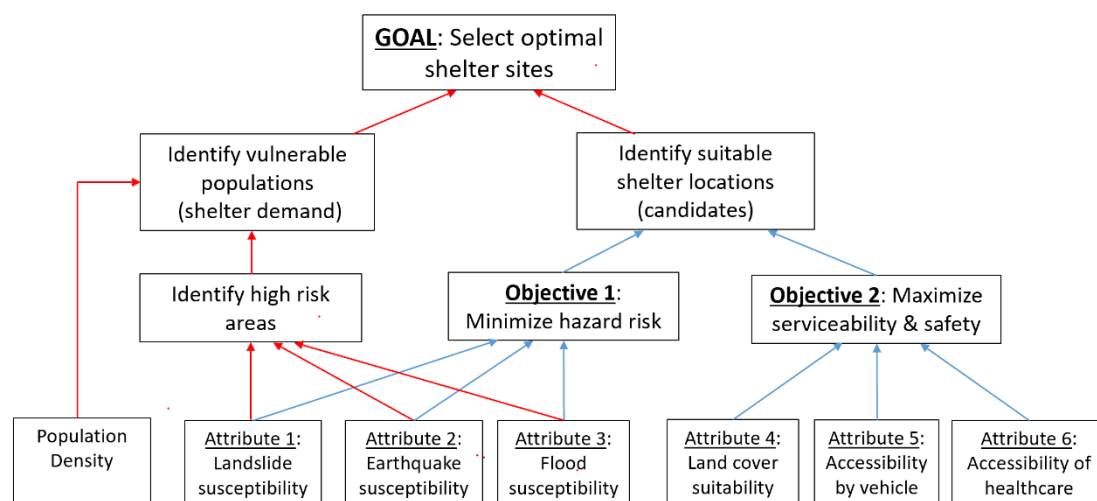


Figure 2. Decision-making hierarchy for spatial multi-criteria decision analysis (SMCDA) process, where blue arrows represent Stage 1 (site suitability) and red represent Stage 2 (site selection).

The tool is demonstrated through a simulated scenario. The scenario-specific goal, to optimize shelter locations, is achieved through the following problem statement: Minimize the number of facilities required, and maximize demand met by vulnerable populations in Haiti while limiting refugee driving time to 60 min. The decision-maker preferences used in this scenario are meant to represent the aggregated inputs of a group of hypothetical stakeholders that reflect their collective priorities. Spatial inputs are used to identify low risk areas (Objective 1) and areas of high serviceability and safety (Objective 2). Various attributes are considered for each objective. Landslide, earthquake, and flood susceptibility were examined to characterize hazard risk, while for serviceability and safety, landcover suitability, accessibility by vehicle, and accessibility of healthcare were considered. These results were then used to spatially identify vulnerable populations and suitable shelter locations, to ultimately select the most optimal shelter sites.

Table 1. Processing of source datasets into attribute layers for each criterion.

Criteria	Source Global Dataset	Processing Performed	Attribute Raster (Metric of Criteria Success)	Standardized Attribute Raster (Metric of Objective Success)
Minimize hazard risk by minimizing landslide susceptibility	Landslide Susceptibility, 30" discrete raster [49]	Project coordinate system and resample resolution	Landslide susceptibility	Landslide risk
Minimize hazard risk by minimizing susceptibility to earthquake damage	30 m Shear Wave Velocity ($V_{S,30}$) [50], 30" continuous raster, Peak Ground Acceleration (PGA) [51] 3' continuous raster	Project coordinate system, resample resolution, reclassify and perform weighted overlay	Seismic site conditions overlaid with expected ground acceleration	Earthquake damage risk
Minimize hazard risk by minimizing susceptibility to fluvial flooding	Rivers, Vector polyline [52]	Euclidean distance tool to estimate floodplains	Distance to rivers	Fluvial flood risk
Maximize serviceability by maximizing accessibility by vehicle	Roads, Vector polyline [53]	Weighted road density by road type classification, discounting insignificant types such as footpaths	Density of roads	Accessibility by transportation
Maximize serviceability by maximizing proximity to healthcare	Healthcare Facilities, Vector point [53]	Weighted point density of permanent healthcare facilities and field hospitals	Density of healthcare facilities	Accessibility to healthcare
Maximize serviceability by maximizing suitability of land cover	Land Cover, 500 m discrete raster [53]	Project coordinate system and resample resolution	Land cover	Suitability of land cover for shelter site

Each attribute is defined to evaluate the criteria to achieve each objective. These criteria are detailed in Table 1 with an overview of the pre-processing completed to transform primary data into attribute layers that serve as a metric of success for their objective. The objectives are weighted, based on decision-maker preference, to optimize the overarching goal. For the development of the framework, only three attributes were selected to measure each objective. The attributes to measure serviceability were selected in accordance with the United Nations High Commissioner for Refugees (UNHCR) Emergency Handbook guidelines [1]. Susceptibilities to common hazards known to affect the area of interest in the demonstrated scenario were assigned as attributes to measure hazard risk. The framework was designed to be adaptable with evolution of data availability and accessibility; in other words, the source global open datasets used in this demonstration of the tool can be easily swapped out as more accurate, comprehensive data is published.

This procedure was automated through ArcMap Model Builder so that this analysis can be completed for any given area of interest. The full workflow is presented in Figure S1a. Details on the components of the Model Builder tool are shown in Figure S1b–f.

2.1. Identifying Suitable Shelter Locations

Attributes and objectives are integrated through the weighted linear combination (WLC) model in Esri ArcGIS 10.7.1 software. It consists of value functions by which each attribute is standardized onto a universal scale, and criteria weights by which stakeholder preferences are accounted for [26]. For this study, a discrete value function of 1–3 was assigned. For the hazard class of attributes, a value of 1 represents low risk, while a value of 3 represents high risk. For the serviceability class of attributes, a value of 1 represents most suitable infrastructure while a value of 3 represents least

suitable infrastructure. Overall, the success of the objectives is optimized by low values on this scale. Figure 3 and Appendix A, Table A1 detail this process for addressing Objective 1, and Figure 4 and Table A2 detail the process for addressing Objective 2. Figures 3 and 4 represent the bottom level of the hierarchy in Figure 2.

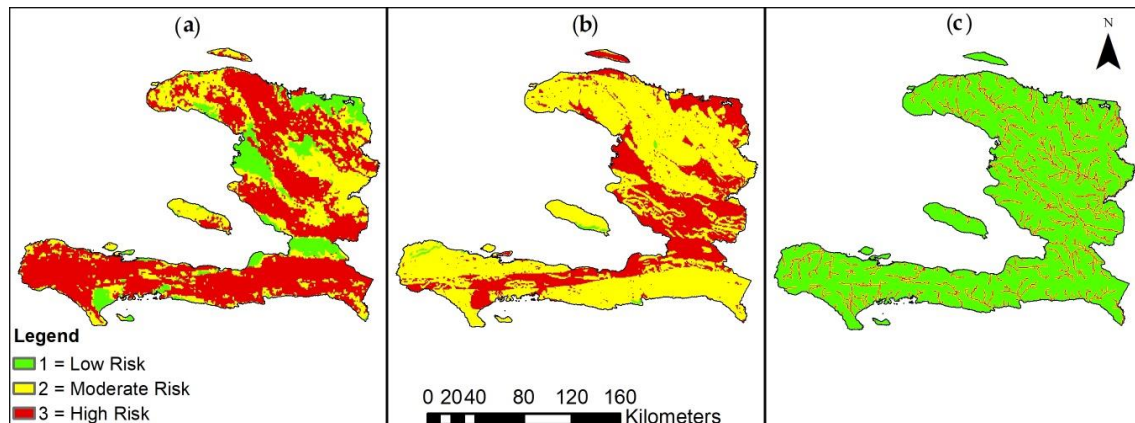


Figure 3. Standardized attribute maps for the objective to minimize risk (Objective 1): (a) Reclassified landslide susceptibility to landslide risk; (b) reclassified earthquake susceptibility to earthquake risk; (c) reclassified fluvial flood susceptibility to flood risk.

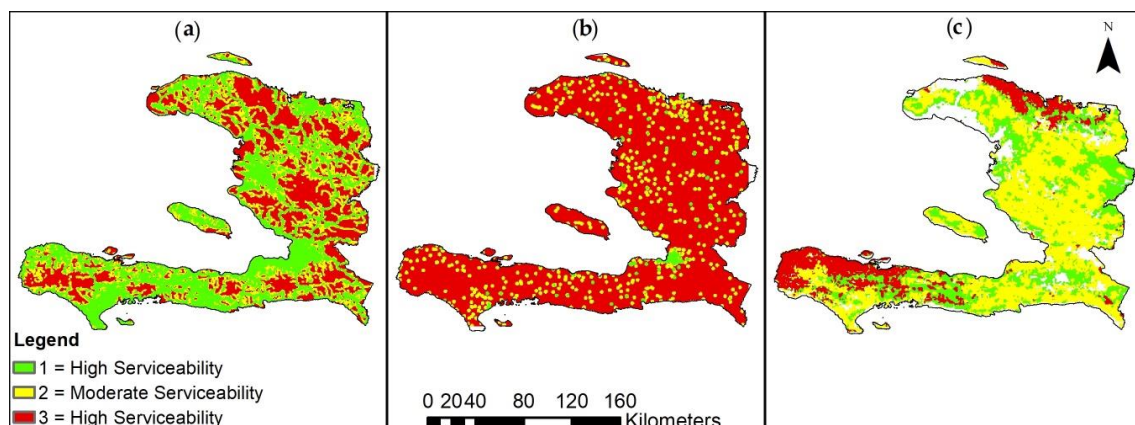


Figure 4. Standardized attribute maps for the objective to maximize serviceability (Objective 2): (a) Reclassified road density to accessibility by vehicle transport; (b) reclassified healthcare facility density to accessibility to healthcare; (c) reclassified land cover to suitability/serviceability of site land cover.

Landslide classes were estimated from NASA's predetermined susceptibility classes, which were established considering topography (slope), seismicity (distance to faults and geological classification), presence of roads, and forest loss [49]. The original global landslide susceptibility map was classified using fuzzy logic to develop a 1–5 scale of very low to very high susceptibility. This was standardized to be conservative of risk, the result shown in Figure 3a.

Earthquake susceptibility was estimated considering site conditions and expected ground accelerations. A global slope-based 30 m shear wave velocity profile ($V_{S,30}$) was used as a proxy for seismic site conditions [50]. $V_{S,30}$ was standardized onto a scale of 1 to 5, where 1 is lowest risk and 5 is highest risk, based on typical shear wave velocities for site classes from hard rock to soft clay accepted by the American Society of Civil Engineers (ASCE) in design code ASCE 7-16 [54]. Rock, as opposed to soft soils, minimizes amplifications of shear waves from seismic activity that can cause large ground deformations and infrastructure damage [55]. Shear wave velocity does not consider the probability of seismic activity or its magnitude; it serves to predict how a site may respond in the event of an earthquake. Peak ground acceleration (PGA) at a 2% probability in 50 years is

used as a metric for expected ground acceleration [51,56]. This data is specific to Haiti, but may be replaced with global models as spatial data is made available for download, such as the Global Earthquake Hazard Model [57]. PGA was standardized onto the same scale as $V_{S,30}$, where the lowest accelerations correspond to low standardized values and very weak ground movement, while high values correspond to high standardized values and violent ground movement [56]. The PGA data is representative only of firm-rock site condition, and considers a 30 m averaged $V_{S,30}$ of 760 m/s [51]. For this reason, PGA was considered with $V_{S,30}$ to account for site-specific seismic response. These two metrics were aggregated to create an earthquake susceptibility map that was standardized onto the 1–3 risk scale, shown in Figure 3b.

Flood susceptibility classes were estimated from distance to rivers, seen in Figure 3c. Floodplain delineation is a complex process that requires a high resolution digital elevation model (DEM) to determine the geometry of the river and the surrounding land [58]. Commonly in developing and data-sparse regions, a coarse global DEM is relied on for hydraulic modeling [58]. Distance to river is used here as a proxy and can be replaced with more comprehensive spatial flood susceptibility data when it becomes available.

Accessibility by vehicle transportation was measured by density of the road network. This attribute serves to maximize accessibility during evacuation and supply delivery. UNHCR recommends that refugees should only be expected to walk short distances [1]. Therefore, an alternative with a high road density should require very little walking from the road, assuming vehicle transportation is available in this scenario. The density values were weighted to give greater priority to major roads. The standardization is shown in Figure 4a.

Healthcare density is used to measure accessibility to healthcare. This criterion is important in minimizing casualties and thus maximizing safety, because disasters often result in injury, as well as illness from contaminated and compromised water sources, for example [59]. Serviceability classes were estimated with judgement based on the range of values in the area of interest for modeling purposes, seen in Figure 4b. Major hospitals were given greater weight than smaller, specialized facilities for standardization.

Land cover classes were based on UNHCR guidelines for ideal shelter sites, seen in Figure 4c [1]. NoData represents a constraint, or a value for a given attribute that disqualifies a location from being suitable. In this case, land covers of inland water and wetlands were assigned as constraints, because those locations are unsuitable for shelter construction.

Through the WLC method, an AHP employs a global method for constructing a priority rating [26]. The WLC model relies on the assumption that attributes are mutually preference independent. Even though this assumption can be problematic in complex spatial problems, this method is generally well accepted in practice [60,61]. It allows for consideration of preferences of multiple decision-makers, which is beneficial because it creates a platform for collaboration between different stakeholders that do not always share political or social initiative. Engaging with stakeholders is important to ensure that disaster planning considers the needs of all affected and relevant parties, including members of vulnerable populations, experts, and governments [5,16,62]. Through the WLC method, criteria are weighted by pairwise comparison. Each pair is compared on a scale of 1 to 9 (Figure 5, Table A) in which the user ranks their preference of one, k , over the other, p [38,63]. A value of 1 signifies equal preference and 9 signifies that criterion k is of extremely greater importance than criterion p . The pairwise comparison values are organized into a matrix where the value c_{kp} , the preference of k over p , is the reciprocal of c_{pk} , the preference of p over k . The user-defined pairwise comparison matrices for this scenario are shown in Table B and C of Figure 5. For example, the value of 2 (see highlighted in Figure 5, Table C) means that, according to the decision-maker, maximizing accessibility by vehicle transportation at a shelter location is slightly more important than maximizing access to healthcare facilities. The highlighted value of 1/5 means that maximizing accessibility by transportation, attribute p , has strong importance over maximizing land cover utility, attribute k , at a shelter location. For that reason, the value of c_{kp} is less than one, calculated as the reciprocal of the preference value

given to p over k , or c_{pk} . In this scenario, all three hazards in consideration are assigned equal weight, represented by values of 1 in the matrix. This was chosen to show the conservative scenario that must meet equal risk requirements for each hazard in consideration. This process is performed separately to compare criteria for each objective, and then the criteria themselves are weighted against one another, in accordance with the hierarchy. The values in Table B and C (Figure 5) are standardized according to the equation shown for c_{kp}^* . The standardized values for this scenario are displayed in Table D and E of Figure 5. The weight given to criterion k is calculated according to the equation shown for w_k , where n is the number of criteria. The scenario-based criteria weights, w_k , are applied to the value function of each attribute k as the combination rule (Figure 5, Table F and G). These weighted value functions measure the success of their corresponding objective at each alternative site; the result corresponds to the second level from the bottom of the hierarchy in Figure 2. The same process is applied to those results, as displayed in Table H, I, and J, to evaluate overall suitability at each alternative. Like the criteria, the objectives are weighted according to decision-maker preference and aggregated. The result corresponds to the box titled “Select Suitable Sites” in Figure 2. In this scenario, minimizing hazard risk is slightly more important to the user than maximizing serviceability at shelter sites, signified by a value of 2 for c_{kp} , where k is Objective 1, and p is Objective 2. The AHP structure combined with the WLC incorporation of user preference allows decision-makers to adjust to their limitations: For example, if funding and resources are no issue, the decision-maker may give strong preference to the “minimize hazard risk” objective because they are confident in the ability to build field hospitals, provide alternate forms of transportation for displaced persons, and supply imports.

2.2. Site Selection Optimization

The final step in the spatial multi-criteria decision analysis is the decision rule through which the goal is achieved. In this framework, the final alternatives are selected through a location-allocation network analysis. Candidate shelters are identified from the suitable alternatives based on the user-specific goal—one could investigate all suitable alternatives in the area of interest, or the ten most suitable in each geographic region, for example. In this scenario, the most suitable 10% of alternatives were analyzed as candidate shelter locations. Hazard exposure is used as an indicator of vulnerability: Population centers that fall within or close to areas experiencing moderate to high risk of all the hazards under consideration are characterized as demand points. Demand points, derived from population density, are used to represent populations to be accommodated by the shelter locations chosen [2,64]. The candidate shelters and demand points become inputs to the location-allocation analysis. The shelter sites are selected from the candidate locations and vulnerable populations are allocated to the sites from the demand points.

Optimal site selection is controlled by the AHP scenario-based, stakeholder-specific goal to “identify optimal shelter locations”. However, the rules for optimization must be defined by the decision-maker. ESRI ArcGIS Pro location-allocation tool was used to select optimal locations. The tool can solve a range of optimization problems, including minimizing impedance from demand points or allocating shelters to meet all demand. The problem type is defined based on limitations such as budget, shelter capacity, transportation, or local law and policy. For example, decision makers could allocate two shelters that meet maximum demand, minimize the number of shelters to meet all demand, or allocate one shelter per region that minimizes impedance. This depends on the decision maker preference and available resources. These considerations are typically country/community/organization specific and therefore are regarded as planning decisions that must be specified for this tool rather than universal parameters. In anticipation of long-term recovery and rehabilitation, decision-makers may limit shelters to a maximum distance from the community center so that members may eventually return to their schools, place of work, etc. In the scenario being demonstrated, the goal is to minimize the number of facilities needed while maximizing demand met within 60 min of driving from vulnerable population points. This scenario assumes that the shelters have no capacity limit for design and that there is access to vehicle transportation.

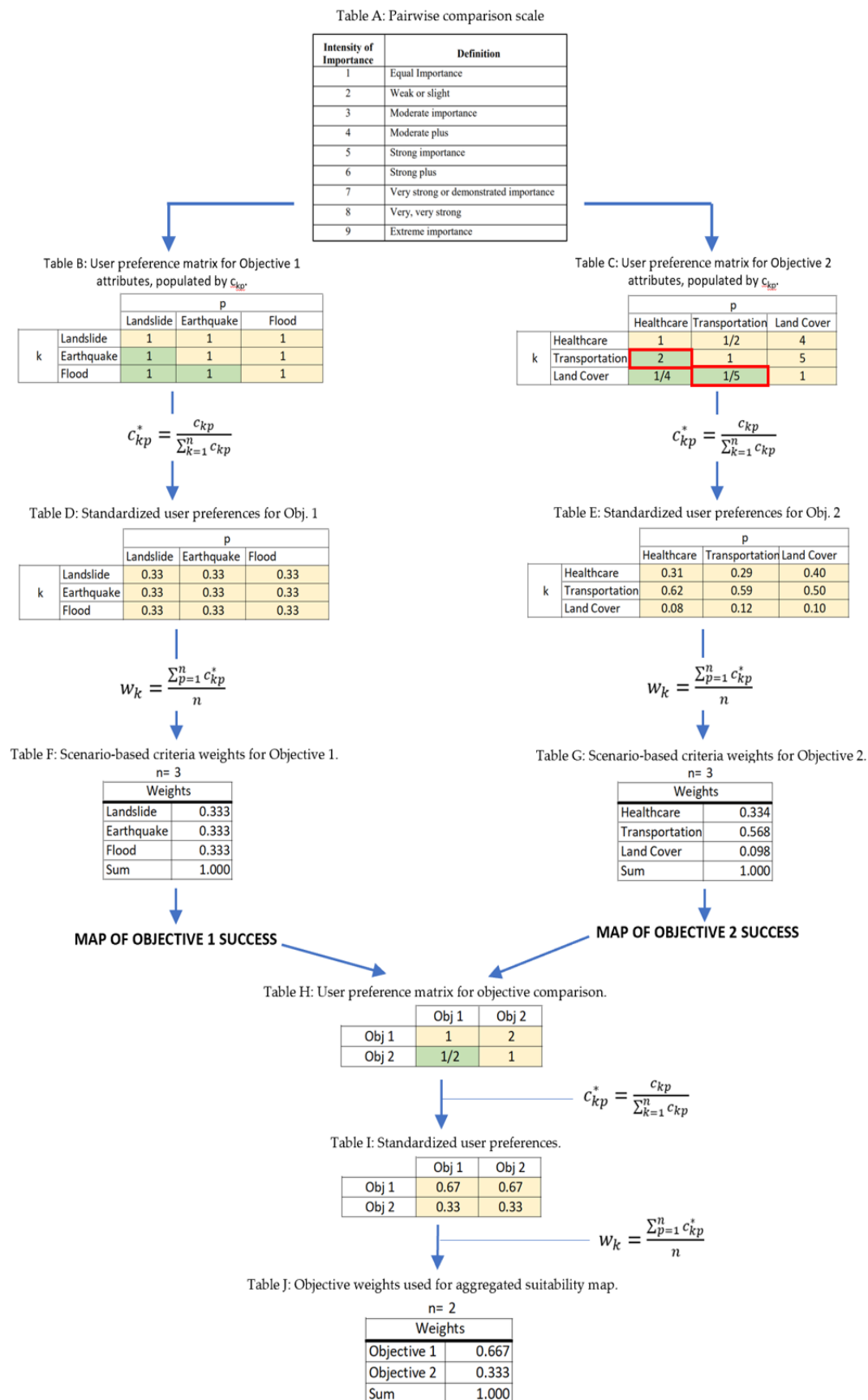


Figure 5. Weighted linear combination process for demonstrated scenario [26,38].

3. Results

3.1. Tool Outputs

The result of the WLC, the first stage, is a suitability map for shelter site location, which is the representative measure of success of the objectives at each alternative. The suitability for the demonstrated scenario is shown in Figure 6.

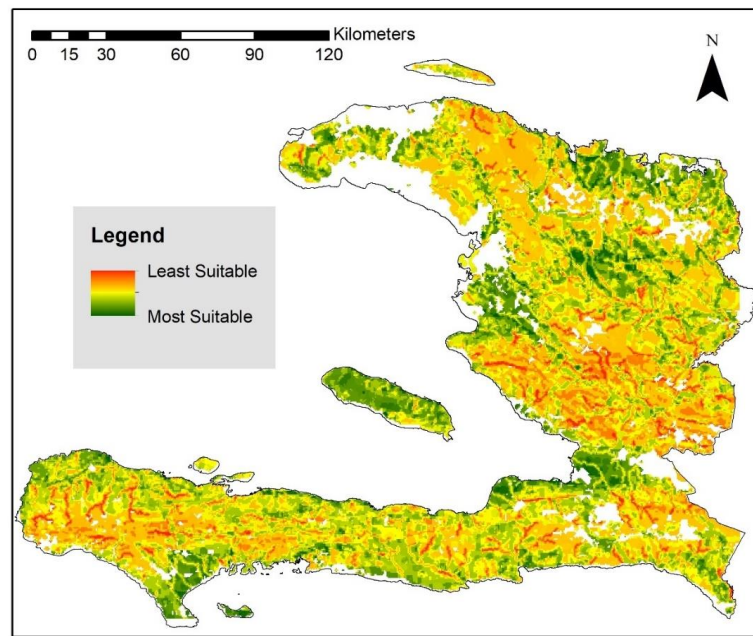


Figure 6. Suitability map for demonstrated scenario.

Figure 7 shows the resulting candidate shelter locations from the site suitability stage and the population demand points, both of which are inputs to the location-allocation analysis.

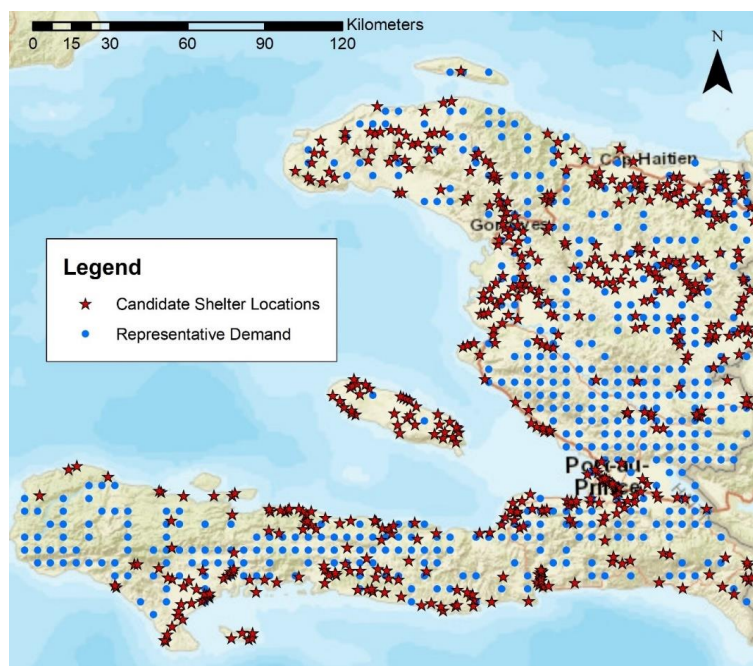


Figure 7. Candidate shelter and representative demand inputs to network analysis for given scenario [48,53].

Figure 8 shows the results of the second stage, location-allocation analysis for the demonstrated scenario: The recommended shelter sites and allocation of vulnerable populations to the shelter sites. Thirty shelters were selected, serving 97.5% of the demand. This scenario was country-wide and focused on major shelter location.

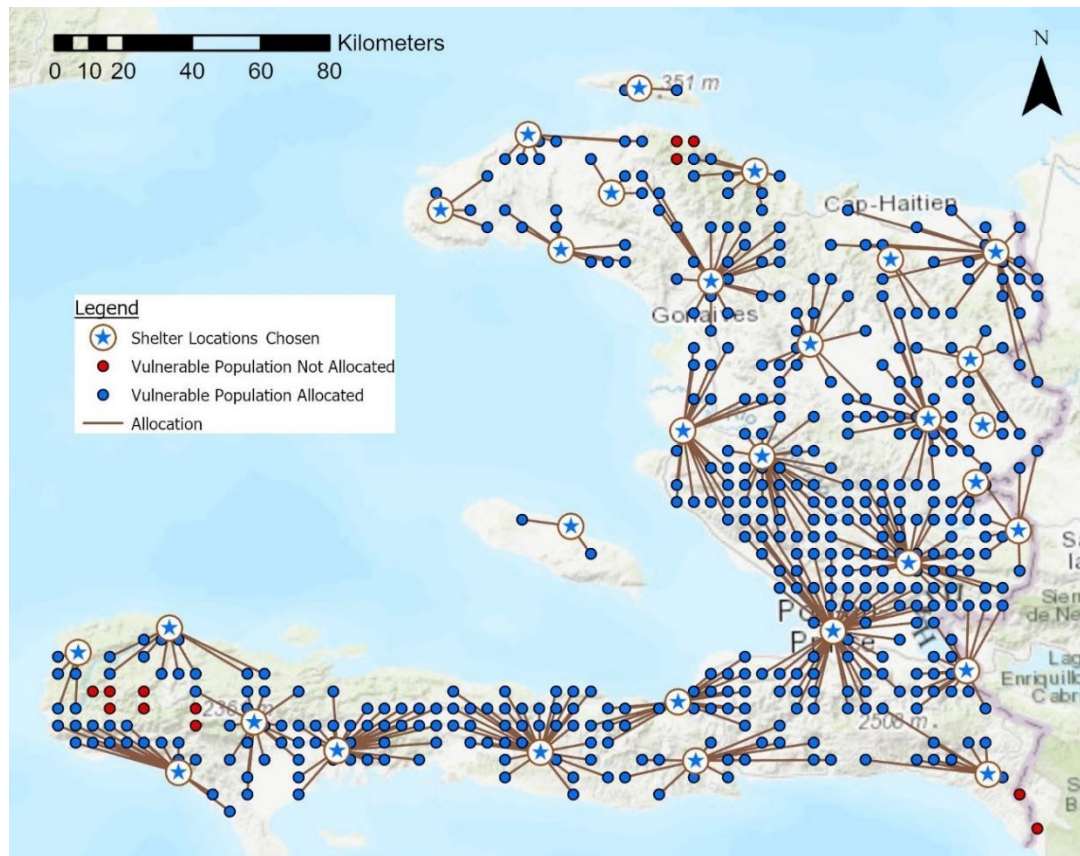


Figure 8. Location-allocation network analysis results [65].

3.2. Sensitivity

A sensitivity analysis was conducted to investigate the impact of decision-maker priority regarding the hazards under consideration on the resulting suitability of the alternatives. The goal was to explore the effect of stakeholder preference with regard to the hazards, over which they have no control, and speculate on the degree to which planning decisions should be informed by technical knowledge where risk is concerned. It is important for stakeholders to understand the impact of their preferences to use the tool effectively. The hazards were initially given equal weights, so for this analysis, each hazard was adjusted to have “strong importance” over the remaining hazards according to the scale in Table A of Figure 5, then that preference was inverted. This is essentially increasing and decreasing the importance of a single hazard with respect to the other hazard criteria. Increasing the priority of earthquake or landslide risk decreases suitable area, while decreasing their priority increases suitable area. As seen in Table 2, decreasing priority of landslide risk increased suitable area by a greater magnitude than decreasing the priority of earthquake risk. Increasing and decreasing the priority of flood risk with respect to the other hazards appears to have the most significant impact on the suitability results. It is important to note, however, that this model is a placeholder for a more comprehensive flood model. These results show that giving high priority to flood risk may yield misleadingly optimistic suitability results.

Table 2. Sensitivity of suitability to weights of hazard criteria.

Scenario	% Suitable Area ¹	% Change in Suitable Area
Original: All hazards equal importance	38.0	N/A
Earthquake strong importance over flood and landslide ²	24.7	−35
Flood and landslide strong importance over earthquake	46.8	23
Landslide strong importance over flood and earthquake	25.1	−34
Flood and earthquake strong importance over landslide	53.2	40
Flood strong importance over earthquake and landslide	82.8	118
Earthquake and landslide strong importance over flood	18.4	−52

¹ Percent of suitable area with a standardized suitability value < 2 on the scale of 1–3. ² Strong importance as defined by Table A of Figure 5.

A brief sensitivity analysis was also conducted on the site selection stage of the decision process to further explore the effect of stakeholder preferences on the resulting decision for shelter location and allocation. The maximum driving time for allocation of vulnerable population to a shelter site was adjusted from 60 to 30 min. The results are shown in Table 3.

Table 3. Results of analysis of sensitivity to impedance cutoff.

Max. Impedance (Driving Minutes)	Number of Candidate Shelters	Number of Shelters Chosen	% of Demand Allocated
30	552	73	85.4
60	552	30	97.5

On a scale of this size, increasing the tolerance for impedance made a significant impact on allocation results—less than half of the number of shelters were required, and almost all the demand was met. This poses the question: What is the maximum distance that a refugee should have to travel in a disaster? Further investigation into the results at other analysis scales may be required to understand the impact of maximum impedance in driving time on the location and allocation of shelters. When the threshold was set to 30 min, many demand points were not allocated. When this is the case, tolerance may need to be adjusted for impedance, criteria weights, or other components of the analysis that are specified by decision-makers.

4. Discussion

The framework developed in this study takes a deterministic approach to the shelter site location problem, with implications for disaster planning in the context of international development. It is adaptable to regions and scenarios around the world, and was designed to be adjustable to new datasets and risk models as they are published. The purpose of this work is to demonstrate a process that is feasible and accessible to decision makers anywhere in order to make resilience more equitable and empower low-income communities through a disaster shelter planning tool. The framework developed here seeks to address the limitations of top-down, segmented, single-hazard approaches to disaster risk management through the integration of data on multiple hazards, and the possibility to integrate input from stakeholders in multiple sectors and areas of expertise, including community members. The framework is applicable using global open data, but has the benefit of being able to implement or substitute local information that may provide higher resolution or stakeholder insight and information that is not represented spatially. The framework was applied in a case study of Haiti, a country susceptible to frequent and diverse natural hazards. The scenario demonstrated in this study was achieved through the optimized allocation of shelters to serve 97.5% of vulnerable population in Haiti. This outcome would vary in another scenario depending on stakeholder preferences, policy constraints, and assumptions on what it means to meet the needs of affected people, but through this

demonstration, the framework was shown to be effective in allocating shelter to serve vulnerable populations under the hypothetical guidelines.

This study is constrained by data availability to characterize both risk and vulnerability, as well as its limited focus on only natural hazards that does not allow consideration of the potential amplification of natural hazards by anthropogenic hazards or the causation of anthropogenic hazards from a natural hazard event. Restrictions in global open data availability prevent this study from considering social or infrastructural dimensions of vulnerability. The ability to account for uncertainty is restricted by the deterministic nature of the framework [21,26]. In addition, there is uncertainty in human decision-making and interpretation. This limitation is addressed in this study through a sensitivity analysis that investigates the impact of variation in stakeholder input on the model output.

In future development, the framework criteria can be expanded to better characterize the complexity of disasters and the associated decision-making. One major limitation is in the data available to characterize risk at a global scale. Data to characterize the infrastructure at a site must be detailed, and it is currently infeasible to collect this information on a global scale. Many of these datasets are not yet available locally in low-resource communities. A wider range of attributes is necessary to encompass the complexity of shelter site selection in disaster planning: Tsunami, coastal flood, and soil liquefaction risk to measure the objective to minimize hazard risk, and sanitation, electric utilities, and land ownership to measure the objective to maximize serviceability. Water source cannot yet be determined at a global scale due to potential water-quality issues, so this methodology assumes that a clean water source may be imported to shelters in the absence of local data availability. Risk exposure is used to represent vulnerability of the physical environment in this study, and should be integrated with a global indicator of social vulnerability in future work. Social vulnerability paired with the risk exposure used in this study to identify shelter demand could better predict populations in need of shelter following a disaster event.

Further sensitivity analyses will be needed to evaluate the impact of user preferences on the resulting suitable alternatives. If there is high sensitivity, the weighted linear combination process may need to be altered to account for bias and varying interpretation of the comparison scale. The discrete nature of classification used in this framework poses a limitation by not allowing it to account for the uncertainty and ambiguity associated with natural hazards and disaster risk management processes, as well as uncertainty associated with the influence of a human stakeholder and varying interpretations of the priority ranking scale. A potential solution to this limitation is the implementation of fuzzy logic [26].

Based on current open global data availability, this framework is more suitable for the allocation of emergency shelters, but has implications for long-term recovery. As more global data is made available, it can be adapted to better address criteria for post-disaster recovery shelter across multiple sectors, particularly those associated with livelihood [66]. In future studies, the research will expand to examine additional scenarios and locations in order to understand the framework's sensitivity to different factors and promote reliable adaptation to communities around the world. In addition, this framework has potential for future application in post-disaster reconnaissance missions to enable users to focus on areas of potential significant damage and their accessibility.

5. Conclusions

There have been many studies utilizing SMCDa for shelter allocation in recent years [33–35,41], but these are all single-hazard studies. They do not address the reality that disasters are not always isolated incidents or the implications of a multi-hazard approach for resolving issues with the traditional segmented approach to disaster risk management. A multi-hazard approach to disaster risk management is promoted by the United Nations [4], and in recent years, this has been reflected in research [38–40]. Through this study, we applied a multi-hazard approach to the disaster risk management task of shelter site selection. The framework described here was designed to facilitate the allocation of emergency shelters with long term post-disaster shelter in consideration, particularly safety

from multiple hazards. As a result, this framework has the potential to promote resilience. The novel use of global open data can make that resilience equitable to low-income communities everywhere.

The framework developed in this study leverages advancements of global data for disaster risk management, but while creating a platform for integrating critical local information through stakeholder participation and collaboration. The framework strengthens resilience by addressing the issues of top-down, segmented, single-hazard approaches to disaster risk management. While the framework was applied to case study, the scenario analyzed in Haiti demonstrated the feasibility and broad applicability of this global, multi-hazard approach to the spatial multi-criteria method for shelter site selection. Ultimately, the goal of the framework developed in this study is to empower community members and aid stakeholders in making disaster planning decisions.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/15/6252/s1>, Figure S1: Automated AHP. (a) Model Builder tool; (b) corresponding hierarchy components; (c) detail of Model Builder section A; (d) detail of Model Builder section B; (e) detail of Model Builder section C; (f) detail of Model Builder section D.

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Appendix A

Table A1. Standardization of attributes for the objective to minimize risk.

Attribute	Standardized Value			Standardized Attribute Meaning
	1 = Low Risk	2 = Moderate Risk	3 = High Risk	
Landslide susceptibility ¹	1	2, 3	4, 5	Landslide risk
Earthquake susceptibility ²	2–5	6–7	7–10	Earthquake risk
Distance to river ³	>500	150–500	<150	Fluvial flood risk

¹ Unitless susceptibility value, 1 being very low and 5 being very high. ² Unitless susceptibility value established in preprocessing, 2 being very low and 10 being very high. ³ Units = meters.

Table A2. Standardization of attributes for the objective to maximize serviceability.

Attribute	Standardized Value				Standardized Attribute Meaning
	1 = High Serviceability	2 = Moderate Serviceability	3 = Low Serviceability	Unsuitable (NoData)	
Road density ¹	>2	0.5–2	<0.5	N/A	Accessibility by vehicle transportation
Healthcare facility density ²	>0.5	0.1–0.5	<0.1	N/A	Accessibility to healthcare
Land cover ³	Grassland, Non/sparsely-vegetated	Cropland, Agriculture	Forest	Wetland, In-land water, Ocean	Serviceability of land cover

¹ Units = kilometers of road per square km. ² Units = facilities per square km. ³ Land use class.

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