logistics

MDPI

*Article*

# Quick-Response Model for Pre- and Post-Disaster Evacuation and Aid Distribution: The Case of the Tula River Flood Event

**Francisca Santana-Robles [1], Eva Selene Hernández-Gress [2,*], Ricardo Martínez-López [1] and Isidro Jesús González-Hernández [1]**

[1] Escuela Superior de Cd. Sahagún, Universidad Autónoma del Estado de Hidalgo, Ciudad Sahagún, Sahagún 43990, Hidalgo, Mexico; profe_7739@uaeh.edu.mx (F.S.-R.); ricardo.martinez@uaeh.edu.mx (R.M.-L.); igonzalez@uaeh.edu.mx (I.J.G.-H.)
[2] Engineering and Sciences School, Tecnologico de Monterrey, Pachuca 42080, Hidalgo, Mexico
* Correspondence: evahgress@tec.mx

**Abstract:** *Background*: In the context of humanitarian logistics, efficiently evacuating people from disaster-stricken areas is a complex challenge. This study focuses on the Tula River region in Hidalgo, Mexico, exploring the evacuation and support of individuals in temporary shelters. Despite the fact that the topic has been addressed in the literature, it is necessary to have quick response methods that can be used by decision-makers to adapt and utilize existing spaces as temporary shelters, in addition to knowing how to evacuate people. *Methods*: Addressing this void, a methodology to minimize evacuation and aid distribution costs is introduced. Leveraging existing algorithms, particularly Integer Linear Programming, the model determines shelter activation and utilizes the Vehicle Routing Problem to assess aid delivery strategies. *Results*: The research identifies optimal evacuation routes from 13 affected areas to 34 shelters and analyzes aid distribution costs under various demand scenarios: original, increased, and decreased by 10%, based on the number of transport units allocated and Google Maps distances. It also evaluates the costs associated with humanitarian aid distribution under varying collection strategies, involving state and municipal governments. *Conclusion*: This approach provides a decision-making foundation and can be adapted for similar analyses in other communities during extreme events.

**Keywords:** Rio Tula Flood; evacuation of people; shelter location; aid collection strategy

check for updates

**Citation:** Santana-Robles, F.; Hernández-Gress, E.S.; Martínez-López, R.; González-Hernández, I.J. Quick-Response Model for Pre- and Post-Disaster Evacuation and Aid Distribution: The Case of the Tula River Flood Event. *Logistics* **2024**, *8*, 8. https://doi.org/10.3390/logistics8010008

Academic Editor: Robert Handfield

Received: 19 September 2023
Revised: 24 November 2023
Accepted: 26 December 2023
Published: 6 January 2024



## 1. Introduction

### *1.1. Problem Statement*

Currently, hazard events pose a significant threat to humanity. According to the United Nations, 90% of extreme events are linked to climate change, indicating a potential increase in their frequency year after year [1]. These events, stemming from destructive origins, result in substantial economic impacts and human losses. In 2021, 401 disasters occurred worldwide, with the Pacific region bearing the brunt of these incidents [2]. Various types of hazard events exist, with earthquakes, droughts, storms, floods, volcanic activity, extreme temperatures, landslides, and forest fires among the most common. Among these, storms and floods were the most frequent, accounting for 223 out of the 401 disasters in 2021 [3]. As shown in Figure 1, floods ranked as the most common hazard events in Latin America and the Caribbean between 2000 and 2019 [4].

Due to the increased frequency of hazard events, the humanitarian supply chain (HSC) has gained significant attention in social, academic, and governmental circles due to its relevance in managing HSC operations, logistics coordination, traditional logistics, performance metrics, and modeling [5]. The primary aim of the HSC is to study various problems, such as facility location, aid distribution, inventory management, and mass evacuation of people, with the overarching goal of safeguarding affected individuals and providing essential resources for their survival.

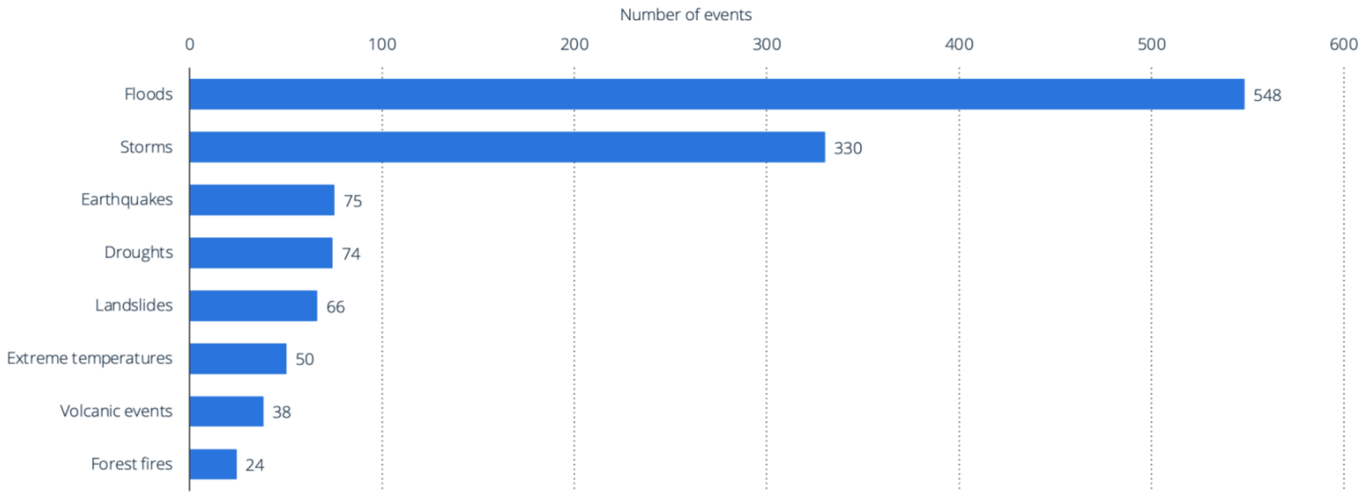


**Figure 1.** Most common hazard events in Latin America and the Caribbean from 2000 to 2019, by number of occurrences. Source: [4].

Facility location pertains to the positioning of warehouses and distribution centers for emergency resources [6,7]. Distribution studies delineate the formation of the distribution network, the choice of transportation modes, and the required capacity to assist people [8,9]. Inventory-related issues revolve around determining resource levels, availability, cost minimization, and demand forecasting [10]. Additionally, addressing the mass evacuation of people encompasses shelter location, evacuation point concentration, transport selection, traffic management, and the time required for evacuation [11,12].

Despite the growing interest in the HSC, the pre-disaster phase has received relatively less attention. However, this phase is of great significance in operations and disaster management, particularly concerning the mass evacuation of people [6,13]. In the context of post-disaster decision-making, numerous proposals exist in the literature for optimizing the distribution of humanitarian aid using various modeling approaches. Nevertheless, they are often designed for diverse scenarios with numerous facilities, leading to complex decision-making processes and unresolved issues. Consequently, future research should explore the characterization of victims' needs and the systematic examination of multilevel service networks [12].

Effective evacuation planning in disaster scenarios must account for both the pre-disaster and post-disaster phases, ensuring the efficient utilization of resources, including public transportation, and addressing the needs of individuals with mobility difficulties and disabilities [14–18]. Notably, various HSC initiatives have been undertaken in Mexico across different domains, such as food banks, vaccine distribution, and food and donation collection, using diverse solution approaches. This study focuses on a case study methodology for evacuating people in a flood scenario. It employs a mathematical optimization model utilizing integer linear programming (ILP). Additionally, this study utilizes the vehicle routing problem (VRP) to assess various strategies for delivering humanitarian aid.

In the State of Hidalgo, Mexico, the Tula River poses a continuous flood threat to the municipalities that it traverses. Although annual flood events are not uncommon in this region, one of the most severe floods in recent memory occurred on 6 September 2021, which was classified as a natural disaster. Unfortunately, this disaster claimed the lives of 15 people and left over 31,000 homes severely affected [19,20]. According to government authorities, the disaster was precipitated by heavy rains in Mexico City and the State of Mexico, leading to the saturation of the drainage system. As a result, the National Water Commission activated the Joint Operation Protocol for Deep Drainage of the Valley of Mexico, causing the Tula River to swell, overflow its banks, and significantly increase its flow. This overflow affected several municipalities, including Tula de Allende, Ixmiquilpan, Tlaxcoapan, Tezontepec de Aldama, Chilcuautla, Tasquillo, Tlahuelilpan, Tepeji del Río, and Mixquiahuala [21].

The drainage system of the metropolitan area in the Valley of Mexico is interconnected through a network of tunnels and canals, facilitating the discharge of water into the Mezquital Valley via the Tula River. However, this setup has adverse consequences for managing urban stormwater. The problem extends beyond just engineering considerations and encompasses a broader perspective that involves public policy [22]. Effectively managing the flood risk stemming from the drainage system of the metropolitan area of the Valley of Mexico requires a comprehensive approach. This approach should encompass geographical and interdisciplinary dimensions, including the construction of defense structures and diversion gates, river realignment, and dredging. Moreover, it should integrate additional measures aimed at reducing the severity of the damage, such as improved damage control and mitigation efforts. Public awareness and preparedness are crucial aspects, ensuring that the population is well-informed about flood risks and is aware of evacuation and safety zones to protect human lives [23].

### *1.2. Problem Description*

This paper presents a comprehensive strategy to evacuate residents from the municipalities impacted by the Tula River prior to a disaster, and to offer humanitarian assistance in shelters after the disaster. This approach aims to minimize costs and collaboratively plan the essential resources, including determining the number and placement of shelters based on calculations of the affected population and establishing routes for delivering aid to these shelters. Importantly, this strategy is grounded in real-world data, incorporating distances and costs, which can serve as valuable decision-making tools for both state and federal governments.

As will be observed in Section 2, there are few works that provide real-world case studies combining both pre- and post-disaster stages. In fact, only Mollah et al. [24] work presents such a case, but their solution method is complex. Although the solution methods utilized in this work have been used before, the motivation here is to explore a straightforward approach that allows for the planning of which shelters to open, how to evacuate the most vulnerable individuals, and how to distribute humanitarian aid. Following a review of the state of the art, the most significant contributions can be summarized as follows:

- A simple decision-making model is proposed.
- Real demographic and social data are employed.
- Consideration is given to the most vulnerable individuals, specifically those over 60 years of age and people with physical disabilities.
- Both the pre- and post-disaster stages are taken into account.

The methodology involved data collection, building the evacuation model, solving the model, and generating options for aid distribution; the research methodology is detailed in Section 3. Section 4 describes the results and discussion, while Section 5 presents the conclusions. In the next section, the literature review is presented.

## 2. Literature Review

In recent years, there has been a substantial surge in publications pertaining to humanitarian supply chains (HSCs). These publications have addressed various key aspects, including facility location, distribution models, inventory management, and mass evacuation procedures. Furthermore, different mathematical models have been put forth for the evacuation of people, employing a range of algorithmic solutions tailored to the unique characteristics of the specific problem at hand. Within the context of HSCs, there exist conditions of uncertainty, particularly in relation to the demand for assistance. Addressing such uncertainty is crucial when devising evacuation models.

In the field of humanitarian logistics, various models have been developed to address diverse objectives. These objectives include the allocation of ambulances under uncertain conditions, the minimization of vehicle numbers, travel cost reduction, limiting maximum latency, optimizing shelter locations, and efficient distribution of aid. Additionally, challenges related to facility location, distribution, inventory management, and mass evacuation have been tackled using multi-objective optimization and multi-period distribution planning, often employing metaheuristic techniques like the Non-Dominated Sorting Genetic Algorithm III, simulated annealing (SA), and variable neighborhood search (VNS) due to the inherent complexity [24–29].

The humanitarian supply chain (HSC) is characterized by four distinct phases: prevention, preparedness, response, and reconstruction and recovery. Decisions made in the pre-disaster phase significantly influence those in the post-disaster phase. The location of distribution centers, the availability of inventory, and the positioning of shelters all play pivotal roles in the distribution of relief supplies and the evacuation of people. Concerning both the pre-disaster and post-disaster phases, problems related to stock prepositioning, facility placement, evacuation planning, and hospital and distribution center locations have been addressed. These complex challenges have been approached using various metaheuristics, including classical approaches (CAs), pattern search algorithms (PSAs), genetic algorithms (GAs), and Non-Dominated Sorting Genetic Algorithm III [15,28–30].

One of the most critical issues within the HSC domain is the efficient mass evacuation of people for providing timely care to victims. The literature offers proposals to minimize the costs of rescue operations while giving priority to injured individuals. These proposals also cover scheduling and assigning rescue teams, taking into account factors like fatigue and deprivation time. Metaheuristic methods, such as genetic algorithms (GAs) and particle swarm optimization (PSO), have been employed to solve these models [16–18].

Among the recent contributions, Shehadeh and Tucker [31] focused on determining the location of humanitarian aid warehouses in both the pre- and post-disaster phases, considering uncertainty, and positioning inventory. Seraji et al. [32] optimized the placement of emergency shelters and coordinated the movement of aid vehicles using two-stage multi-objective metaheuristics. Table 1 provides a summary of the articles found in the literature that explore approaches in both pre- and post-disaster scenarios, along with the solution methods, some of which have been applied in real-world cases.

**Table 1.** Models proposed for the attention of natural disasters.

| Author(s) | Problem | Phase (Pre- or Post-Disaster) | Solution Method (Approach) | Case Study |
|---|---|---|---|---|
| Babaei and Shahanaghi [25] | Multilevel location allocation and emergency routing problem in uncertain conditions | Post-disaster | Monte Carlo simulation and simulated annealing | No |
| Molina [26] | Multi-objective capacitated vehicle routing problem to deal with the lack of available vehicles and the need for quick evacuation | Post-disaster | MultiStart algorithm with intelligent neighborhood selection (NSGA-II) | No |
| Molla et al. [24] | Relief distribution during flooding and the evacuation of people | Pre- and post-disaster | Mixed-integer programming and genetic algorithms | Yes |
| Jha et al. [27] | Humanitarian relief chain that includes a relief goods supply chain and an evacuation chain in case of natural disaster | Pre- and post-disaster | Mixed-integer programming and NSGA-II | No |
| Doodman et al. [28] | Relief item prepositioning and multi-period distribution planning | Post-disaster | Multi-objective two-stage stochastic programming and TH method | No |

**Table 1.** *Cont.*

| Author(s) | Problem | Phase (Pre- or Post-Disaster) | Solution Method (Approach) | Case Study |
|---|---|---|---|---|
| Seraji et al. [32] | Location of shelters in the first phase and demands after accommodation in the second phase | Pre- and post-disaster | Two-stage stochastic programming | No |
| Zhu et al. [16] | Emergency relief routing optimization considering equity and priority issues | Post-disaster | Metaheuristic based on ant colony optimization | Yes |
| Mansoori et al. [18] | Minimize (a) the total number of people not transferred to hospitals and homeless not evacuated, and (b) total relief commodities | Post-disaster | Multi-objective mathematical model | Yes |
| Nayeri et al. [17] | Allocate and schedule rescue teams considering deprivation costs and times | Pre-disaster | Multi-objective mixed-integer programming using the LP method and a metaheuristic algorithm | No |
| Shehade and Tucker [31] | Determine where to open warehouses and how much inventory to preposition in each | Pre- and post-disaster | Two-stage stochastic programming and distributionally robust optimization (DRO) models | No |
| Madani et al. [33] | Multi-echelon and multi-objective relief network, location of hospitals, local warehouse hybrid centers, and evacuation of people | Pre- and post-disaster | Hybrid non-dominated sorting genetic algorithm and variable neighborhood search | No |
| Agarwal et al. [30] | Logistics stock prepositioning and evacuation planning | Pre- and post-disaster | Mathematical model for decision making with pattern simulated annealing and genetic algorithms | Yes |
| Seraji et al. [32] | Optimize the location of emergency shelters and coordinate the movement of relief vehicles considering distributive injustice and dissatisfaction | Pre- and post-disaster | Two stage multi-objective metaheuristics: multi-objective vibration damping and NSGA II | No |

Other works involving individuals with disabilities include the one by Yazdani and Haghani [34], where they presented a case study in Australia for evacuating the elderly using optimization algorithms combined with behavioral training. The same authors also introduced an emergency plan for relocating vulnerable individuals to shelters in response to heatwaves, presenting a method that they tested in a set of randomly generated locations [35].

While more methods with broader scope exist, involving larger networks and traffic modeling, and considering human behavior [36], in the case of the Tula River, the network only encompasses 50 possible shelters, 9 assembly points, and 2 distribution centers for aid, also without different route options. Thus, integer programming models are sufficient for making quick decisions. The concept of nearest and safest allocation, as outlined by Southworth [37] and Barrett et al. [38], is employed, and this planning is conducted in advance of flooding.

## 3. Research Methodology

The methodology to address the problem proposed in this work is composed of four stages: (1) data collection, (2) evacuation model, (3) model solution, and (4) distribution of humanitarian aid (Figure 2).

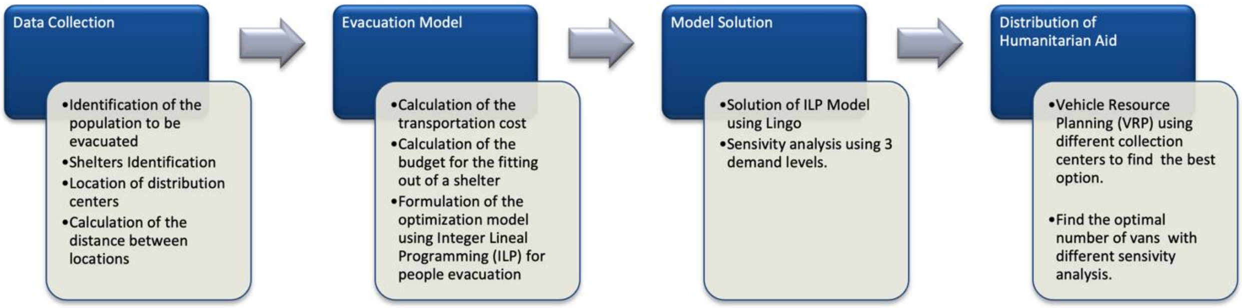


**Figure 2.** Research methodology. Source: own elaboration.

Step (1)—Data Collection: The initial phase involves complete data collection to establish a solid foundation of understanding of the problem for further analysis. The data collected cover the calculation of the population that requires evacuation, the identification of possible shelters, the location of distribution centers for humanitarian aid, and the calculation of distances between affected areas and shelters.

Step (2)—Evacuation Model: This step involves the formulation of the optimization model using integer linear programming. It begins with the calculation of transportation costs for the evaluation of people and the distribution of aid, as well as the calculation of the budget for the qualification of the shelters. These costs are the basis for the optimization of the model; subsequently, the variables involved in the mathematical model are established, and the objective function and the set of restrictions are formulated.

Step (3)—Model Solution: The third phase includes the search for tools to provide a solution to the proposed model and establish the procedure to perform the sensitivity analysis.

Step (4)—Distribution of Humanitarian Aid: This phase considers the use of the VRP technique to determine the collection routes for the distribution of humanitarian aid from the distribution centers to the shelters. In addition, the routes for the evacuation of people are determined and the time required for said evacuation is calculated.

### *3.1. Data Collection*

In the initial phase, the municipalities situated closest to the Tula River were identified. Subsequently, the 13 municipalities that were deemed to be the most severely affected were chosen. The municipalities considered in the State of Hidalgo were Alfajayucan, Atitalaquia, Atotonilco de Tula, Ixmiquilpan, Mixquiahuala, Tasquillo, Tepeji del Río, Tezontepec de Aldama, Tlahuelilpan, Tlaxcoapan, Tula de Allende and Zimapán, and for the State of Mexico we considered the municipality Apaxco.

The method for estimating the number of people requiring evacuation relied on data sourced from the 2020 Population and Housing Census, which was conducted by the National Institute of Statistics and Geography (INEGI 2021) [39]. Notably, this analysis considered two specific groups: individuals aged 60 years or older, and those with physical disabilities, as these populations are the most vulnerable during a disaster. The calculation of the number of people to be evacuated for each municipality involved summing the percentages of people aged over 60 and people with physical disabilities, and then multiplying the total by the municipality's overall population. Additional details can be found in Table 2.

**Table 2.** Calculation of the evacuee population.

| Municipality | Total Population | Pensioners or Retired People (%) | People with Disabilities (%) | Quantity to Evacuate |
|---|---|---|---|---|
| Alfajayucan | 19,162 | 1.13 | 6.4 | 1475 |
| Apaxco | 39,898 | 6.1 | 4.9 | 3509 |
| Atitalaquia | 31,525 | 10 | 4.6 | 4603 |
| Atotonilco de Tula | 62,470 | 5.9 | 4.6 | 5559 |
| Ixmiquilpan | 98,654 | 5.1 | 5.6 | 10,556 |
| Mixquiahuala | 47,222 | 4.7 | 5.6 | 4864 |
| Tasquillo | 17,441 | 4 | 6.9 | 1901 |
| Tepeji del Río | 90,546 | 7.7 | 4.6 | 11,137 |
| Tezontepec | 55,134 | 2.1 | 5 | 3915 |
| Tlahuelilpan | 19,067 | 3 | 5.4 | 1602 |
| Tlaxcoapan | 28,626 | 3.4 | 3.4 | 1947 |
| Tula | 115,107 | 10.3 | 5.2 | 17,842 |
| Zimapán | 39,927 | 2.4 | 5.1 | 2995 |

Regarding the selection of temporary shelters, public spaces like auditoriums, schools, and churches were considered, with a preference for locations situated at a significant distance from the Tula River. Initially, 50 such sites were identified. However, after a thorough analysis of infrastructure and distances, the list was refined to 37. These selected facilities were subsequently integrated into the mathematical optimization model. For a comprehensive list of these shelters and their respective capacities, please refer to Table A1 in Appendix A.

To determine the locations of distribution centers, two distinct strategies were evaluated: The first strategy involved utilizing municipal presidencies as collection points, from which aid would be dispatched to various shelters. This approach was made feasible by strategically stockpiling a certain amount of food during the disaster preparedness phase. In the second strategy, the team considered the Government Palace, the National System for the Integral Development of the Family (DIF), and the Tula Presidency as distribution centers. This approach assumes that there exists a disaster relief fund that could be employed to directly dispatch aid kits to the shelters without necessitating intermediary distribution centers. The shelters, affected areas, and distribution centers are shown on the map in Figure 3.

To calculate the distances between the affected areas and the temporary shelters, we relied on real-time data obtained through Google Maps coordinates. This methodology was also applied to determine the distances between the distribution centers and the shelters. More detailed information is accessible through the provided repository [40].

### *3.2. Evacuation Model*

In the second phase, the transportation costs were calculated. These costs were derived from selecting a particular type of transportation (NISSAN/URVAN/2015) with a capacity of 15 passengers. To compute the cost per trip, the fuel cost was used, which depended on the distance traveled, and a fixed cost was added for renting the vehicle. The fuel consumption per kilometer was determined based on data provided by the Ministry of Environment and Human Resources, while the fixed cost was obtained through price consultations with transportation providers [41].

The budget calculation for equipping a shelter involved selecting a closed facility and determining the necessary items for its preparation. The essential requirements included portable toilets, sinks, a semi-industrial kitchen, aluminum cookware, basic utensils, plastic sinks, mattresses, bedspreads, blankets, waste containers, tents, tables, and chairs. The calculation was made to accommodate approximately 150 to 200 people, resulting in a budget of MXN 159,147. Detailed information can be found in Table A2 in Appendix A.

The formulation of the optimization model employed integer linear programming (ILP) for evacuating people. In this model, the decision variables included the assignment of individuals to be evacuated from each affected area to each temporary shelter and the quantity of aid to be dispatched from each distribution center to each temporary shelter. The primary objective was to minimize transportation costs.

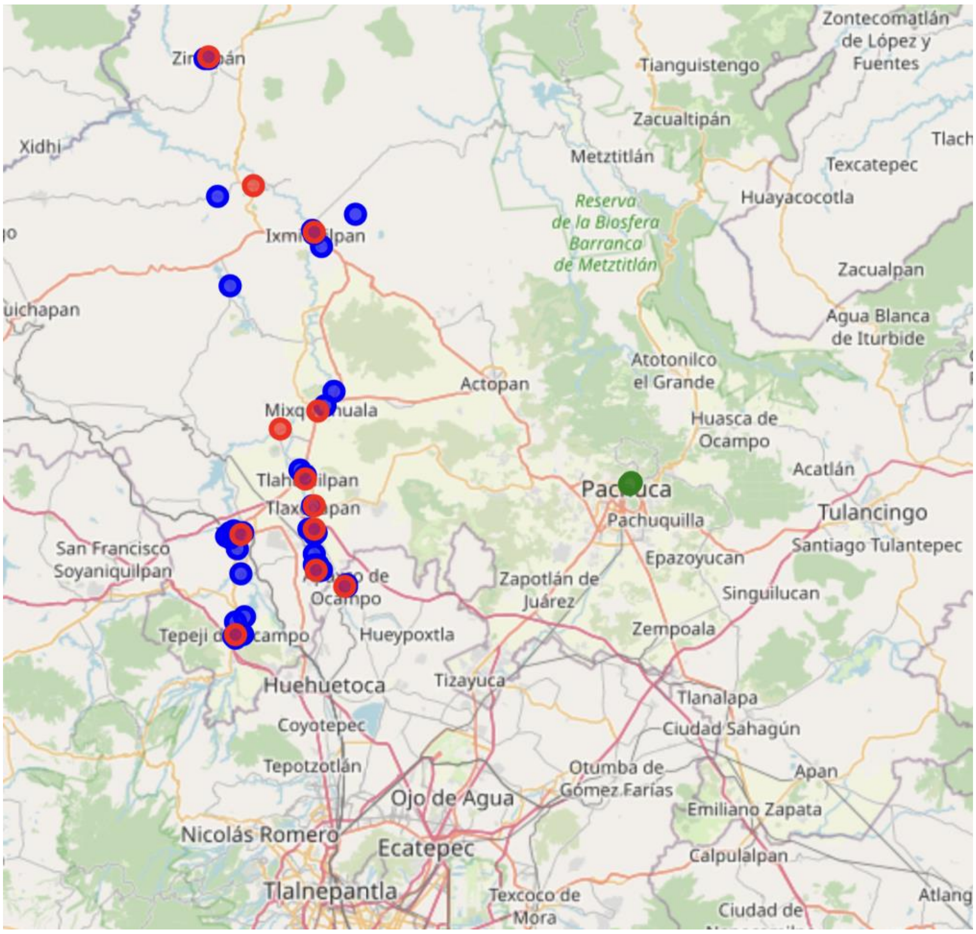


**Figure 3.** Shelters (blue dots), municipal presidencies (red dots) and distribution centers (green dots). Source: own elaboration in Gurobi-Python.

The model is as follows:

$$\min = \sum_{kj \in V} C_{kj} x_{kj} + \sum_{j \in J} f_j y_i + \left( \sum_{i \in I} \frac{p_i}{ca} * r \right) * q \mathit{subject\ to} \tag{1}$$

$$\sum_{i \in I} \sum_{j \in J} x_{ij} \leq A_i \tag{2}$$

$$\sum_{i \in I} \sum_{j \in J} x_{ij} = p_i \tag{3}$$

$$\sum_{k \in K} \sum_{j \in J} x_{kj} = \sum_{i \in I} \sum_{j \in J} x_{ij} \tag{4}$$

$$\sum_{k \in K} \sum_{j \in J} x_{kj} \leq B_k \tag{5}$$

$$\sum_{ij \in Z} c_{ij} x_{ij} + \sum_{kj \in V} C_{kj} x_{kj} + \sum_{j \in J} f_j y_i + \left( \sum_{i \in I} \frac{p_i}{ca} * r \right) * q \leq pr \tag{6}$$

$$y_i = \{1\ \mathit{if\ the\ shelter\ opens},\ 0\ \mathit{otherwise}\} \tag{7}$$

Equation (1) represents the objective function that minimizes the evacuation and the humanitarian aid distribution costs, considering the distances from the affected municipalities to the shelters and the distances from the distribution centers to the shelters. Additionally, the rental cost of the transport units is considered for evacuating people to the shelters. Equation (2) ensures that the number of people evacuated from municipality $i$ is less than the capacity of shelter $j$. Equation (3) establishes that the total number of people who need to be evacuated must be sent to a shelter. Equation (4) ensures that the number of humanitarian aid kits that must be sent from distribution center $k$ to shelter $j$ is equal to the number of people sent to this shelter. Equation (5) establishes that the number of humanitarian aid kits that must be sent from distribution center $k$ to shelter $j$ is less than the capacity of the distribution center. Equation (6) allows that the costs of evacuating people and the distribution of humanitarian aid are less than the budget allocated to manage a flood disaster. Finally, Equation (7) establishes that the variable $y_j$ is 1 if the shelter opens and 0 otherwise.

Table 3 provides the notation used in the ILP model proposed for the evacuation problem.

**Table 3.** Notation used in the linear programming model for the evacuation problem.

| Sets: | |
|---|---|
| $i \epsilon I$ | Set of municipalities affected |
| $j \epsilon J$ | Set of temporary shelter |
| $k \epsilon K$ | Set of distribution centers |
| $i, j \epsilon Z$ | Set of origins $i$ and destinations $j$ |
| $k, j \in V$ | Set of origins $k$ and destinations $j$ |
| Parameters: | |
| $C_{ij}$ | Cost of transportation from the affected municipality $i$ to shelter $j$ |
| $C_{kj}$ | Transportation cost from distribution center $k$ to shelter $j$ |
| $f_j$ | Fixed cost of opening shelter $j$ |
| $d_{ij}$ | Distance from origin $i$ to destination $j$ |
| $d_{kj}$ | Distance from origin $k$ to destination $j$ |
| $\mathrm{P_i}$ | Population to evacuate |
| $q$ | Fixed cost of renting a van to transport people |
| $A_j$ | Shelter capacity |
| $B_k$ | Distribution center capacity |
| $ca$ | Capacity of the van to transport people |
| $r$ | Percentage of vans considered for rental |
| $pr$ | Budget available for disaster care |
| Variables: | |
| $x_{ij}$ | Number of people evacuated from the affected municipality $i$ to shelter $j$ |
| $y_j$ | Binary variable indicating whether the camp is open or not |

### *3.3. Model Solution*

To address the ILP model for the evacuation described in Equations (1)–(7), we employed Lingo 17.0 software, a tool specifically designed for constructing and solving mathematical optimization models.

To conduct sensitivity analysis, the number of people to be evacuated was used as an input parameter in the Lingo model. After obtaining the optimal response with the original data, the model was solved with a 10% variation in demand (both increasing and decreasing). This was performed to examine how the total cost of evacuation and humanitarian aid delivery behaves under different demand scenarios.

### *3.4. Distribution of Humanitarian Aid*

In this research, a vehicle routing problem (VRP) was used for determining the routes of the collection centers. The VRP can be represented as the following graph theory problem: $let\ G = (V, A)$ be a complete graph, where $V = \{0, 1, ..., n\}$ is the set of vertices and A is the set of arches. The vertices $j = 1, \ldots, n$ correspond to customers, each with a known non-negative demand, while vertex 0 corresponds to the deposit. A non-negative cost is associated with each arc and represents the cost of traveling from vertex $i$ to vertex $j$. The VRP consists of finding a set $k$ of simple circuits, each one corresponding to a vehicular route with a minimum cost defined as the sum of the costs of the arcs of the circuits, in such a way that (a) each circuit visits vertex 0, (b) each vertex $j$ is visited by exactly one circuit, and (c) the sum of the demands of the vertices visited by a circuit does not exceed the capacity of the vehicle [42].

The VRP that we used considered the allocation of a vehicle at each distribution center, specifically at the State of Hidalgo Government, DIF Hidalgo, and the Presidency of Tula. The investigation encompassed 34 shelters characterized by normal demand. To obtain real coordinates and estimated travel times, while accounting for traffic conditions, Bing Maps data were utilized. The analysis assumed that each humanitarian aid kit weighed approximately 1 kg and that articulated vehicles with a capacity of 25,000 kg were employed, allowing each vehicle to transport 25,000 kits. These vehicles were assumed to possess a fuel efficiency of 100 km per 35 L of diesel [43], resulting in a cost of MXN 8.28 per kilometer traveled. Additionally, a delivery cost of MXN 500 was incorporated for each humanitarian aid drop-off. The VRP model was implemented with a single vehicle at each distribution center. Subsequently, the number of vans was determined through sensitivity analysis. To estimate the hours required for evacuation, the research considered the deployment of 5, 10, 15, and 20 vans. Furthermore, a 10% variation in demand was considered, encompassing both decreases and increases.

This methodology provides a well-structured guide to address the identified problem in a systematic and effective way. It should be noted that this methodology was designed for quick responses in pre- and post-disaster evacuation and aid distribution, with few temporary shelters and a small population.

## 4. Results

### *4.1. Evacuation Model*

To solve the ILP for the evacuation model proposed in Equations (1)–(7), Lingo 17.0 software was used. Solving the model through the branch-and-bound solver included in Lingo, the optimal allocation was obtained from each of the affected municipalities (concentration centers for victims) to the different shelters, and at the same time the optimal distribution of aid was determined. It should be noted that a sensitivity analysis was carried out by modifying the demand parameters, with a variation of 10% above and below, and these were used as input parameters in Lingo. The objective function with the initial demand was MXN 2,969,813.00, with decreasing demand by 10% it was MXN 2,635,202.00, and with increasing demand by 10% it was MXN 3,250,149.00. It can be seen that with a small modification of the demand, the cost of evacuation and distribution of aid increases by 9% (MXN 280,336.00) with respect to the initial demand because, to meet the demand, three more shelters must be opened (see Figure 4).

The solutions for the three different scenarios of demand are shown in the repository [40]; only 34 shelters were opened, and the shelter information can be found in Table 4. Considering the solution in the repository for the original demand, the people who need to be evacuated from a central location can be determined; for example, the Tula Presidency moves 4500 people (p) to the Tula Sports Unit, 4000 p to the Tula Municipal Auditorium, 4000 p to the Infonavit San Marcos Auditorium, 2000 p to the Cathedral of Tula, 1342 p to the Benito Juárez Elementary School, and 2000 p to the Miguel Hidalgo y Costilla Elementary School, giving a total of 17,842 p.

### *4.2. Evacuation Time and Vans Required*

Based on the best results in the provided repository [40], the required evacuation time was calculated, considering variations in the number of vans for the transfer of people; it was considered that each van has a transfer capacity of 15 people. In order to know the number of hours required for evacuation, 5, 10, 15, and 20 vans were considered, as well as considering a 10% variation in the demand (decrease and increase). Since the municipalities of Tula, Tepeji, and Ixmiquilpan are the ones with the largest numbers of people to evacuate, they are also the ones that require the longest time. For example, if 5 vans are assigned to the Tepeji Presidency, considering the average demand, 62.04 h is required to evacuate, while with 10 vans 31.0244 h is required, and with 20 vans 15.51 h is required, changing proportionally. The total time varies between 8.65% and 11.38% less when the demand goes down and increases by between 25.48% and 29.34% when the demand increases (see Table 5).

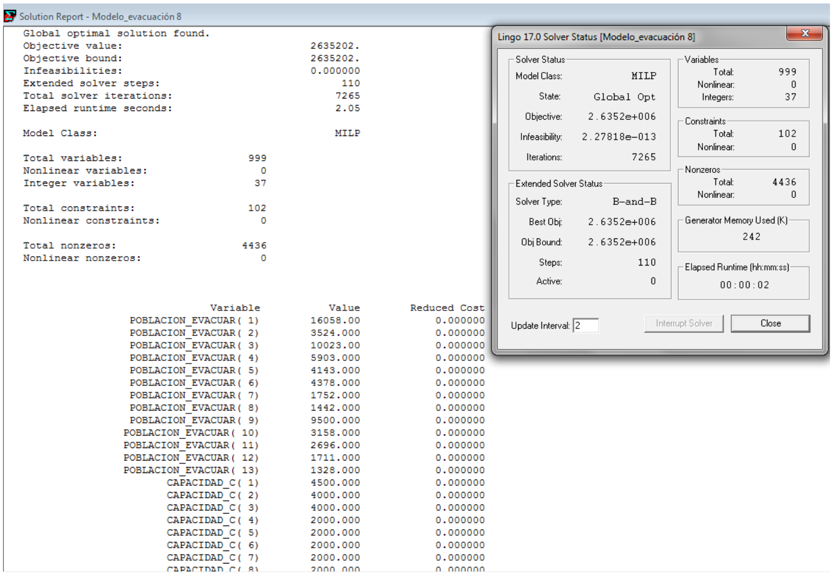


**Figure 4.** Solution of the evacuation model in Lingo. Source: own elaboration.

**Table 4.** Shelter information.

| Shelters | Address | Latitude | Longitude |
|---|---|---|---|
| Unidad Deportiva de Tula | Osa Mayor 15, El Cielito, 42803 Tula. | 20.0526796 | −99.3315105 |
| Auditorio Municipal de Tula | Centro, Tula de Allende, Hgo. | 20.0559197 | −99.3428116 |
| Auditorio Infonavit San Marcos | San Marcos, 42831 San Marcos, Hgo. | 20.0293121 | −99.3379669 |
| Escuela Primaria Francisco Sarabia, Pueblo Nuevo | Pueblo Nuevo, 42845 San Miguel Vindho, Hgo. | 19.9939747 | −99.3316803 |
| Catedral de Tula | 5 de Mayo #5, Centro, 42800 Tula de Allende, Hgo. | 20.0543701 | −99.3441306 |
| Escuela Primaria Benito Juárez | C. Sabino 37, Barrio Alto, 42800 Tula de Allende, Hgo. | 20.0471437 | −99.3560835 |
| Escuela Primaria Miguel Hidalgo y Costilla | C. Francisco Zarco 529, Barrio Alto 2da Secc, 42807 Tula de Allende, Hgo. | 20.0536890 | −99.3493398 |
| Escueal Secundaria General Niños Héroes | Emiliano Zapata 1, Centro, 42760 Tezontepec de Aldama, Hgo. | 20.1424996 | −99.2413238 |
| Escuela Primaria María Angeles | Rep Mexicana 40, Noxtongo 1ra, 42850 Tepeji del Rio de Ocampo, Hgo. | 19.9047249 | −99.3394578 |
| Escuela Melchor Ocampo | Juan Rulfo, Tlaxinacalpan, 42855 Tepeji del Rio de Ocampo, Hgo. | 19.9232103 | −99.3418594 |
| Escuela Primaria Lázaro Cárdenas | 42853, Av. Melchor Ocampo 37, San Mateo 1ra, Tepeji del Rio de Ocampo, Hgo. | 19.9004832 | −99.3418973 |

**Table 4.** *Cont.*

| Shelters | Address | Latitude | Longitude |
|---|---|---|---|
| Colegio Simón Bolivar | C. Guillermo Prieto 17, San Francisco 1ra, 42854 Tepeji del Rio de Ocampo, Hgo. | 19.9028700 | −99.3446700 |
| Iglesia Cristiana Maranatha | San Mateo 1ra, 42853 Tepeji del Rio de Ocampo, Hgo. | 19.9072718 | −99.3313870 |
| Escuela Primaria General 1ro de mayo | Bóvedas, 42982 Atotonilco de Tula, Hgo. | 20.0224432 | −99.2202657 |
| Escuela Secundaria General Felipe Ángeles | 16 de Enero S/N, Centro, 42980 Atotonilco de Tula, Hgo. | 20.0078759 | −99.2150485 |
| Escuela Secundaria Tecnica No.58 | Av. del Trabajo SN, Boxfi, 42980 Atotonilco de Tula, Hgo. | 19.9996695 | −99.2095964 |
| Colegio de Bachillerato del Estado de Hidalgo | C. República del Salvador SN, Bóvedas, 42980 Atotonilco de Tula, Hgo. | 20.0064429 | −99.2210060 |
| Escuela Primaria Francisco Sarabia | Iturbide, Dendho, 42970 Cardonal, Hgo. | 20.0572434 | −99.2279053 |
| Prepa Fray Diego de Rodríguez | Insurgentes 77, El Tablón, 42970 Atitalaquia, Hgo. | 20.0541176 | −99.2162695 |
| Escuela Primaria Adolfo López Mateos | Veracruz 4, El Tablón, 42970 Atitalaquia, Hgo. | 20.0496058 | −99.2193827 |
| Escuela Primaria Urbana General Ma. Anaya | Niños Héroes 88, 3ra Demarcación, 42700 Mixquiahuala de Juárez, Hgo. | 20.2370703 | −99.2043504 |
| Escuela Primaria Amado Nervo | Gabino Barreda 1, Centro, 1ra Demarcación Poniente, 42700 Mixquiahuala de Juárez, Hgo. | 20.2563827 | −99.1903234 |
| Escuela Primaria Pedro Ma. Anaya | Miguel Hidalgo 6, Educación, 42952 Tlaxcoapan, Hgo. | 20.0912805 | −99.2242954 |
| Escuela Primaria Urbana General Ford 72 | Fco Villa 20, Rancho Viejo, 42780 Tlahuelilpan, Hgo. | 20.1353506 | −99.2340138 |
| Escuela Primaria Miguel Hidalgo Loma México | 42325 Ixmiquilpan, Hgo. | 20.4835415 | −99.2191544 |
| Escuela Primaria General Ignacio Zaragoza | San Pedro Capula, Ixmiquilpan, Hgo. | 20.5124985 | −99.1572957 |
| Escuela Primaria Francisco I.Madero | Progreso, 42302 Ixmiquilpan, Hgo. | 20.4898208 | −99.2222736 |
| Escuela Secundaria General Libertadores de América | Libertadores de América 12, El Fithzi, 42300 Ixmiquilpan, Hgo. | 20.4658258 | −99.2092965 |
| Escuela Primaria Teniente Juan de la Barrera | Fco I Madero Sn, El Fithzi, 42300 Ixmiquilpan, Hgo. | 20.4836712 | −99.2192688 |
| Escuela Primaria Lázaro Cárdenas del Rio | C. Allende 1, El Mirador, 55660 Apaxco de Ocampo, Méx. | 19.9763946 | −99.1715745 |
| Escuela Primaria Club de Leones | Del Trabajo y, Santa Anita, 42337 Zimapán, Hgo. | 20.7356244 | −99.3867279 |
| Escuela Secundaria General Josefa Bustamante | Heroico Colegio Militar 11, Centro, 42330 Zimapán, Hgo. | 20.7365736 | −99.3834011 |
| Escuela Primaria Alvaro Obregón | Seguro Social 2, Calvario Bajo, 42381 Tasquillo, Hgo. | 20.5387707 | −99.3689880 |
| Bachillerato Alfajayucan TES | Colonia Centro, 42390 Alfajayucan, Hgo. | 20.4080620 | −99.3495331 |

To provide an adequate response to the evacuation problem in the face of a natural disaster, time is a key factor. In this sense, the numbers of vans required to evacuate in smaller timeframes (3, 5, and 8 h) were calculated. Table 5 shows that when demand decreases, the number of trucks needed decreases by between 10.65% and 11.11%, while if demand increases, the number of trucks needed increases by between 24.71% and 25.12%. The number of vans required to evacuate the population using the average demand would be 418 for a time of 5 h, while 3 h would require 693 vans, and for 8 h 263 vans would be needed; for more information, consider Table A5.

**Table 5.** Time for evacuation, original demand.

| **Presidency** | **5 [a] Vans** | **10 Vans** | **15 Vans** | **20 Vans** | **3 [b] h** | **4 h** | **8 h** |
|---|---|---|---|---|---|---|---|
| Tula | 52.50 [c] | 25.13 | 17.50 | 13.13 | 88 [d] | 53 | 33 |
| Tezontepec | 27.56 | 13.78 | 9.19 | 6.89 | 46 | 28 | 18 |
| Tepeji | 62.05 | 31.02 | 20.68 | 15.51 | 104 | 63 | 39 |
| Atotonilco de Tula | 30.93 | 15.47 | 10.31 | 7.73 | 52 | 31 | 20 |
| Atitalaquia | 26.02 | 13.01 | 8.67 | 6.50 | 44 | 27 | 17 |
| Mixquiahuala | 44.10 | 22.05 | 14.70 | 10.24 | 74 | 45 | 28 |
| Tlaxcoapan | 21.84 | 10.92 | 7.28 | 5.46 | 37 | 22 | 14 |
| Tlahuelilpan | 9.07 | 4.53 | 3.02 | 1.71 | 16 | 10 | 6 |
| Ixmiquilpan | 120.93 | 60.46 | 40.31 | 29.58 | 202 | 121 | 76 |
| Apaxco | 17.65 | 8.83 | 5.88 | 3.34 | 30 | 18 | 12 |
| Zimapán | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 |
| Tasquillo | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 |
| Alfajayucan | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 |
| Total vans | | | | | 693 | 418 | 263 |

[a] Five vans assigned to every presidency; [b] hours needed for evacuation; [c] time in hours; [d] vans required.

Concerning the strategy evaluation for using different distribution centers using the VRP, the VRP Spreadsheet Solver v3.8 was used. Two different strategies were evaluated. The first strategy made use of three collection centers: two in Pachuca (DIF Hidalgo and State of Hidalgo Government) and the third center in the Tula Presidency, each with one articulated vehicle with a capacity of 25,000 kits; the solution is shown in Tables A6–A8 in Appendix A, where the routes to be followed, approximate time, and total cost each time that the aid is delivered (MXN 19,646) are shown. The second strategy made use of only two collection centers: DIF Hidalgo, with one vehicle, and a second center in the Tula Presidency with two vehicles. The routes are shown in Tables A7–A9. The second strategy was the best, with a cost of MXN 18,611 each time that the kits are delivered.

## 5. Conclusions

Currently, hazard events represent a great threat to humanity. A further increase in their incidence is expected due to climate change. This is why the HSC is gaining more and more interest in academia, government, and society. Some relevant problems are the location of shelters, the distribution of aid, inventories, and the mass evacuation of people.

In the literature reviewed here, each author adapted the model and solution strategies to the specific case that they were trying to solve. In this article, shelters are selected, people are evacuated to the shelters and, finally, strategies to distribute aid are explored considering demographic and real geographic data for the evacuation of people with mobility difficulties and disabilities.

The flood that occurred on 6 September 2021 was considered to be an extreme event, and year after year there are flooding problems. The main idea of this study was to provide strategies for municipal and state governments to make decisions about how many shelters to open and how to distribute the aid. The methodology consisted of calculating the population to be evacuated, identifying the possible shelters that could be set up, deciding where it would be convenient to locate the distribution centers, calculating the distance between locations and the expenses incurred to adapt a temporary shelter, and formulating the optimization model to decide which shelters would be opened and how people would be evacuated. Finally, a VRP with different strategies to distribute humanitarian aid was presented.

An analysis was conducted with three types of demand—the original, increased by 10%, and decreased by 10%—to evaluate the adequacy of the planned shelters. Furthermore, we calculated the number of vans needed to execute the evacuation. Our hope, as natives of this region, is that this research serves as a foundation for decision-making and can be employed to conduct similar analyses in other communities during extreme events.

Some of the limitations of this work include the reliance on Google Maps distances for the integer linear programming (ILP), which do not account for real-time traffic conditions. Future research may involve considering the evacuation of other vulnerable individuals in the region, such as those in hospitals, prisons, etc., in the event of other extreme events. Additionally, it could explore how aerial evacuations would be conducted in situations where all routes are obstructed and strategize on the organization of brigades within shelters and/or evacuation points.

**Author Contributions:** Conceptualization, F.S.-R. and E.S.H.-G.; methodology, F.S.-R. and E.S.H.-G.; software, F.S.-R., E.S.H.-G. and R.M.-L.; validation, R.M.-L. and I.J.G.-H.; formal analysis, F.S.-R. and E.S.H.-G.; investigation, F.S.-R. and E.S.H.-G.; data curation, F.S.-R., E.S.H.-G. and R.M.-L.; writing—original draft preparation, F.S.-R. and E.S.H.-G., writing—review and editing methodology, F.S.-R. and E.S.H.-G., visualization, F.S.-R. and E.S.H.-G.; supervision, E.S.H.-G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data are available at the repository https://doi.org/10.6084/m9.figshare.23680881.v1 (accessed on 12 December 2023) [40] and can be requested from the corresponding author when necessary.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

**Table A1.** Selection of properties for the location of shelters. Source: own work.

| Municipality | Property Name | Occupant Capacity |
|---|---|---|
| Alfajayucan | Bachillerato Alfajayucan TES | 2000 |
| Apaxco | Escuela Primaria Lázaro Cárdenas del Rio | 2000 |
| | Escuela Angel Gabriel | 2000 |
| Atitalaquia | Escuela Primaria Urbana General Ma. Anaya | 2000 |
| | Escuela Primaria Amado Nervo | 2000 |
| Atotonilco de Tula | Escuela Primaria General Primero de Mayo | 2000 |
| | Escuela Secundaria General Felipe Ángeles | 2000 |
| | Escuela Secundaria Técnica No. 58 | 2000 |
| | Colegio de Bachillerato del Estado de Hidalgo | 2000 |
| Ixmiquilpan | Escuela Primaria Miguel Hidalgo Loma Hidalgo México | 2000 |
| | Escuela Primaria General Ignacio Zaragoza | 2000 |
| | Escuela Primaria Francisco I. Madero | 2000 |
| | Escuela Secundaria General Libertadores de America | 2000 |
| | Escuela Primaria "Teniente Juan de la Barrera" | 2000 |
| Mixquiahuala | Escuela Primaria Urbana General Ma. Anaya | 2000 |
| | Escuela Primaria Amado Nervo | 2000 |
| Tasquillo | Escuela Primaria Alvaro Obregón | 2000 |
| Tepeji del Río | Escuela Primaria Maria Angeles | 2000 |
| | Escuela Melchor Ocampo (Morelos) | 2000 |
| | Escuela Melchor Ocampo (Tlaxinacalpan) | 2000 |
| | Escuela Primaria Lázaro Cárdenas | 2000 |
| | Colegio Simón Bolívar | 2000 |
| | Iglesia Cristiana Maranatha | 2000 |

**Table A1.** *Cont.*

| Municipality | Property Name | Occupant Capacity |
|---|---|---|
| Tezontepec | Escuela Secundaria General Niños Heroes | 2000 |
| Tlahuelilpan | Escuela Primaria Urbana General Ford 72 | 2000 |
| Tlaxcoapan | Escuela Primaria Pedro Ma. Anaya | 2000 |
| Tula | Unidad Deportiva de Tula | 4500 |
| | Auditorio Municipal de Tula | 4000 |
| | Auditorio Infonavit San Marcos | 4000 |
| | Escuela Primaria Francisco Sarabia | 2000 |
| | Capilla Parroquia Sagrado Corazón de Jesús | 2000 |
| | Catedral de Tula (San José) | 2000 |
| | Escuela Primaria Benito Juarez | 2000 |
| | Escuela Primaria Miguel Hidalgo y Costilla | 2000 |
| Zimapán | Escuela Primaria Club de leones | 2000 |
| | Escuela Secundaria General Joséfa Bustamante | 2000 |

**Table A2.** Items required to outfit a shelter.

| Item | Unit Price | Amount | Total |
|---|---|---|---|
| Portable toilets | MXN 2500.00 | 2 | MXN 5000.00 |
| Portable sink | MXN 800.00 | 3 | MXN 2400.00 |
| Semi-industrial kitchen | MXN 1600.00 | 1 | MXN 1600.00 |
| Aluminum saucepan | MXN 1200.00 | 3 | MXN 3600.00 |
| Aluminum pot | MXN 900.00 | 2 | MXN 1800.00 |
| Basic utensils | MXN 500.00 | 1 | MXN 500.00 |
| Plastic sink | MXN 1200.00 | 3 | MXN 3600.00 |
| Hostel mattresses | MXN 1500.00 | 60 | MXN 90,000.00 |
| Bedspreads and blankets | MXN 150.00 | 60 | MXN 9000.00 |
| Trash bins | MXN 1400.00 | 5 | MXN 7000.00 |
| Installation of tents | MXN 6249.00 | 3 | MXN 18,747.00 |
| Tables | MXN 1300.00 | 3 | MXN 3900 |
| Total | | | MXN 159,147.00 |

**Table A3.** Numbers of trucks required for evacuation within 3, 5, and 8 h.

| Presidency | 3 h | | | 5 h | | | 8 h | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10% Less | Average | 10% More | 10% Less | Average | 10% More | 10% Less | Average | 10% More |
| Tula | 73 | 88 | 160 | 44 | 53 | 96 | 28 | 33 | 60 |
| Tezontepec | 46 | 46 | 61 | 28 | 28 | 37 | 18 | 18 | 23 |
| Tepeji | 79 | 104 | 123 | 48 | 63 | 74 | 30 | 39 | 46 |
| Atotonilco de Tula | 41 | 52 | 55 | 25 | 31 | 33 | 16 | 20 | 21 |
| Atitalaquia | 52 | 44 | 50 | 31 | 27 | 30 | 20 | 17 | 19 |
| Mixquiahuala | 59 | 74 | 87 | 35 | 45 | 53 | 22 | 28 | 33 |
| Tlaxcoapan | 37 | 37 | 37 | 22 | 22 | 22 | 14 | 14 | 14 |
| Tlahuelilpan | 7 | 16 | 36 | 5 | 10 | 22 | 3 | 6 | 14 |
| Ixmiquilpan | 170 | 202 | 223 | 102 | 121 | 134 | 64 | 76 | 84 |
| Apaxco | 24 | 30 | 32 | 14 | 18 | 20 | 9 | 12 | 12 |
| Zimapán | 28 | 0 | 0 | 17 | 0 | 0 | 11 | 0 | 0 |
| Tasquillo | 0 | 0 | 3 | 0 | 0 | 2 | 0 | 0 | 2 |
| Alfajayucan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total vans | 616 | 693 | 867 | 371 | 418 | 523 | 235 | 263 | 328 |
| Difference with average | −11.1% | | +25.11% | −11.24% | | +25.12% | −10.65% | | +24.71% |

**Table A4.** Routes and approximate times for delivery of kits by vehicle 1—first strategy.

| **Vehicle:** | **V1** | **Stops:** | **12** | **Net Profit:** | **−6607.80** | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | Gobierno del Estado | 0.00 | 0.00 | | 08:00 | 0.00 | 0 | 24,500 |
| 1 | Escuela Primaria Pedro Ma. Anaya | 74.33 | 1:02 | 9:02 | 09:02 | 1:02 | 0 | 22,500 |
| 2 | Prepa Fray Diego de Rodríguez | 79.13 | 1:14 | 9:14 | 09:14 | 1:14 | 0 | 20,500 |
| 3 | Escuela Primaria Adolfo López Mateos | 80.14 | 1:17 | 9:17 | 09:17 | 1:17 | 0 | 18,500 |
| 4 | Escuela Primaria Francisco Sarabia | 82.49 | 1:24 | 9:24 | 09:24 | 1:24 | 0 | 16,500 |
| 5 | Catedral de Tula | 97.02 | 1:49 | 9:49 | 09:49 | 1:49 | 0 | 14,500 |
| 6 | Unidad Deportiva de Tula | 98.62 | 1:54 | 9:54 | 09:54 | 1:54 | 0 | 10,000 |
| 7 | Escuela Primaria General 1ro de Mayo | 115.28 | 2:18 | 10:18 | 10:18 | 2:18 | 0 | 8000 |
| 8 | Colegio de Bachilleres del Estado de Hidalgo | 117.32 | 2:24 | 10:24 | 10:24 | 2:24 | 0 | 6000 |
| 9 | Escuela Secundaria General Felipe Ángeles | 118.10 | 2:27 | 10:27 | 10:27 | 2:27 | 0 | 4000 |
| 10 | Escuela Secundaria Técnica No.58 | 120.39 | 2:34 | 10:34 | 10:34 | 2:34 | 0 | 2000 |
| 11 | Escuela Primaria Lázaro Cárdenas del Rio | 127.41 | 2:50 | 10:50 | 10:50 | 2:50 | 0 | 0 |
| 12 | Gobierno del Estado | 194.18 | 4:03 | 12:03 | | 4:03 | 0 | 0 |

**Table A5.** Routes and approximate times for delivery of kits by vehicle 2—first strategy.

| **Vehicle:** | **V2** | **Stops:** | **14** | **Net Profit:** | **−7652.10** | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | DIF Hidalgo | 0.00 | 0:00 | | 08:00 | 0:00 | 0 | 24,927 |
| 1 | Escuela Primaria Amado Nervo | 63.41 | 1:15 | 09:15 | 09:15 | 1:15 | 0 | 22,927 |
| 2 | Escuela Primaria Urbana General Ma. Anaya | 67.67 | 1:25 | 09:25 | 09:25 | 1:25 | 0 | 20,927 |
| 3 | Escuela Secundaria General Niños Héroes | 79.84 | 1:45 | 09:45 | 09:45 | 1:45 | 0 | 18,927 |
| 4 | Escuela Primaria Urbana General Ford 72 | 81.76 | 1:51 | 09:51 | 09:51 | 1:51 | 0 | 16,927 |
| 5 | Bachillerato Alfajayucan TES | 128.09 | 3:01 | 11:01 | 11:01 | 3:01 | 0 | 14,995 |
| 6 | Escuela Primaria Álvaro Obregón | 144.88 | 3:36 | 11:36 | 11:36 | 3:36 | 0 | 12,995 |

**Table A5.** *Cont.*

| Vehicle: | V2 | Stops: | 14 | Net Profit: | −7652.10 | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 7 | Escuela Secundaria General Josefa Bustamante | 177.57 | 4:20 | 12:20 | 12:20 | 4:20 | 0 | 10,995 |
| 8 | Escuela Primaria Club de Leones | 178.06 | 4:22 | 12:22 | 12:22 | 4:22 | 0 | 10,000 |
| 9 | Escuela Primaria Francisco I. Madero | 226.92 | 5:28 | 13:28 | 13:28 | 5:28 | 0 | 8000 |
| 10 | Escuela Primaria Teniente Juan de la Barrera | 228.03 | 5:31 | 13:31 | 13:31 | 5:31 | 0 | 6000 |
| 11 | Escuela Primaria Miguel Hidalgo Loma México | 228.05 | 5:31 | 13:31 | 13:31 | 5:31 | 0 | 4000 |
| 12 | Escuela Secundaria General Libertadores de América | 231.17 | 5:40 | 13:40 | 13:40 | 5:40 | 0 | 2000 |
| 13 | Escuela Primaria General Ignacio Zaragoza | 240.45 | 6:03 | 14:03 | 14:03 | 6:03 | 0 | 0 |
| 14 | DIF Hidalgo | 320.30 | 7:40 | 15:40 | | 7:40 | 0 | 0 |

**Table A6.** Routes and approximate times for delivery of kits by vehicle 3—first strategy.

| Vehicle: | V3 | Stops: | 11 | Net Profit: | −5386.58 | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | Presidencia de Tula | 0.00 | 0:00 | | 08:00 | 0:00 | 0 | 23,478 |
| 1 | Auditorio Municipal de Tula | 1.45 | 0:05 | 08:05 | 08:05 | 0:05 | 0 | 19,478 |
| 2 | Escuela Primaria Miguel Hidalgo y Costilla | 2.46 | 0:09 | 08:09 | 08:09 | 0:09 | 0 | 17,478 |
| 3 | Escuela Primaria Benito Juárez | 3.85 | 0:14 | 08:14 | 08:14 | 0:14 | 0 | 15,478 |
| 4 | Colegio Simón Bolivar | 22.16 | 0:49 | 08:49 | 08:49 | 0:49 | 0 | 13,478 |
| 5 | Escuela Primaria Lázaro Cárdenas | 22.90 | 0:52 | 08:52 | 08:52 | 0:52 | 0 | 11,478 |
| 6 | Escuela Primaria María Ángeles | 23.56 | 0:54 | 08:54 | 08:54 | 0:54 | 0 | 9478 |
| 7 | Iglesia Cristiana Maranatha | 25.66 | 1:00 | 09:00 | 09:00 | 1:00 | 0 | 7478 |
| 8 | Escuela Melchor Ocampo | 28.36 | 1:08 | 09:08 | 09:08 | 1:08 | 0 | 5478 |
| 9 | Escuela Primaria Francisco Sarabia, Pueblo Nuevo | 37.69 | 1:24 | 09:24 | 09:24 | 1:24 | 0 | 4000 |
| 10 | Auditorio Infonavit San Marcos | 43.51 | 1:39 | 09:39 | 09:39 | 1:39 | 0 | 0 |
| 11 | Presidencia de Tula | 46.69 | 1:49 | 09:49 | | 1:49 | 0 | 0 |

**Table A7.** Routes and approximate times for delivery of kits by vehicle 1—second strategy.

| Vehicle: | V1 | Stops: | 14 | Net Profit: | −7652.10 | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | DIF Hidalgo | 0.00 | 0:00 | | 08:00 | 0:00 | 0 | 24,927 |
| 1 | Escuela Primaria Amado Nervo | 63.41 | 1:15 | 9:15 | 09:15 | 1:15 | 0 | 22,927 |
| 2 | Escuela Primaria Urbana General Ma. Anaya | 67.67 | 1:25 | 9:25 | 09:25 | 1:25 | 0 | 20,927 |
| 3 | Escuela Secundaria General Niños Héroes | 79.84 | 1:45 | 09:45 | 09:45 | 1:45 | 0 | 18,927 |
| 4 | Escuela Primaria Urbana General Ford 72 | 81.76 | 1:51 | 09:51 | 09:51 | 1:51 | 0 | 16,927 |
| 5 | Bachillerato Alfajayucan TES | 128.09 | 3:01 | 11:01 | 11:01 | 3:01 | 0 | 14,995 |
| 6 | Escuela Primaria Álvaro Obregón | 144.88 | 3:36 | 11:36 | 11:36 | 3:36 | 0 | 12,995 |
| 7 | Escuela Secundaria General Josefa Bustamante | 177.57 | 4:20 | 12:20 | 12:20 | 4:20 | 0 | 10,995 |
| 8 | Escuela Primaria Club de Leones | 178.06 | 4:22 | 12:22 | 12:22 | 4:22 | 0 | 10,000 |
| 9 | Escuela Primaria Francisco I. Madero | 226.92 | 5:28 | 13:28 | 13:28 | 5:28 | 0 | 8000 |
| 10 | Escuela Primaria Teniente Juan de la Barrera | 228.03 | 5:31 | 13:31 | 13:31 | 5:31 | 0 | 6000 |
| 11 | Escuela Primaria Miguel Hidalgo Loma México | 228.05 | 5:31 | 13:31 | 13:31 | 5:31 | 0 | 4000 |
| 12 | Escuela Secundaria General Libertadores de América | 231.17 | 5:40 | 13:40 | 13:40 | 5:40 | 0 | 2000 |
| 13 | Escuela Primaria General Ignacio Zaragoza | 240.45 | 6:03 | 14:03 | 14:03 | 6:03 | 0 | 0 |
| 14 | DIF Hidalgo | 320.30 | 7:40 | 15:40 | | 7:40 | 0 | 0 |

**Table A8.** Routes and approximate times for delivery of kits by vehicle 2—second strategy.

| Vehicle: | V2 | Stops: | 11 | Net Profit: | −5399.32 | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | Presidencia de Tula | 0.00 | 0:00 | | 08:00 | 0:00 | 0 | 23,978 |
| 1 | Auditorio Infonavit San Marcos | 3.08 | 0:09 | 08:09 | 08:09 | 0:09 | 0 | 19,978 |
| 2 | Escuela Primaria Francisco Sarabia, Pueblo Nuevo | 8.82 | 0:25 | 08:25 | 08:25 | 0:25 | 0 | 18,500 |

**Table A8.** *Cont.*

| **Vehicle:** | **V2** | **Stops:** | **11** | **Net Profit:** | **−5399.32** | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 3 | Colegio Simón Bolivar | 20.78 | 0:46 | 08:46 | 08:46 | 0:46 | 0 | 16,500 |
| 4 | Escuela Primaria Lázaro Cárdenas | 21.52 | 0:49 | 08:49 | 08:49 | 0:49 | 0 | 14,500 |
| 5 | Escuela Primaria María Ángeles | 22.17 | 0:51 | 08:51 | 08:51 | 0:51 | 0 | 12,500 |
| 6 | Iglesia Cristiana Maranatha | 24.28 | 0:57 | 08:57 | 08:57 | 0:57 | 0 | 10,500 |
| 7 | Escuela Melchor Ocampo | 26.98 | 1:05 | 09:05 | 09:05 | 1:05 | 0 | 8500 |
| 8 | Escuela Primaria Benito Juárez | 43.43 | 1:37 | 09:37 | 09:37 | 1:37 | 0 | 6500 |
| 9 | Escuela Primaria Miguel Hidalgo y Costilla | 45.13 | 1:42 | 09:42 | 09:42 | 1:42 | 0 | 4500 |
| 10 | Unidad Deportiva de Tula | 47.45 | 1:50 | 09:50 | 09:50 | 1:50 | 0 | 0 |
| 11 | Presidencia de Tula | 48.23 | 1:54 | 09:54 | | 1:54 | 0 | 0 |

**Table A9.** Routes and approximate times for delivery of kits by vehicle 3—second strategy.

| **Vehicle:** | **V3** | **Stops:** | **12** | **Net Profit:** | **−5560.40** | | | |
|---|---|---|---|---|---|---|---|---|
| **Stop Count** | **Location Name** | **Distance Travelled** | **Driving Time** | **Arrival Time** | **Departure Time** | **Working Time** | **Profit Collected** | **Load** |
| 0 | Presidencia de Tula | 0.00 | 0:00 | | 08:00 | 0:00 | 0 | 24,000 |
| 1 | Auditorio Municipal de Tula | 1.45 | 0:05 | 08:05 | 08:05 | 0:05 | 0 | 20,000 |
| 2 | Catedral de Tula | 1.75 | 0:06 | 08:06 | 08:06 | 0:06 | 0 | 18,000 |
| 3 | Escuela Primaria Pedro Ma. Anaya | 17.52 | 0:32 | 08:32 | 08:32 | 0:32 | 0 | 16,000 |
| 4 | Prepa Fray Diego de Rodríguez | 22.32 | 0:44 | 08:44 | 08:44 | 0:44 | 0 | 14,000 |
| 5 | Escuela Primaria Adolfo López Mateos | 23.34 | 0:47 | 08:47 | 08:47 | 0:47 | 0 | 12,000 |
| 6 | Escuela Primaria Francisco Sarabia | 25.68 | 0:54 | 08:54 | 08:54 | 0:54 | 0 | 10,000 |
| 7 | Escuela Primaria General 1ro de Mayo | 31.29 | 1:08 | 09:08 | 09:08 | 1:08 | 0 | 8000 |
| 8 | Colegio de Bachilleres del Estado de Hidalgo | 33.33 | 1:14 | 09:14 | 09:14 | 1:14 | 0 | 6000 |
| 9 | Escuela Secundaria Técnica no.58 | 35.06 | 1:19 | 09:19 | 09:19 | 1:19 | 0 | 4000 |
| 10 | Escuela Primaria Lázaro Cárdenas del Rio | 42.08 | 1:35 | 09:35 | 09:35 | 1:35 | 0 | 2000 |
| 11 | Escuela Secundaria General Felipe Ángeles | 51.18 | 1:55 | 09:55 | 09:55 | 1:55 | 0 | 0 |
| 12 | Presidencia de Tula | 67.68 | 2:19 | 10:19 | | 2:19 | 0 | 0 |

## References


1. Organización de la Naciones Unidas. Los Desastres son la Nueva Normalidad. Available online: https://news.un.org/es/interview/2019/11/1465021 (accessed on 20 October 2023).
2. Statista Research Department. Annual Number of Natural Disaster Events Globally from 2007 to 2021. Available online: https://www.statista.com/statistics/510959/number-of-natural-disasters-events-globally/ (accessed on 15 September 2023).
3. Statista Research Department. Countries with the Most Natural Disasters in 2021. 2022. Available online: https://www.statista.com/statistics/269652/countries-with-the-most-natural-disasters/ (accessed on 12 September 2023).
4. UNOCHA. Most Common Natural Disasters in Latin America and the Caribbean from 2000 to 2019. 2023. Available online: https://0-www-statista-com.biblioteca-ils.tec.mx/statistics/1140110/number-natural-disasters-type-latin-america/ (accessed on 10 September 2023).
5. Chiappetta, C.J.; Sobreiro, V.A.; de Sousa Jabbour, A.B.L.; Campos, L.M.S.; Mariano, E.B.; Renwick, D.W.S. An analysis of the literature on humanitarian logistics and supply chain management: Paving the way for future studies. *Ann. Oper. Res.* **2019**, *283*, 289–307. [CrossRef]
6. Hezam, I.M.; Nayeem, M.K. A Systematic Literature Review on Mathematical Models of Humanitarian Logistics. *Symmetry* **2020**, *13*, 11. [CrossRef]
7. Nunes, R.M.S.; Pereira, S.C.F. Intellectual structure and trends in the humanitarian operations field. *Ann. Oper. Res.* **2022**, *319*, 1099–1157. [CrossRef]
8. Witkowski, J.; Marcinkowski, J. Initiators and motives for cooperation in humanitarian supply chains. *LogForum* **2022**, *18*, 263–274. [CrossRef]
9. Repík, D.; Foltin, P. Applications of Performance Indicators for Optimization of Humanitarian Chains. *LogForum* **2022**, *18*, 495–504. [CrossRef]
10. Shafiq, M.; Soratana, K. Humanitarian Logistics and Supply Chain Management-A Qualitative Study. *LogForum* **2019**, *15*, 19–38. [CrossRef]
11. Habib, M.S.; Lee, Y.H.; Memon, M.S. Mathematical models in humanitarian supply chain management: A systematic literature review. *Math. Probl. Eng.* **2016**, *2016*, 3212095. [CrossRef]
12. Zhang, L.; Cui, N. Humanitarian logistics and emergency relief management: Hot perspectives and its optimization approach, 5th International Conference on Advances in Energy. *J. Environ. Chem.* **2021**, *245*, 03036. [CrossRef]
13. Santana-Robles, F.; Hernández-Gress, E.S.; Hernández-Gress, N.; Granillo-Macias, R. Metaheuristics in the Humanitarian Supply Chain. *Algorithms* **2021**, *14*, 364. [CrossRef]
14. Baou, E.; Koutras, V.P.; Zeimpekis, V.; Minis, I. Emergency evacuation planning in natural disasters under diverse population and fleet characteristics. *J. Humanit. Logist. Supply Chain Manag.* **2018**, *8*, 447–476. [CrossRef]
15. Seraji, H.; Tavakkoli-Moghaddam, R.; Soltani, R. A two-stage mathematical model for evacuation planning and relief logistics in a response phase. *Int. J. Ind. Syst.* **2019**, *12*, 129–146. Available online: https://www.jise.ir/article_76547.html#ar_info_pnl_cite (accessed on 20 October 2023).
16. Zhu, L.; Gong, Y.; Xu, Y.; Gu, Y. Emergency relief routing models for injured victims considering equity and priority. *Ann. Oper.* **2019**, *283*, 1573–1606. [CrossRef]
17. Nayeri, S.; Tavakkoli-Moghaddam, R.; Sazvar, Z.; Heydari, J. Solving an Emergency Resource Planning Problem with Deprivation Time by a Hybrid MetaHeuristic Algorithm. *J. Qual. Eng. Prod. Optim.* **2020**, *5*, 65–86. [CrossRef]
18. Mansoori, S.; Bozorgi-Amiri, A.; Pishvaee, M.S. A robust multi-objective humanitarian relief chain network design for earthquake response, with evacuation assumption under uncertainties. *Neural Comput. Appl.* **2020**, *32*, 2183–2203. [CrossRef]
19. Infobae. El Agua Sigue Subiendo: 17 Muertos en IMSS de Tula, Hidalgo Por Desbordamiento. 2022. Available online: https://www.infobae.com/america/mexico/2021/09/07/el-agua-sigue-subiendo-al-menos-10-muertos-en-imss-en-tula-hidalgo-por-lluvias-y-desbordamiento-de-rios/ (accessed on 15 March 2023).
20. El Universal. Mueren 17 Hospitalizados Por Inundación en Tula, Hidalgo. Available online: https://www.eluniversal.com.mx/estados/mueren-17-hospitalizados-por-inundacion-en-tula-hidalgo (accessed on 10 April 2023).
21. Infobae. MCCI: Damnificados de la Inundación en Tula Denunciaron Negligencia, Corrupción y Apoyos Insuficientes. 2022. Available online: https://www.infobae.com/america/mexico/2022/05/25/mcci-damnificados-de-la-inundacion-en-tula-denunciaron-negligencia-corrupcion-y-apoyos-insuficientes/ (accessed on 15 April 2023).
22. Instituto Mexicano de Tecnología del Agua. Hacia una Gestión de las Aguas Urbanas Basada en la Naturaleza, Perspectivas IMTA. Available online: https://www.gob.mx/imta/articulos/hacia-una-gestion-de-las-aguas-urbanas-basada-en-la-naturaleza?idiom=es (accessed on 20 May 2023).
23. Escobar, C. Las inundaciones en el Valle del Mezquital: Un síntoma de los límites de la ingeniería convencional. *Perspect. IMTA* **2021**, *36*, 1. [CrossRef]
24. Mollah, A.K.; Sadhukhan, S.; Das, P.; Anis, M.Z. A cost optimization model and solutions for shelter allocation and relief distribution in flood scenario. *IJDRR Int. J. Disaster Risk Reduct.* **2018**, *31*, 1187–1198. [CrossRef]
25. Babaei, A.; Shahanaghi, K. A Novel Algorithm for Identifying and Analyzing Humanitarian Relief Logistics Problems: Studying Uncertainty on the Basis of Interaction with the Decision Maker. *Process. Integr. Optim. Sustain.* **2018**, *2*, 27–45. [CrossRef]
26. Molina, J.; López, A.; Hernández, A.; Martínez, I. A Multi-start Algorithm with Intelligent Neighborhood Selection for solving multi-objective humanitarian vehicle routing problems. *J. Heuristics* **2017**, *24*, 111–133. [CrossRef]

27. Jha, A.; Acharya, D.; Tiwari, M.K. Humanitarian relief supply chain: A multi-objective model and solution. *Sādhanā* **2017**, *42*, 1167–1174. [CrossRef]
28. Doodman, M.; Shokr, I.; Bozorgi-Amiri, A.; Jolai, F. Pre-positioning and dynamic operations planning in pre-and post-disaster phases with lateral transhipment under uncertainty and disruption. *J. Ind. Eng. Int.* **2019**, *15*, 53–68. [CrossRef]
29. Ghasemi, P.; Khalili-Damghani, K.; Hafezalkotob, A.; Raissi, S. Stochastic optimization model for distribution and evacuation planning (A case study of Tehran earthquake). *Socio-Econ. Plan. Sci.* **2019**, *71*, 100745. [CrossRef]
30. Agarwal, S.; Kant, R.; Shankar, R. Humanitarian supply chain management: Modeling the pre and post-disaster relief operations. *Int. J. Disaster Resil. Built Environ.* **2021**, *13*, 421–439. [CrossRef]
31. Shehadeh, K.S.; Tucker, E.L. Stochastic Optimization Models for Location and Inventory Prepositioning of Disaster Relief Supplies. *Optim. Control* **2022**, *144*, 103871. [CrossRef]
32. Seraji, H.; Tavakkoli-Moghaddam, R.; Asian, S.; Kaur, H. An integrative location-allocation model for humanitarian logistics with distributive injustice and dissatisfaction under uncertainty. *Ann. Oper. Res.* **2022**, *319*, 211–257. [CrossRef]
33. Madani, S.H.; Arshadi, K.A.; Tavakkoli-Moghaddam, R. Solving a new bi-objective model for relief logistics in a humanitarian supply chain by bi-objective meta-heuristic algorithms. *Sci. Iran.* **2021**, *28*, 2948–2971. [CrossRef]
34. Yazdani, M.; Haghani, M. Elderly people evacuation planning in response to extreme flood events using optimisation-based decision-making systems: A case study: Knowledge-Based Systems Western Sydney, Australia. *Knowl.-Based Syst.* **2023**, *274*, 110629. [CrossRef]
35. Yazdani, M.; Haghani, M. A Dynamic Emergency Planning System for Relocating Vulnerable People to Safe Shelters in Response to Heat Waves. *Expert Syst. Appl.* **2023**, *228*, 120224. [CrossRef]
36. Bayram, V. Optimization models for large scale network evacuation planning and management: A literature review. *Surv. Oper. Res. Manag. Sci.* **2016**, *21*, 63–84. [CrossRef]
37. Southworth, F. *Regional Evacuation Modeling: A State-of-the-Art Review*; Technical Report; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 1991.
38. Barrett, B.; Ran, B.; Pillai, R. Developing a dynamic traffic management modeling framework for hurricane evacuation. *Transp. Res. Rec. J. Transp. Res. Board* **2000**, *1733*, 115–121. [CrossRef]
39. INEGI. Panorama Sociodemográfico de Hidalgo: Censo de Población y Vivienda 2020. Available online: http://www.inegi.org.mx (accessed on 12 May 2023).
40. Hernández-Gress, E.S.; Santana-Robles, F. Pre and post disaster model for a flood event: Rio Tula, Hidalgo State, Mexico. *Figshare Dataset* **2023**. [CrossRef]
41. Portal de Indicadores de Eficiencia Energética y Emisiones Vehiculares. Available online: https://ecovehiculos.inecc.gob.mx/ (accessed on 15 September 2023).
42. Eksioglu, B.; Vural, A.V.; Reisman, A. The vehicle routing problem: A taxonomic review. *CAIE Comput. Ind. Eng.* **2009**, *57*, 1472–1483. [CrossRef]
43. Webfleet. ¿Cuánto Combustible Consume un Camión por Kilómetro? Retrieved in 2023. Available online: https://www.webfleet.com/es_es/webfleet/blog/conoces-el-consumo-de-diesel-de-un-camion-por-km/#:~:text=Como%20es%20l%C3%B3gico,%20depende%20de,40%20litros%20cada%20100%20km (accessed on 10 May 2023).