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Optimizing Evacuation Site Allocation for Mount Pinatubo Eruption in Pampanga, the Philippines, Using Linear Programming

Paula Nicole O. Mojica, Destiny S. Lutero, Gimelle B. Gamilla-Amorosa, and Monica C. Torres*

Institute of Mathematical Sciences, University of the Philippines Los Baños, College, Laguna 4031 the Philippines

Natural disasters have been more frequent and severe, making mitigation policies such as evacuation protocols extremely important in reducing the negative impact of such disasters. Volcanic eruptions, in particular, may cause damage to properties and thousands of deaths. The unique tectonic setting of the Philippines makes it particularly prone to volcanic events. One of the most disastrous volcanic eruptions in the 20th century was caused by Mount Pinatubo in 1991, with the province of Pampanga as one of the most affected. The recent volcanic activities and the changing population and economic dynamics near and around the volcano suggest that communities and local government units in the region should re-evaluate, establish, and reinforce their contingency, emergency, and other disaster preparation plans such as their evacuation protocols since this is the most common approach in avoiding the loss of life and property in the face of a volcanic eruption. An aspect of evacuation planning is the evacuation site assignment of stakeholders. To move individuals from hazardous conditions to safe ones, mathematical models are used, focusing on determining the best utilization of routes and vehicles in complex urban transportation systems. While there are several studies on Mount Pinatubo, the literature is very limited in terms of the mathematical models used in the evacuation site assignment of affected communities. A transportation model is used to assign residents of Pampanga affected, as observed in the Lahar Zonation map, to evacuation sites outside the 40-km danger zone. The goal is to minimize the total distance traveled by the evacuees from their respective municipalities to the evacuation sites. Three cases were considered in the study. The first case allocates evacuees to provincial evacuation centers only. As provincial evacuation centers are not sufficient, covered courts in Pampanga were included as evacuation sites in the second case. Lastly, a prioritization scheme is implemented in the third case. The number of affected populations for each municipality, the list of evacuation centers and covered courts with their capacity, and the distances between each municipality and an evacuation site were gathered. Results of each case are presented, and network flow models are used to present the allocation of evacuees to the sites.

Keywords: evacuation site allocation, network flow models, Pinatubo eruption, transportation model

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*Corresponding author: mctorres4@up.edu.ph

INTRODUCTION

Natural disasters such as volcanic eruptions are unavoidable occurrences that can cause significant economic losses, especially in countries like the Philippines that experience population growth and anthropogenic climate changes (Botzen *et al.* 2019; Seidler *et al.* 2018). Designing mitigation policies such as evacuation protocols is imperative in reducing the negative impact of such disasters (Botzen *et al.* 2019; Buckle 2012; Bakar *et al.* 2023).

The Philippines has a distinct tectonic geography that causes frequent volcanic activities and has one of the largest numbers of active volcanoes on Earth (Paguican *et al.* 2021). One of the largest volcanic eruptions in the 20th century was caused by Mount Pinatubo in 1991 (Tayag and Punongbayan 1994; USGS 2016). More than 250,000 people were evacuated, and the provinces of Zambales and Pampanga produced most of the casualties (Wendel and Kumar 2016). In 2021, Mount Pinatubo showed volcanic activity in the form of phreatic eruptions or steam explosions (PHIVOLCS 2021). Residents in several areas around the volcano were then advised by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) to avoid going near the volcano. Although zonation maps and warning systems have already been in place since 1991 for Mount Pinatubo (Tayag and Punongbayan 1994), the recent volcanic activities and the changing population and economic dynamics near and around the volcano suggest that communities and local government units in the region should re-evaluate, establish, and reinforce their contingency, emergency, and other disaster preparation plans such as their evacuation protocols (PHIVOLCS 2021).

Disaster preparedness is crucial in identifying effective safety measures implemented by local government units to reduce the impact of an impending disaster (Dariagan *et al.* 2021; Newhall and Solidum 2018). Public perception and reception of a volcanic hazard is an important consideration in evacuation planning (Bird *et al.* 2009; Ong *et al.* 2021; Thakur *et al.* 2022). In a 2021 study by Ong *et al.*, it was identified that asset damage and eruption characteristics significantly influenced the perceived severity of volcanic activity in Taal, Batangas, the Philippines. Furthermore, Dariagan *et al.* (2021) found that although Filipinos are highly vulnerable to natural disasters, they were seen as only partially prepared due to the conflicting perspectives of stakeholders, poor execution and information dissemination of disaster management strategies, and the absence of disaster risk management in educational curricula. Since evacuation is the most common approach in avoiding the loss of life and property in the face of a volcanic eruption (Wild *et al.* 2023), evacuation plans, therefore, must be properly trickled down to communities ahead of time, especially in highly vulnerable communities.

One aspect of evacuation planning is the evacuation site assignment of stakeholders. While there are several studies on Mount Pinatubo, to the best of our knowledge, literature is very limited in terms of the mathematical models used in the evacuation site assignment of affected communities. To move individuals from hazardous conditions to safe ones, mathematical models used in evacuation planning concentrate on determining the best utilization of routes and vehicles in complex urban transportation systems. Some mathematical models use multi-step approaches (Rembulan and Nurprihatin 2023; Nurprihatin *et al.* 2021), and vehicle routing problems with time windows (Rembulan *et al.* 2022). Other models may be found in Bretschneider (2013) and Aldahlawi *et al.* (2024).

The area of study of mathematical modeling for evacuation planning is expanding, and there is still more work to be done to create an optimal approach with certain objectives (Murray-Tuite and Wolshon 2013). An example of a mathematical model is the transportation model, which is a special case of a linear programming model (Taha 2022). When it comes to evacuation planning, Oh *et al.* (2017) used linear programming but with the use of other modes of transportation such as helicopters and with different evacuation urgency levels.

In the aftermath of natural disasters, optimal evacuation planning plays a crucial role in saving people's lives. This paper aims to formulate an integer linear program that minimizes the total distance the evacuees must travel from municipalities to evacuation sites and assign municipal residents of Pampanga who are in the lahar zonation map to evacuation sites outside the 40-km radius of Mount Pinatubo. Although greatly affected by the eruption, studies regarding evacuation planning in the municipalities of Pampanga are insufficient. In relation to Oh *et al.* (2017), the proposed model does not consider specific types of transportation modalities under different urgency levels since the aim of this study is to identify a baseline model for evacuation policies in Pampanga that can be later on improved upon identification and collection of other datasets. The model was subjected to constraints such that all residents were ensured to be allocated, and the total number of evacuees was not more than the total capacity of evacuation facilities.

The paper is organized as follows. The methodology section presents the general model utilized in the current study and the data used to apply the model in the province of Pampanga concerning Mt. Pinatubo eruption. The results and discussion part shows the specific model used and the output for different scenarios that were observed. The last part discusses the conclusions and the suggested future directions of the study.

MATERIALS AND METHODS

Transportation Model and Network Flow

A transportation model was proposed to distribute the evacuees to different evacuation sites. This is used to look for the most efficient approach to reach an objective while spending the least amount of resources (Taha 2022). The model is typically illustrated using the network diagram shown in Figure 1.

The goal of the transportation model is to determine the least expensive way to move a good from a number of sources (m) to a number of destinations (n). Let s_i be the number of supply units available at source i $(i = 1, 2, \ldots, m)$, d_j be the number of demand units needed at destination j $(j = 1, 2, \ldots, m)$, and let c_{ij} be the cost of transporting each unit from source i to destination j. The aim is to minimize the total cost of transportation and identify the maximum number of units that can be transported from source i to destination j. If x_{ij} is the number of units shipped from source i to destination j, the objective is to

$$\text{Min } Z = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{1}$$

$$\sum_{j=1}^{n} x_{ij} = s_i \text{ for } i = 1,2,\ldots,m \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} = d_j \text{ for } j = 1,2,\ldots,n \tag{3}$$

$$x_{ij} \geq 0, \text{integer for all } i \text{ and } j \tag{4}$$

This is an optimization problem with integer variables and linear objective function (Equation 1) and constraints (Equations 2–4). Equation 2 guarantees that all supply for each source i is distributed, whereas Equation 3 assures that the demand for each destination j is reached. Equation 4 guarantees that non-negative integer values are assigned to the decision variables. Note that in the above model, a balanced case is assumed, *i.e.* total demand is equal to total supply. In an unbalanced case, a dummy source or destination is added to reestablish balance. In this study, the transportation model was employed to find a solution to the allocation of evacuees from their municipalities to evacuation facilities in Pampanga. In the specific problem, the sources here are the affected municipalities of Pampanga, whereas the destinations are the different evacuation facilities. The cost that is considered is the distance from a municipality to an evacuation site.

To show how individuals or other components in a network are connected, a network diagram employs a set of nodes and lines that link them, as shown in Figure 1. Social network analysis usually results in it. The presentation of the lines, which vary in width, color, and arrowheads, indicate different characteristics and serve as a visual representation of their connections. The placements of the nodes also suggest whether they are near or far from the network by nature of their location (Taha 2022). In this study, network flow diagrams were constructed using Diagrams.net, which illustrates the transportation of evacuees.

Application of the Model

Mount Pinatubo lahar zonation map. The lahar zonation map in Figure 2 is utilized to identify the areas in the province of Pampanga that are susceptible to lahar under different zones. Each zone in Figure 2 is color-coded, describing the susceptibility of different areas to lahar. These colors and the corresponding code descriptions are

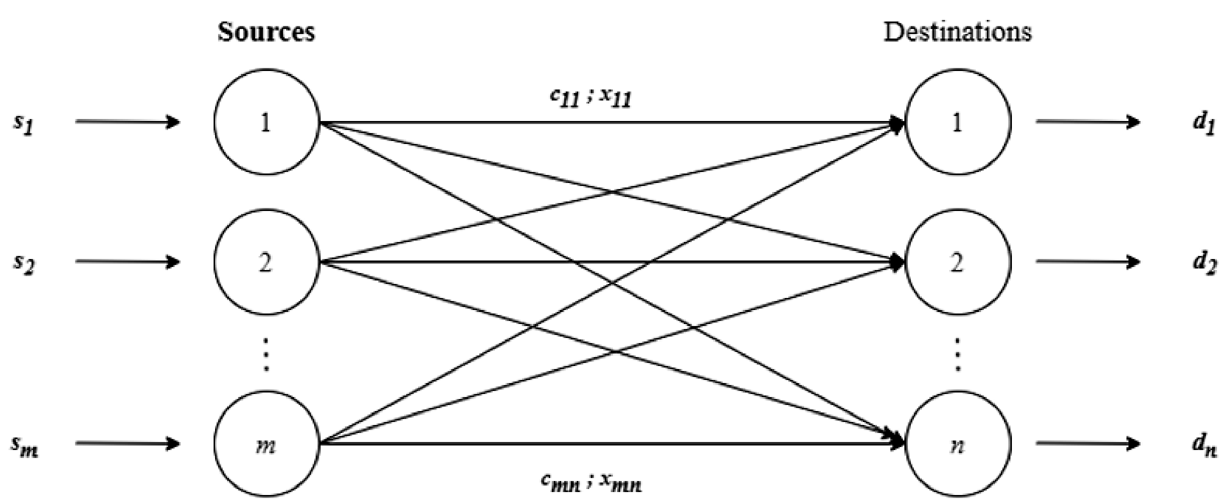


Figure 1. Network diagram used in transportation model.

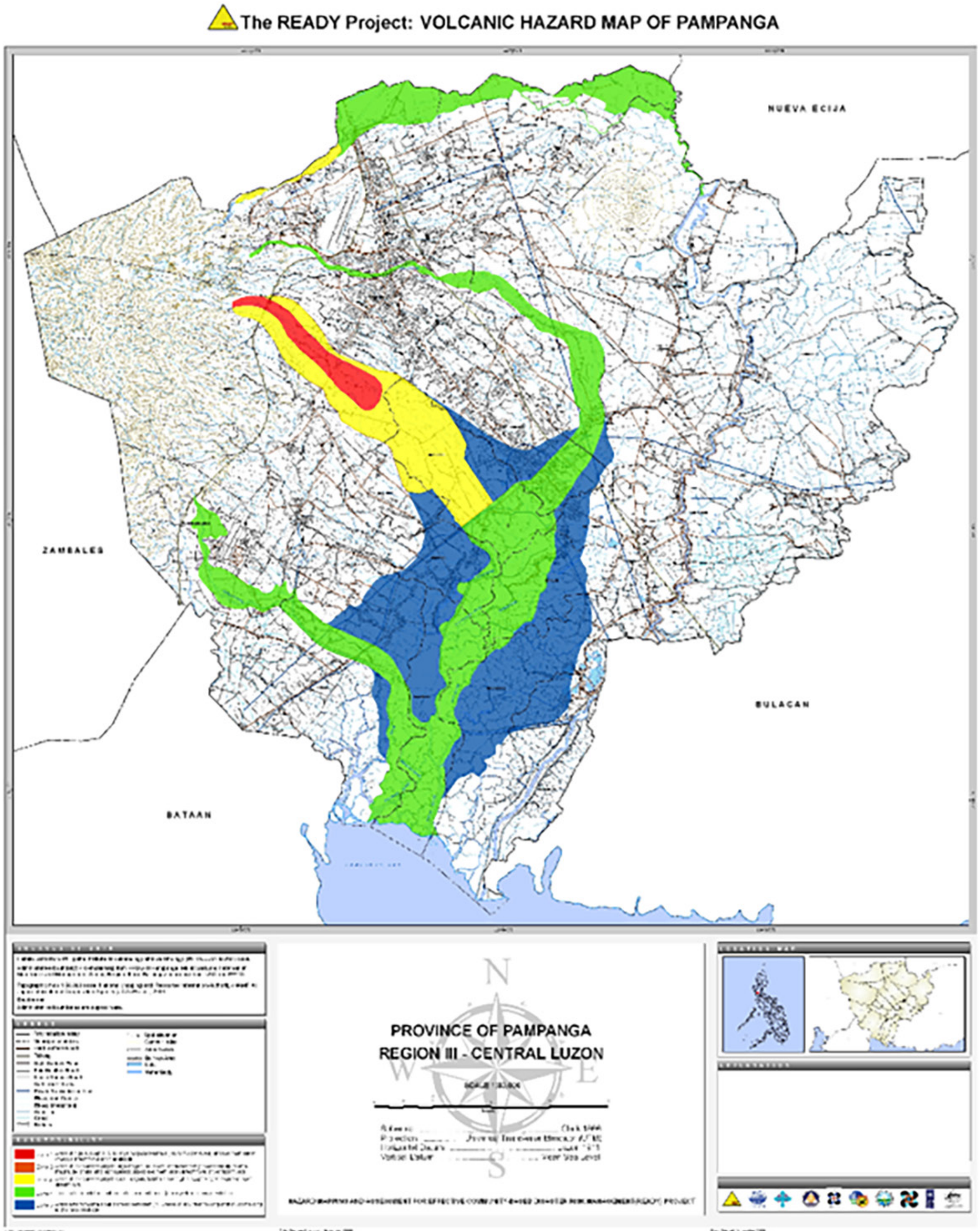


Figure 2. Mount Pinatubo lahar zonation map of Pampanga.

shown in Table 1. The lahar zonation map (Figure 2) and the susceptibility guide (Table 1) were obtained from the volcano hazard maps and summary of prone *barangays* (PHIVOLCS 2009).

Mount Pinatubo radius map. During the 1991 eruption, Mount Pinatubo's danger zone in kilometer radius enlarged – from 10 to 20 km radius, then to 20 to 30 km radius, and definitively to 40 km radius. Some evacuees relocated nine times before settling on a partially permanent location (Bautista 1999). Thus, in the current work, the regions outside the 40-km danger zone were considered secure areas for the destination of evacuees. Figure 3 shows the radius map created using Google Maps.

Data Preparation

Affected population. The municipalities at risk were first determined from the lahar zonation map. Then, the affected population in these municipalities was gathered from GeoAnalytics PH (GeoAnalyticsPH 2018). This set of data is shown in Table 2.

Table 1. Lahar susceptibility guide for Mount Pinatubo.

Zone	Color	Code description
Zone 1	Red	Areas at high susceptibility to large magnitude lahars (> 10 M m^3/event) and sediment-laden (muddy) stream flows and flash floods
Zone 2	Orange	Areas at low susceptibility to large magnitude lahars; moderate to high susceptibility to small-magnitude lahars, and high susceptibility to sediment-laden streamflow or flash floods
Zone 3	Yellow	Areas at low susceptibility to small magnitude lahars and high susceptibility to sediment-laden streamflow
Zone 4	Green	Areas safe from lahars but prone to sediment-laden (muddy) streamflow or siltation
Zone 5	Blue	Areas safe from lahars but prone to persistent (> 1 wk) or recurrent flooding and/or back flooding to drainage blockage

Table 2. Number of evacuees from each affected municipality of Pampanga.

Municipality	Number of evacuees	Municipality	Number of evacuees
Arayat	307	Masantol	22495
Bacolor	27313	Mexico	45037
San Fernando City	123345	Minalin	28536
Floridablanca	16657	Porac	6893
Guagua	75714	Santa Rita	8137
Lubao	61350	Santo Tomas	31068
Mabalacat City	23026	Sasmuan	27969
Macabebe	39382	Angeles	29456
Magalang	9216		

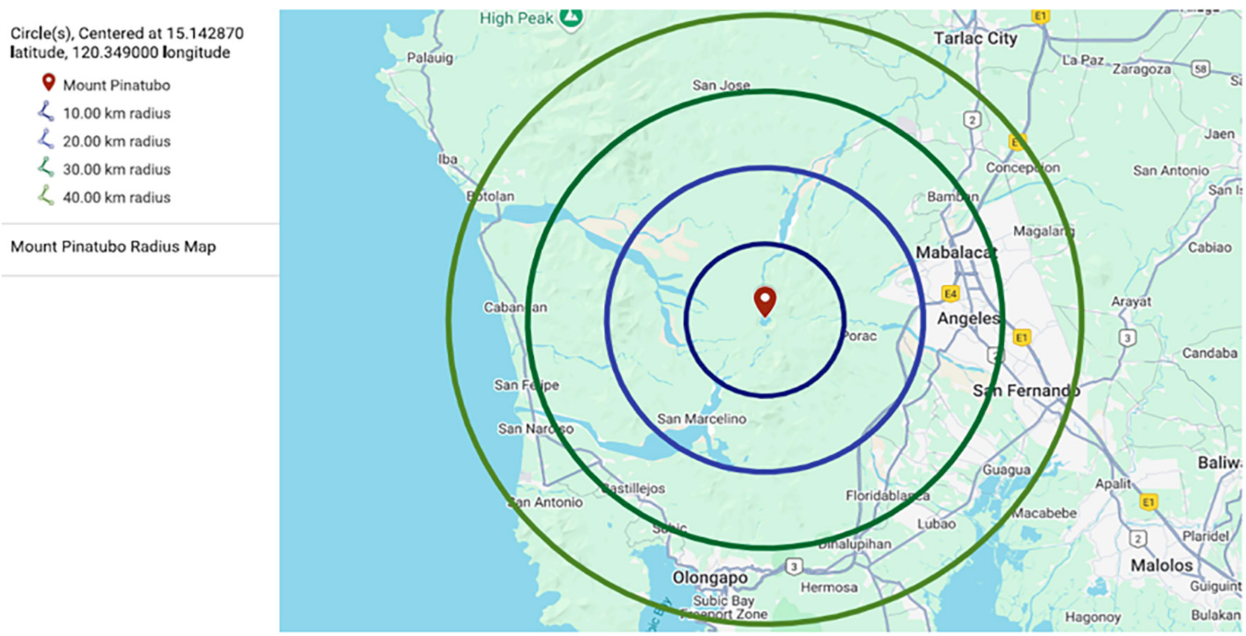


Figure 3. 10-, 20-, 30-, and 40-km radius map of Mount Pinatubo.

Evacuation sites. The list of provincial evacuation centers in Pampanga is listed in Table 3. This data was obtained from the Pampanga Provincial Disaster Risk and Reduction Management Council (PDRRMC 2021).

The hazard map (Figure 2) and the radius map (Figure 3) were used in strategically planning PDRRMC operations in the instance of a volcanic eruption (PDRRMC 2021). Note that since the evacuation sites inside the 40-km radius and those that are in Zones 1–5 are not considered safe areas, they were excluded from the list. The list was reduced to San Roque Provincial Evacuation Center only for Case 1. However, in this research, three different cases were considered. San Roque Provincial Evacuation Center was the only evacuation site considered in the first case considering the criteria set for safe areas.

Since the capacity of the designated evacuation site is not sufficient, Case 2 was formulated, wherein covered courts in Pampanga were also considered evacuation sites. This set of data was gathered from Google Maps. Covered courts located outside the 40-km danger zone and that are not in Zones 1–5 were considered safe areas for evacuees. Google Earth was used to identify the covered courts that satisfied the criteria. This list of covered courts and their respective locations are presented in Table 4. According

Table 3. List of provincial evacuation centers in Pampanga.

Provincial evacuation centers of Pampanga facility	Location	Area	Capacity (pax)
San Isidro Provincial Evacuation Center	San Isidro Resettlement Site, Magalang	5 ha	1,015
San Roque Provincial Evacuation Center (*funded by DPWH)	San Roque, Mexico	10.7 ha	500
Santa Catalina Provincial Evacuation Center (*funded by DPWH)	Santa Catalina, Lubao	42 ha	500
Porac Technocenter (*under usufruct with DOST)	Porac	1.3 ha	800
Floridablanca Technocenter *(under usufruct with DOST)	Floridablanca Resettlement Site, Floridablanca	1.3 ha	800
Vacant lot	Telepayong, Arayat	10 ha	N/A

Table 4. List of evacuation sites for Case 2 and their location.

Evacuation sites	Location	Evacuation sites	Location
San Roque Provincial Evacuation Center	San Roque	San Luis Gymnasium	San Luis
Conception San Simon Covered Court	San Simon	Musni Basketball Court	San Luis
San Simon Covered Court 1	San Simon	Covered Court Sta. Maria	Mexico
San Simon Covered Court 2	San Simon	San Lorenzo Covered Court	Mexico
Dela Paz Covered Court	San Simon	Mangga Covered Basketball Court	Candaba
Paligui Covered Court 1	Apalit	Magumbali Covered Court	Candaba
Dolores Piring Covered Court	Mexico	Bahay Pare Covered Basketball Court	Candaba
Apalit Covered Court	Apalit	Salapungan Hall Covered Court	Candaba
Sampaloc Basketball Covered Court	Apalit	Paroba Covered Court	Candaba
Northville Covered Court	Angeles	Pulong Palazan Covered Basketball Court	Candaba
Calantipe Covered Court	Apalit	Talang Covered Court	Candaba
Sulipan Bario Proper Basketball Court	Apalit	Pansinao Basketball Court	Candaba
Paligui Covered Court 2	Candaba	Covered Court–Santa Ana	Santa Ana
Covered Court–San Luis	San Luis	San Pedro Covered Court–Santa Ana	Santa Ana
DG Covered Court	Mexico	*Brgy.* Santiago Covered Court	Santa Ana
DC Covered Court	Mexico	Old Covered Court–Santa Ana	Santa Ana
Bebe Anac Covered Court	Masantol	Santiago New Covered Court	Santa Ana
San Agustin Covered Court	Masantol	San Isidro Covered Court–Santa Ana	Santa Ana
Dalayap Covered Court	Candaba	Santa Lucia Basketball Court	Santa Ana
Court of Champaca, Caduang Macabebe	Macabebe	Covered Court–Arayat	Arayat
San Pablo Libutad Covered Court	San Simon	San Luis Gymnasium	San Luis
Santo Domingo Multi-purpose Covered Court	Santa Ana	Musni Basketball Court	San Luis
San Juan, San Luis Covered Court	San Luis	Covered Court Sta. Maria	Mexico
San Isidro Covered Basketball Court–San Luis	San Luis	San Lorenzo Covered Court	Mexico
San Jose Covered Court	San Luis	Mangga Covered Basketball Court	Candaba
San Pedro Covered Court–San Simon	San Simon		

to the alternative temporary shelter system, the standard capacity of covered courts for evacuation is 336 (CARE Philippines n/d). This was considered in this study.

Distances from municipalities to evacuation sites. Distances (measured in kilometers) between the municipalities and evacuation centers were gathered using Google Maps. All possible routes were considered, and the shortest one was set as the distance variable. A part of the distance matrix from the municipality M_i for $i = 1, 2, \ldots, n_m$ to evacuation sites E_j for $j = 1, 2, \ldots, n_e$ is presented in Table 5.

Table 5. A part of the distance (in kilometer) matrix from a municipality to an evacuation

Municipality	San Roque Provincial Evacuation Center (E_1)	Conception San Simon Covered Court (E_2)	San Simon Covered Court 1 (E_3)	San Simon Covered Court 2 (E_4)	dela Paz Covered Court 2 (E_5)
Arayat (M_1)	11	28.2	21.1	23.8	17.4
Bacolor (M_2)	17	26	18.2	19.1	12.8
San Fernando City (M_3)	11	20.9	13.1	14	7.7
Floridablanca (M_4)	32	41.8	34	34.9	29
Guagua (M_5)	22	30.7	24	23.8	17
Lubao (M_6)	26	36	28.2	29.1	23
Mabalacat City (M_7)	36	48.5	40.7	41.7	42
Macabebe (M_8)	23	21.6	14.2	15.1	18
Magalang (M_9)	23	39.7	31.3	32.5	29
Masantol (M_{10})	25	22.5	16.4	17.3	20
Mexico (M_{11})	5.3	22.2	13.8	15	11
Minalin (M_{12})	18	23.2	15.4	16.3	10
Porac (M_{13})	36	45.3	37.5	38.4	32
Santa Rita (M_{14})	22	31.5	23.7	24.6	18
Santo Tomas (M_{15})	15	17	9.1	10.1	3.7
Sasmuan (M_{16})	18	34.5	30.5	27.6	21
Angeles (M_{17})	26.2	38.1	30.3	31.3	27

RESULTS AND DISCUSSION

Model Assumptions

The following are the assumptions developed for the study:

1. Municipalities identified as lahar-prone were included in the study. Population prone to lahar per municipality was gathered from GeoAnalytics PH and was used as the number of evacuees.
2. Evacuation sites were chosen such that they are outside the 40-km danger zone and do not belong to the lahar zonation.
3. Both the distance on main highways and alternative routes were considered. The shortest route in kilometers was used as the distance between the municipality and the evacuation site.
4. The study only considered distances to allocate evacuees. Deliberations of routes that are possibly hazardous (*i.e.* those along rivers) were not part of the study.
5. Capacities were limited to space for evacuees. Areas designated for equipment, food storage, and command and control centers were excluded from the study.
6. Evacuees are ready and willing for evacuation. Preparation matters for evacuation were not covered in this study.

Definition of Parameters

Let n_m be the total number of affected municipalities and n_e be the total number of evacuation sites. The study focused on a transportation problem where municipalities M_i for $i = 1, 2, \ldots, n_m$ served as the sources, and evacuation sites E_j for $j = 1, 2, \ldots, n_e$) acted as the destinations. The parameters are summarized in Table 6:

Model Development

The primary goal is to minimize the total distance travelled by the evacuees from the municipality M_i to evacuation site E_j. The integer linear programming model is constructed as:

Table 6. The parameters used in the mathematical model.

Parameter	Parameter description
$d_{M_iE_j}$	Distance between municipality M_i and evacuation site E_j in kilometer
r_{M_i}	Total number of evacuees from municipality M_i
c_{E_j}	Capacity of evacuation site E_j

Decision variables: let $x_{M_iE_j}$ be the number of evacuees to be transported from the municipality M_i for $i = 1, 2, ..., n_m$ to evacuation site E_j for $j = 1, 2, ..., n_e$.

Objective

$$\text{Min } Z = \sum_{i=1}^{n_m} \sum_{j=1}^{n_e} d_{M_i E_j} x_{M_i E_j} \quad (5)$$

Subject to:

$$\sum_{j=1}^{n_e} x_{M_i E_j} = r_{M_i} \text{ (for all } M_i) \quad (6)$$

$$\sum_{i=1}^{n_m} x_{M_i E_j} \leq c_{E_j} \text{ (for all } E_j) \quad (7)$$

$$x_{M_i E_j} \geq 0, \text{integer (for all } M_i \text{ and } E_j) \quad (8$$

The objective function in Equation 5 minimizes the total distance taken by evacuees from the municipality M_i to the evacuation site E_j. Equation 6 assures that every resident from each municipality is assigned to an evacuation site. Equation 7 ensures that the capacity of the evacuation facility E_j is not exceeded. Equation 8 guarantees that non-negative integer values are assigned to the decision variables. The problem was also checked to see if it was a balanced case. That is, the total supply or number of residents to be evacuated must be equal to the total demand or the capacity of the facilities. Otherwise, dummy evacuation centers or evacuees were utilized to make the problem balance.

Case 1

For Case 1, the provincial evacuation centers of Pampanga were considered. Evacuation sites located within the 40-km radius or in Zones 1–5 are not considered safe. Thus, they were excluded from the list. Moreover, since the total capacity of the evacuation center was not sufficient, a dummy evacuation center was included to make the problem balance. The model was programmed and solved in GUSEK, a standalone executable that merges the SCIntilla-based text editor and the linear programming solver GLPK. Table 7 indicates the municipality and quantity of residents to be evacuated to the evacuation center for Case 1.

For Case 1, the total capacity of the evacuation facility is 500. Table 7 shows that 500 residents or 1.110% of the affected population of Mexico were allocated to the San Roque Provincial Evacuation Center. The San Roque Provincial Evacuation Center is also located in Mexico. Since the model's objective function goals to minimize the total distance traveled by the evacuees, the model assigned the residents in the same municipality. Note that some of the areas of the municipality of Mexico are within the 40-km radius and are near the mentioned evacuation center. Since this is the only evacuation center for Case 1, capacity was insufficient to accommodate residents from other municipalities. Note also that only 98.90% of affected residents of Mexico were not assigned to evacuation sites along with the entire affected population of the other municipalities. This case shows that the capacity of the qualified evacuation center is insufficient since it cannot hold most of the affected municipalities. Hence, another case was considered in which covered courts in Pampanga were added as evacuation sites.

Case 2

For Case 2, the list of covered courts in Pampanga that are outside the 40-km danger zone and are not in the lahar zonation map was gathered using Google Maps. Moreover, it was assumed in this study that the capacity of all covered courts is constant. The standard capacity of a covered court in holding evacuees, which is 336, is lifted from the alternative temporary shelter system of 2018 (CARE Philippines n/d). Table 8 shows the number of evacuees allocated from each municipality to evacuation sites.

Results show that 100% of the total affected population or 307 residents from Arayat must be allocated to Covered Court–Arayat. There are 1680 residents or 4.265% of the affected population of Macabebe to be allocated to Apalit Covered Court, Northville Covered Court, Sulipan Bario Proper Basketball Court, Court of Champaca Caduang Macabebe, and San Pablo Libutad Covered Court – filling up the capacity of each site with 336 evacuees. The detailed distribution of evacuees is presented in Table 8.

Table 7. Summary of municipality and residents of Pampanga to be allocated for Case

Municipality	Assigned provincial evacuation centers	Location	No. of evacuees	Total evacuees per municipality	Percentage evacuated
Mexico (M_{11})	San Roque Provincial Evacuation Center (E_1)	Mexico	500	45037	1.110%

Table 8. Summary of the number of residents from each municipality of Pampanga to be allocated and their respective allocation site for Case 2.

Municipalities	Assigned evacuation site	Location	No. of evacuees	Total evacuees per municipality	Percentage evacuated
Arayat (M_1)	Covered Court–Arayat (E_{46})	Arayat	307	307	100%
Macabebe (M_8)	Apalit Covered Court (E_8)	Apalit	336	39382	0.853%
	Northville Covered Court (E_{10})	Macabebe	336		0.853%
	Sulipan Bario Proper Basketball Court (E_{12})	Apalit	336		0.853%
	Court of Champaca, Caduang Macabebe (E_{20})	Macabebe	336		0.853%
	San Pablo Libutad Covered Court (E_{21})	San Simon	336		0.853%
Masantol (M_{10})	Bebe Anac Covered Court (E_{17})	Masantol	336	22495	1.494%
	San Agustin Covered Court (E_{18})	Masantol	336		1.494%
Mexico (M_{11})	San Roque Provincial Evacuation Center (E_1)	Mexico	500	45037	1.110%
	Paligui Covered Court 2 (E_{13})	Apalit	336		0.746%
	Covered Court, San Luis (E_{14})	San Luis	336		0.746%
	DG Covered Court (E_{15})	Mexico	336		0.746%
	Dalayap Covered Court (E_{19})	Candaba	336		0.746%
	Santo Domingo Multi-purpose Covered Court (E_{22})	San Simon	336		0.746%
	San Juan, San Luis Covered Court (E_{23})	San Luis	336		0.746%
	San Isidro Covered Basketball Court–San Luis (E_{24})	San Luis	336		0.746%
	San Luis Gymnasium (E_{27})	San Luis	336		0.746%
	Musni Basketball Court (E_{28})	San Luis	336		0.746%
	Covered Court Sta. Maria (E_{29})	Mexico	336		0.746%
	San Lorenzo Covered Court (E_{30})	Mexico	336		0.746%
	Mangga Covered Basketball Court (E_{31})	Candaba	336		0.746%
	Magumbali Covered Court E_{32}	Candaba	336		0.746%
	Bahay Pare Covered Basketball Court (E_{33})	Candaba	336		0.746%
	Salapungan Hall Covered Court (E_{34})	Candaba	336		0.746%
	Paroba Covered Court (E_{35})	Candaba	336		0.746%
	Pulong Palazan Covered Basketball Court (E_{36})	Candaba	336		0.746%
	Talang Covered Court E_{37})	Candaba	336		0.746%
	Pansinao Basketball Court (E_{38})	Candaba	336		0.746%
	Covered Court–Santa Ana (E_{39})	Candaba	336		0.746%
	San Pedro Covered Court–Santa Ana (E_{40})	Santa Ana	336		0.746%
	Brgy. Santiago Covered Court (E_{41})	Santa Ana	336		0.746%
	Old Covered Court–Santa Ana (E_{42})	Santa Ana	336		0.746%
	Santiago New Covered Court (E_{43})	Santa Ana	336		0.746%
	San Isidro Covered Court–Santa Ana (E_{44})	Santa Ana	336		0.746%
	Santa Lucia Basketball Court (E_{45})	Santa Ana	336		0.746%
	Covered Court–Arayat (E_{46})	Arayat	29		0.064%

Table 8. Cont.

Municipalities	Assigned evacuation site	Location	No. of evacuees	Total evacuees per municipality	Percentage evacuated
Santo Tomas (M_{15})	Conception San Simon Covered Court (E_2)	San Simon	336	31068	1.081%
	San Simon Covered Court 1 (E_3)	San Simon	336		1.081%
	San Simon Covered Court 2 (E_4)	San Simon	336		1.081%
	dela Paz Covered Court (E_5)	San Simon	336		1.081%
	Paligui Covered Court 1 (E_6)	Apalit	336		1.081%
	Dolores Piring Covered Court (E_7)	Mexico	336		1.081%
	Sampaloc Basketball Covered Court (E_9)	Apalit	336		1.081%
	Calantipe Covered Court (E_{11})	Apalit	336		1.081%
	San Jose Covered Court (E_{25})	San Luis	336		1.081%
	San Pedro Covered Court–San Simon (E_{26})	San Simon	336		1.081%
Angeles (M_{17})	DC Covered Court (E_{16})	Mexico	336	29456	1.141%

Furthermore, Mexico has the most numbered residents to be allocated with a total of 9265 residents or 20.572% of the total affected population.

Sensitivity analysis for Case 2 was generated from GUSEK. The optimality range for the variable representing Mexico to San Roque Provincial Evacuation Center is in Figure 4. As long as the distance is within 11 km, the results stay optimal. Therefore, alternate routes that cover 11 km in length will give the same solution. All other variables follow the same explanation.

It is observed that although covered courts were added as additional evacuation sites, the capacity is still insufficient compared to the total number of individuals who must be evacuated. A dummy evacuation center was then again used to serve as a destination for those who were not assigned to evacuation centers and covered courts to balance the problem.

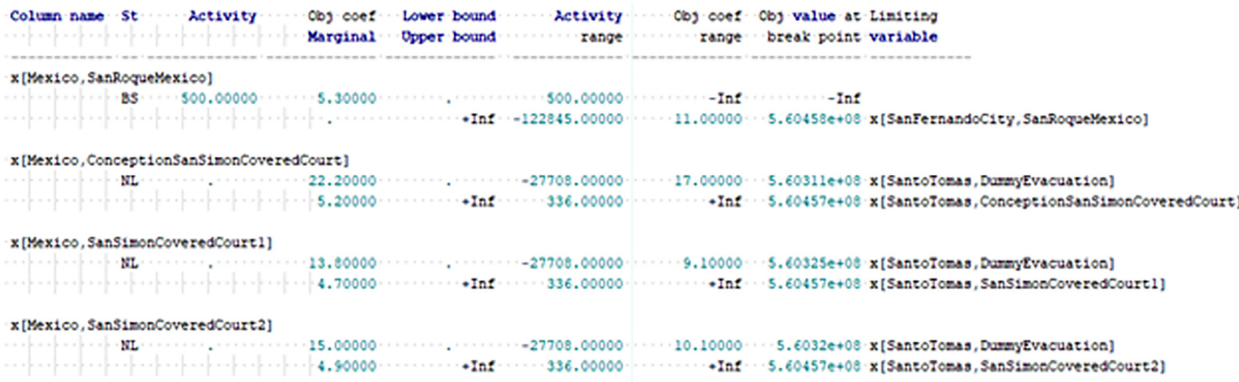
The number of evacuees that were not assigned to any evacuation site is presented in Table 9. This shows that 100% of the total affected population of Bacolor, San Fernando City, Floridablanca, Guagua, Lubao, Mabalacat City, Magalang, Minalin, Porac, Santa Rita, and Sasmuan were incapable of being allocated to actual evacuation sites. Mexico has the lowest percentage of residents that were not allocated, which is 79.428%. At the same time, 89.185, 95.734, and 97.013% of the total affected population of Santo Tomas, Macabebe, and Masantol were undesignated, respectively. Figure 5 illustrates the network flow diagram of the results, wherein the green arrows indicate that residents in each municipality should be designated to the respective evacuation site. The black arrows indicate the number of people that were not allocated. Thus, these arrows are connected to the dummy evacuation site. Denoted along the green arrows are the number of evacuees to be transported from each source to their respective destinations (x_{ij}). Meanwhile, the numbers beside the black arrows show the number of individuals not evacuated.

Since the objective function aims to minimize the distance between affected municipalities to evacuation sites outside the 40 km radius, the model first allocated residents near the 40 km radius. This left the municipalities closer to the crater of Mount Pinatubo such as Porac and Mabalacat to be unassigned to any evacuation site. Hence, another Case was considered.

Case 3

Zone 1. In this case, residents in the municipalities with high susceptibility to lahar will be assigned first. Residents from Zone 1 of the lahar zonation map will be allocated first, followed by Zone 2, and so forth up to Zone 5 or until evacuation sites are fully occupied. According to GeoAnalytics PH, two municipalities belong to Zone 1 or the areas that are highly susceptible to large magnitude lahar (> 10 Mm^3 per event) and sediment-laden stream flows and flash floods (GeoAnalyticsPH 2018). These municipalities are Bacolor and Porac with 397 and 2912 affected populations, respectively. With the same objective of minimizing the total distance traveled by the residents going to the designated evacuation sites, we obtained the following results shown in Table 10.

Results in Table 10 show that 61 and 336 evacuees from Bacolor are to be transported to dela Paz Covered Court and Paligui Covered Court, respectively. From Porac, 336 evacuees each will be transferred to DG Covered Court, DC Covered Court, San Pablo Libutad Covered Court, Santo Domingo Multi-purpose Covered Court, Covered



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Column name  St    Activity     Obj coef   Lower bound      Activity      Obj coef  Obj value at Limiting
                                Marginal   Upper bound         range         range   break point variable
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x[Mexico,SanRoqueMexico]
             BS    500.00000      5.30000            .     500.00000         -Inf         -Inf
                                        .         +Inf -122845.00000     11.00000 5.60458e+08 x[SanFernandoCity,SanRoqueMexico]

x[Mexico,ConceptionSanSimonCoveredCourt]
             NL            .     22.20000            .   -27708.00000    17.00000 5.60311e+08 x[SantoTomas,DummyEvacuation]
                                  5.20000         +Inf     336.00000         +Inf 5.60457e+08 x[SantoTomas,ConceptionSanSimonCoveredCourt]

x[Mexico,SanSimonCoveredCourt1]
             NL            .     13.80000            .   -27708.00000     9.10000 5.60325e+08 x[SantoTomas,DummyEvacuation]
                                  4.70000         +Inf     336.00000         +Inf 5.60457e+08 x[SantoTomas,SanSimonCoveredCourt1]

x[Mexico,SanSimonCoveredCourt2]
             NL            .     15.00000            .   -27708.00000    10.10000  5.6032e+08 x[SantoTomas,DummyEvacuation]
                                  4.90000         +Inf     336.00000         +Inf 5.60457e+08 x[SantoTomas,SanSimonCoveredCourt2]
```

Figure 4. Sensitivity analysis on decision variables of Case 2.

Table 9. Summary of municipalities and residents of Pampanga that cannot be allocated for Case 2.

Municipalities	Number of evacuees not evacuated	Total per municipality	Percentage of total population
Bacolor (M_2)	27313	27313	100%
San Fernando City (M_3)	123345	123345	100%
Floridablanca (M_4)	16657	16657	100%
Guagua (M_5)	75714	75714	100%
Lubao (M_6)	61350	61350	100%
Mabalacat City (M_7)	23026	23026	100%
Macabebe (M_8)	37702	39382	95.734%
Magalang (M_9)	9216	9216	100%
Masantol (M_{10})	21823	22495	97.013%
Mexico (M_{11})	35772	45037	79.428%
Minalin (M_{12})	28536	28536	100%
Porac (M_{13})	6893	6893	100%
Santa Rita (M_{14})	8137	8137	100%
Santo Tomas (M_{15})	27708	31068	89.185%
Sasmuan (M_{16})	27969	27969	100%
Angeles (M_{17})	29120	29456	98.859%

Table 10. Summary of the number of residents from areas in Zone 1 to be allocated and their respective allocation sites.

Municipalities	Assigned evacuation site	Location	No. of evacuees	Total evacuees per municipality	Percentage evacuated
Bacolor (M_2)	dela Paz Covered Court (E_5)	San Simon	61	397	15.365%
	Paligui Covered Court (E_6)	Apalit	336		84.635%
Porac (M_{13})	dela Paz Covered Court (E_5)	San Simon	275	2912	9.444%
	DG Covered Court (E_{15})	Mexico	336		11.538%
	DC Covered Court (E_{16})	Mexico	336		11.538%
	San Pablo Libutad Covered Court (E_{21})	San Simon	336		11.538%
	Santo Domingo Multi-purpose Covered Court (E_{22})	San Simon	336		11.538%
	Covered Court Sta. Maria (E_{29})	Mexico	336		11.538%
	San Lorenzo Covered Court (E_{30})	Mexico	336		11.538%
	Covered Court Santa Ana (E_{39})	Santa Ana	285		9.787%
	San Pedro Covered Court–Santa Ana (E_{40})	Santa Ana	336		11.538%

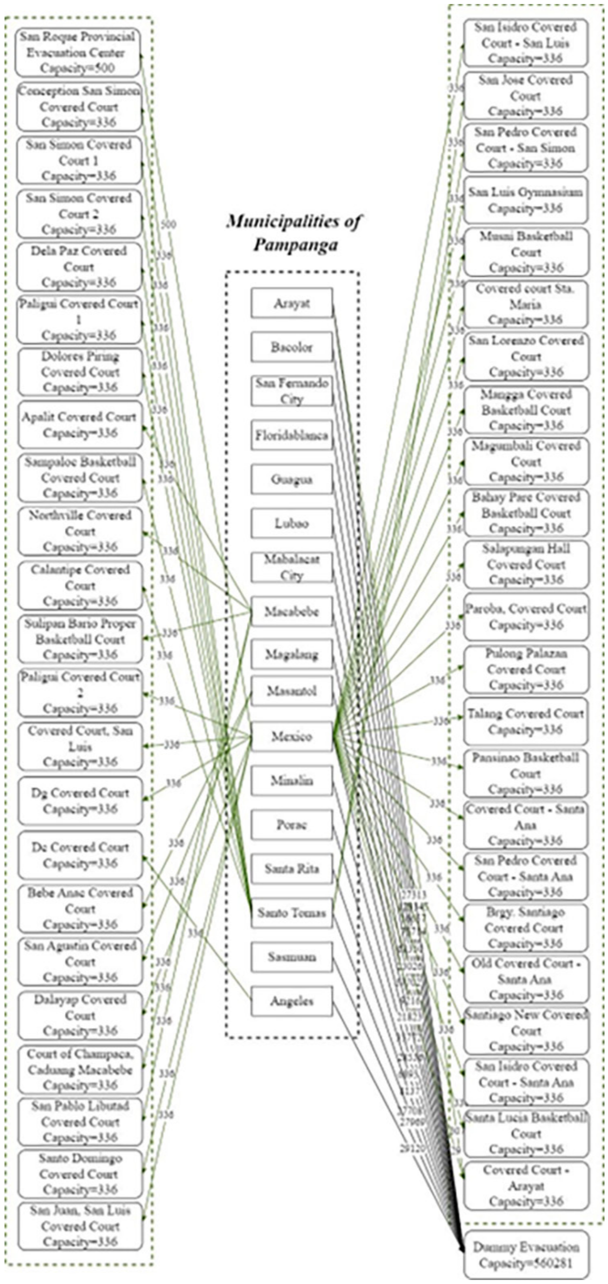

Figure 5. Network flow diagram of generated results for Case 2.

Court Sta. Marua, San Lorenzo Covered Court, and San Pedro Covered Court–Santa Ana. The remaining 275 in the capacity of dela Paz Covered Court will also be used by residents of Porac and 285 residents were allocated to Covered Court Santa Ana, with 51 left that can be occupied by residents from other zones. Figure 6 depicts the network flow chart representing the outcomes in this case for Zone 1. The green arrows signify the allocation of residents from each municipality to their designated evacuation sites. Alongside these arrows, the figures denote the number of evacuees to be moved from each source to their respective destinations.

Zones 2 and 3. After allocating areas in Zone 1, there were 37 evacuation sites left to be occupied with a total capacity of 12,311. However, within Pampanga, there were no areas included in Zone 2. Areas in Zone 3 are described as at low susceptibility to small-magnitude lahars and high susceptibility to sediment-laden streamflow. In

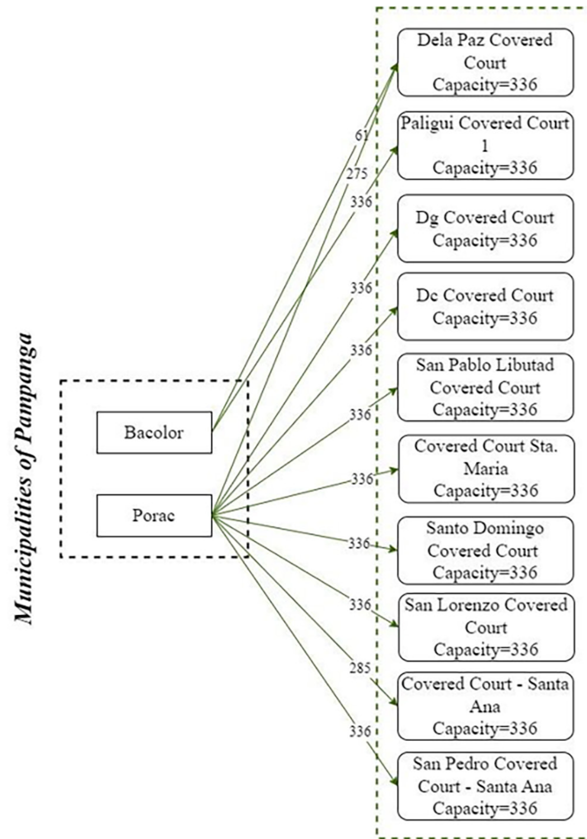

Figure 6. Network flow diagram of generated results for Case 2.

Pampanga, five municipalities belong to this zone: Bacolor, San Fernando City, Mabalacat City, Porac, and Santa Rita. Removing the occupied spaces after allocating the municipalities in Zone 1, the model was again solved in GUSEK. Table 11 shows the summary of the resulting allocation.

It is shown in Table 11 that Conception San Simon Covered Court, San Simon Covered Court 1, San Simon Covered Court 2, Dolores Piring Covered Court, Apalit Covered Court, Sampaloc Basketball Covered Court, Calantipe Covered Court, Sulipan Bario Proper Basketball Court, Bebe Anac Covered Court, San Agustin Covered Court, Dalayap Covered Court, San Jose Covered Court, and San Jose Covered Court serve as evacuation sites with 336 evacuees each (7.298% of total affected population) from Bacolor municipality. Please refer to Table 12 for other allocation results. Although 12,311 of the population

Table 11. Summary of the number of residents from areas in Zone 3 to be allocated and their respective allocation sites.

Municipalities	Municipalities	Assigned evacuation site	Location	No. of evacuees	Total evacuees per municipality
Bacolor (M_2)	Conception San Simon Covered Court (E_2)	San Simon	336	4604	7.298%
	San Simon Covered Court 1 (E_3)	San Simon	336		7.298%
	San Simon Covered Court 2 (E_4)	San Simon	336		7.298%
	Dolores Piring Covered Court (E_7)	Mexico	336		7.298%
	Apalit Covered Court (E_8)	Apalit	336		7.298%
	Sampaloc Basketball Covered Court (E_9)	Apalit	336		7.298%
	Northville Covered Court (E_{10})	Macabebe	246		5.343%
	Calantipe Covered Court (E_{11})	Apalit	336		7.298%
	Sulipan Bario Proper Basketball Court (E_{12})	Apalit	336		7.298%
	Bebe Anac Covered Court (E_{17})	Masantol	336		7.298%
	San Agustin Covered Court (E_{18})	Masantol	336		7.298%
	Dalayap Covered Court (E_{19})	Candaba	336		7.298%
	Court of Champaca, Caduang Macabebe (E_{20})	Macabebe	326		7.081%
	San Jose Covered Court (E_{25})	San Luis	336		7.298%
San Fernando City (M_3)	San Roque Provincial Evacuation Center (E_1)	Mexico	40	232	17.241%
	Covered Court San Luis (E_{14})	San Luis	192		82.759%
Mabalacat (M_7)	San Roque Provincial Evacuation Center (E_1)	Mexico	460	4493	10.238%
	Paligui Covered Court 2 (E_{13})	Apalit	336		7.478%
	Magumbali Covered Court (E_{32})	Candaba	336		7.478%
	Bahay Pare Covered Basketball Court (E_{33})	Candaba	336		7.478%
	Salapungan Hall Covered Court (E_{34})	Candaba	336		7.478%
	Paroba Covered Court (E_{35})	Candaba	336		7.478%
	Pansinao Basketball Court (E_{38})	Candaba	336		7.478%
	Brgy. Santiago Covered Court (E_{41})	Santa Ana	336		7.478%
	San Isidro Covered Court–Santa Ana (E_{44})	Santa Ana	336		7.478%
	Covered Court–Arayat (E_{46})	Arayat	336		7.478%
Porac (M_{13})	Northville Covered Court (E_{10})	Macabebe	90	3981	2.261%
	Covered Court San Luis (E_{14})	San Luis	144		3.617%
	San Juan, San Luis Covered Court (E_{23})	San Luis	336		8.440%
	San Isidro Covered Basketball Court–San Luis (E_{24})	San Luis	336		8.440%
	San Pedro Covered Court–San Simon (E_{26})	San Simon	336		8.440%
	San Luis Gymnasium (E_{27})	San Luis	336		8.440%
	Musni Basketball Court (E_{28})	San Luis	336		8.440%
	Mangga Covered Basketball Court (E_{31})	Candaba	336		8.440%
	Pulong Palazan Covered Basketball Court (E_{36})	Candaba	336		8.440%
	Talang Covered Court (E_{37})	Candaba	336		8.440%
	Covered Court–Santa Ana (E_{39})	Santa Ana	51		1.281%
	Old Covered Court–Santa Ana (E_{42})	Santa Ana	336		8.440%
	Santiago New Covered Court (E_{43})	Santa Ana	336		8.440%
	Santa Lucia Basketball Court (E_{45})	Santa Ana	336		8.440%
Santa Rita (M_{14})	Court of Champaca, Caduang Macabebe (E_{20})	Macabebe	10	10	100%

in Zone 3 were allocated, there are still individuals who were not assigned to an evacuation site.

Table 12 shows that 1009 people from Mabalacat City were not allocated. This means that the capacities of evacuation centers are already full, and further allocation would not be possible. Furthermore, there are still at least 270,000 residents in Zone 4 and at least 300,000 in Zone 5 who are not assigned.

The network flow diagram for Zone 3 is illustrated in Figure 7. The green arrows represent the assignment of residents from every municipality to their specified 38 evacuation locations. In contrast, the black arrows indicate the number of individuals who cannot be allocated and are, therefore, connected to a dummy evacuation site.

Table 12. Summary of municipalities and residents of Pampanga that cannot be allocated for Zone 3.

Municipality	Number of evacuees not evacuated	Total Per municipality	Percentage of total population
Mabalacat (M_7)	1009	4493	22.457%

The figures displayed alongside these arrows indicate the number of evacuees to be transported from each source to their designated destinations. The numbers on the arrows show the number of people who need to be evacuated between the nodes to which they are connected.

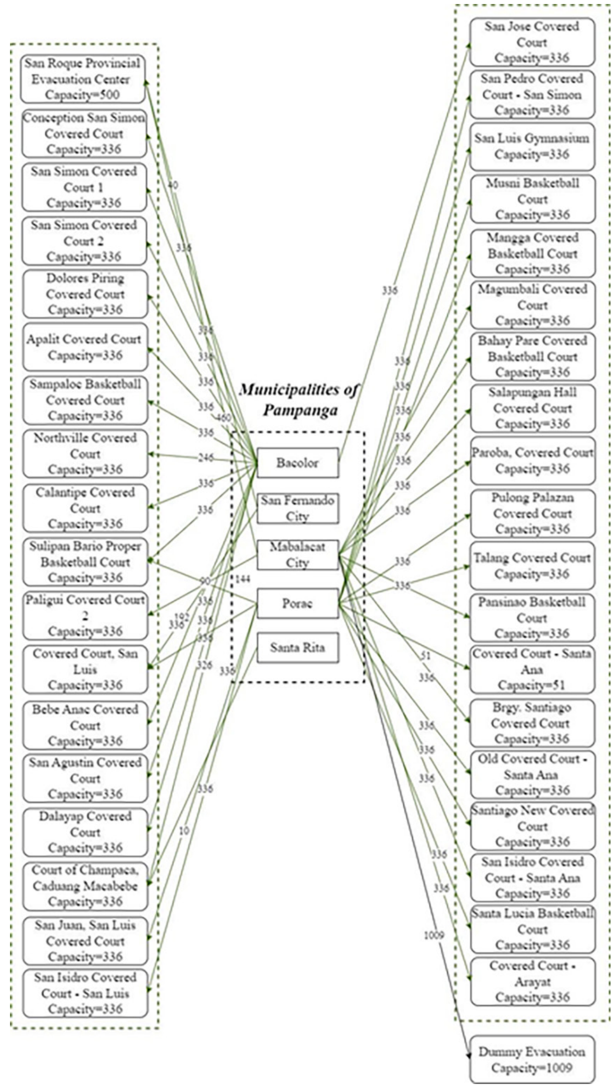

Figure 7. Network flow diagram of generated results for Zone 3.

CONCLUSION AND RECOMMENDATIONS

This study aimed to apply the transportation model to allocate the residents of the affected municipalities of Pampanga to evacuation sites for the Mount Pinatubo eruption. Three cases were formulated in the study. Generated results showed the allocation of residents to specific evacuation sites outside the 40-km Mount Pinatubo radius. In Case 1, provincial evacuation centers were considered and 500 over 575901 total affected population of Pampanga were assigned. Since only 0.0868% were allocated in Case 1, additional evacuation facilities are considered such as the covered courts in Pampanga. In Case 2, 15620 which is 2.712% of the total population of Pampanga was allocated. Moreover, since the objective of the study is to minimize the total distance between municipalities and evacuation sites, it was observed that municipalities near the 40-km radius boundary were first allocated. Hence, to cater to areas that are more prone to lahar, Case 3 was formulated which implemented a prioritization scheme. In this case, iterations were created such that the affected population in Zone 1 was allocated first, followed by those in Zone 2, and so forth until the capacity of all evacuation facilities was full. For Zone 1, 3309 affected populations from Bacolor and Porac were allocated. The remaining capacity, which is 12311, was allocated to residents from Bacolor, San Fernando City, Mabalacat City, Porac, and Santa Rita, whereas the other 1009 residents from Mabalacat City were no longer allocated. Since all evacuation sites are already occupied, the model no longer proceeded in allocating residents from Zones 4 and 5.

The findings of the study suggested the need for furtherance in evacuation plans, especially in regions prone to volcanic eruptions. Although the model obtained the objective of assigning residents to safer areas, the capacity of evacuation sites is insufficient to hold the total affected population. This shows that an increase in the number of evacuation sites could significantly enhance preparedness and minimize the potential risk for the affected citizens. Additional evacuation centers that are in safe areas are necessary to cater to all affected populations. Furthermore, since evacuation plans and research studies heavily rely on available data, it is important that local government units continuously update the required data such as the list of possible evacuation sites.

This research presents a framework for evacuation site allocation for areas susceptible to volcanic eruption using linear programming. It also utilized network flow diagrams to illustrate the allotment. The framework is simple so the local or provincial government officials may consider these results as initial proposals during evacuation planning and implementing transportation strategies for evacuees. Furthermore, other areas with the same concern may apply this framework.

Since this is an initial proposal, we acknowledge that there are still several future research directions that may be explored. The limitation of the study includes factors like traffic and road hazards that might affect the transit of and the routes taken by evacuees. Thus, for future direction, the research also recommends taking these factors into consideration. Future studies may also explore aspects such as the vehicles that are available in each municipality to transport evacuees. Behavioral aspects such as the residents' preparedness and their willingness to be evacuated may also be examined. Aside from distance covered, other factors may be analyzed such as reducing time traveled, energy consumed, or carbon footprint, depending on the priorities of government agencies. Other recommendations include studying the optimal location of possible additional evacuation facilities considering only safe areas. This may further address the problem of lack of resources or shelter for evacuees.

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STATEMENT ON CONFLICT OF INTEREST

The authors have declared no competing interests.

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