



# Multi-Period Evacuation Shelter Selection Considering Dynamic Hazards Assessment

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## ABSTRACT

Natural phenomena may lead to a huge disaster that is affected by triggering phenomenon and the following phenomena that occurred afterward. Nevertheless, following single scenario of disaster to create a disaster emergency plan might lead to an incomparable estimation of risk. The decision maker could reduce the risk and perform an efficient evacuation, By understanding disaster prone area based on hazard assessment. This study proposed a multi-period shelter selection and relocation by considering possible impact due to cascading effect and secondary disaster. The objective was to minimize the cost associated with transport and relocation shelter during the evacuation process. A simple yet powerful Simulated Annealing was proposed to solve the model. This study compared the cost that occurred based on two approaches, hazard assessment map, and radius based map. The result showed that model with hazard map generated a better result in comparison with radius based map. Hazard map could offer different subsets of the shelters identified in the first stage to be selected, thereby producing a minimum number of evacuees.

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## 1. INTRODUCTION

During a disaster, an efficient evacuation can lead to minimizing loss of life (Yan et al., 2018). Evacuation process is an action for immediately moved people away from the threat or actual occurrence of a hazard to safer places, need to be considered carefully before, during, and after the disaster. According to Institute of

Medicine (US) Roundtable on Environmental Health Sciences, Research, and Medicine (2007), one important point of an evacuation plan is to identify where the evacuation facilities / shelters should be located. Truthfully, identifying safe zone is important as hazard mapping is the first step to develop an effective disaster evacuation plan. Hazard map is developed for understanding the nature of hazards occurring across a geographical

area and provide an important tool to get a comprehensive picture of inundation risk areas (Liu et al., 2015). Based on hazard map, the decision maker can understand evacuation strategy easily, and the decision on shelter locations can be arranged. The decision on which shelters to open is decided before the actual disaster occurrence as part of disaster contingency plan. Unfortunately, real life practices show how disasters can be dynamic and unpredictable (Schooler, 2001). Likewise, when hazard move outside the “predicted” zone, the prepared shelters cannot be utilized.

In many cases, the contingency plan is proposed to cover one/certain disaster scenario. Those might not be a good strategic planning as one disaster could have a cascading effect and followed by bigger disaster, or even trigger some aftershock that needs to be aware. Tsunami Aceh 2004 which triggered by 8.9 richer scale earthquake (Ophiyandri et al., 2010); Katrina Hurricane 2005 followed by big waves and floods (Boyd et al., 2009), Auckland Volcanic Field 2002 (Tomsen et al., 2014), Merapi Eruption 2010 (Mei et al., 2013) and East Japan Earthquake and Tsunami 2011 (Mimura et al., 2011) which lead to the breakout of Fukushima nuclear reactor; were some of the examples.

Some studies focused on hazard assessment which determines the probability of occurrence of a certain hazard in certain intensity, while other studies focused on doing hazard mapping with the aim of evacuation plan revision. The needs of doing hazard and safe zone mapping become important due to some degree of a disaster occurrence. In many disaster cases, hazard and safe zone mapping is part of government policy to minimize the disaster risk in many aspects. Most of the time, this particular map is develop based on historical disaster data and expert judgments considering the ge-

ographical condition. Nevertheless, as disaster cannot be predicted, it is also important to make assumptions and prepare the deviation “allowance”, in respect with some probability for bigger disaster. The Great East Japan Earthquake 2011 proven that hazard assessment needed to be done in several scenarios, considering the lightest to the worst (Mimura et al., 2011). Japanese scientists made a serious mistake in thinking that a few hundred years of history defined the limit of how large earthquakes in the Japan Trench subduction zone could get (Stein et al., 2012).

Many researchers also have done some studies about how people should be evacuated during disaster in order to minimize travel time or clearance time. In mathematical form, facility location model also has been used widely for selecting evacuation facilities (Kongsomsaksakul et al., 2005; Li et al., 2012; Xu et al., 2016). Several models and algorithms have been developed to clarify evacuation processes into macroscopic models and microscopic models. While macroscopic models are mainly based on network flow models and ignore individual behaviors, microscopic models take the individual characteristics and interactions in evacuation process into account (Gai et al., 2016). However, not many studies take into account the possibility of secondary disaster or cascading effect due to the aftershock. Thus, in practice, it will be more effective to consider multiple scenarios as a contingency plan as such catastrophic situations which resulted in a high number of affected people might be predicted and the impact can be minimized.

To fill that gap, the objective of this research effort is to develop a model for shelter selection and relocation under dynamic nature of disaster within a certain period. To effectively achieve this objective, it is critical to understand the nature of the disaster, which will be influenced

by the types of hazard involved, historical data, and geographical condition at the moment of the disaster alert. However, it is not enough simply to decide the evacuation radius; rather, it is important to map hazard/risk in detail to minimize the number of evacuee and chaos during an evacuation. Thus, using the geographical based for hazard analysis, multi-period shelter selection, and relocation model were developed. In this case, the population at risk was determined by the possibility of dynamic hazard due to after-shocks and secondary disasters.

**2. PROBLEM DESCRIPTION**

The model was developed to tackle multi-period shelter relocation in disaster prone area. The decision made will be based on two scopes of prior, geographical area, and time horizon. The geographical area will be divided based on historical data into a zone area, and time horizon will be in the form of discrete periods. The number of evacuees will increase during the time periods as the hazardous area widen, thus the needs of shelters opened will base on the new demand/new number of the evacuee. The problem was modified generalized multi-weber problem with capacity constraint. This model deals with relocating some set of shelters, to new shelters to minimize the cost, consisting of travel cost and relocation cost within a certain period.

**Indices and Parameters**

$I \subset R^2$	Set of existing shelters
$i$	Index of the existing shelters
$J \subset R^2$	Set of new shelters
$j$	Index of the new shelters
$T$	Set of time periods
$t$	Index of time periods

$\beta \subset R^2$	Restricted/Hazardous area, neither locating shelter nor traveling is permitted
$F = R^2 \setminus int(\beta)$	Feasible area can be used to locate new shelters
$P$	Path/link connecting two locations
$x_i$	Shelter $i$ location
$l(P)$	Length of the path
$D_\beta(x, a)$	Feasible distance with both $(x,a)$ location of path $P$ . $D_\beta(x,a) := \inf\{l(P) : P \text{ feasible } (x,a)\text{-path}\}$ .
$w_{jt}$	the number of evacuees that allocate to new shelter $j$ during period $t$
$f_z$	relocation cost will occur if within a different period, current shelters were included inside the hazardous area
$Q_j$	Shelter $j$ maximal capacity

**Decision Variable**

$y_{ijt}$	Binary variable contain the information to relocate to shelter $j$ from the previous shelter $i$ ,
$v_{jt}$	Equal to 1 if shelter $v$ is open at node $j$
$z_t$	Decision variable if the relocation happens between periods, and then relocation cost occurred.

The problem is formulated using the description above, as follow.

**Objective**

$$\min \left\{ \sum_{t=1}^T \sum_{j=1}^J \sum_{i=1}^I \{y_{ijt} \cdot w_{jt} \cdot D_\beta(x_j, a_i)\} + \sum_{t=2}^T f_z \cdot z_t \right\}$$

$$(1)$$

**Subject to**

$$\sum_{j=1}^J y_{ijt} = 1, \quad \forall i, \forall t \quad (2)$$

$$\sum_{j \notin \beta} y_{ijt} \leq v_{jt}, \quad \forall i, \forall t \quad (3)$$

$$w_{jt} \cdot y_{ijt} \leq Q_j \cdot v_{jt} \quad \forall j, \forall t \quad (4)$$

$$z_t = \begin{cases} 1, & v_{j(t-1)}, j \in \beta \\ 0, & v_{j(t-1)}, j \notin \beta \end{cases} \quad (5)$$

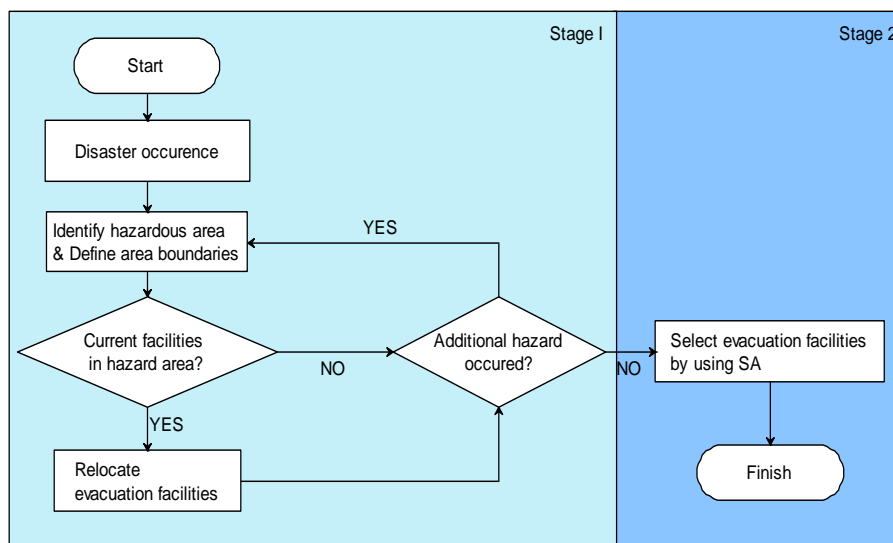
$$y_{ijt}, v_{jt}, z_t \in \{0,1\}, \quad \forall t \quad (6)$$

The objective (1) is to minimize the total cost considering travel cost based on travel distance and relocation cost. The relocation cost was calculated if the relocation happens after the first period ( $t > 1$ ). Constraint (2) makes sure that if the relocation happens, one shelter can only be allocated to one new shelter. Constraint (3) ensures that shelter that located in barrier area will not be chosen, and constraint (4) denotes that each shelter can only accept evacuee based on their capacity. If the relocation due to the previous

shelter is included in barrier area, the relocation cost will occur stated in constraint (5). If the location of shelter is inside the barrier ( $v_{j(t-1)}, j \in \beta$ ), then the evacuee needs to be evacuated to other location ( $z_t = 1$ ). Finally, binary variables were explained in constraint (6).

### 3. SOLUTION PROCEDURE

This study was conducted in two stages, hazard assessment stage and shelter selection stage. First, a hazard assessment map was constructed based on the probability of disaster occurrence and its likelihood of major hazards protruding the area. The area boundaries then defined and the second stage was proceed. The shelter availability and demand/evacuee depend on the area boundaries. We simulated the evacuation by timely increment to enact boundaries progress. If during the process, the shelter deemed unsafe and included in barrier area, the shelter would be closed, and the evacuees was relocated to a new shelter. In summary, the solution procedure is shown in **Figure 1**.



**Figure 1. Detail framework used in this study**

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Input:  $T_0$ ,  $T_f$ ,  $\alpha$ ,  $K$ ,  $N_{\text{non-improving}}$ ,  $I_{\text{iteration}}$ 
Initialization: Find an initial solution  $X$  randomly;
Let  $T=T_0$ ,  $I=0$ ,  $J=0$ ,  $N=0$ ,  $F_{\text{best}}=\text{obj}(X)$ ,  $X_{\text{best}}=X$ 
   $I = I + 1$ 
  Generating  $Y$  based on  $X$ 
    Generate  $r=\text{random}(0,1)$ 
    If  $r < 0.33$ , Swap
    If  $0.333 \leq r < 0.667$ , Insertion
    If  $0.667 \leq r < 1.0$ , Reverse
  If  $\text{obj}(Y) - \text{obj}(X) \leq 0 \rightarrow X$ 
  else
    generate  $r=\text{random}(0,1)$ 
    if  $r < \exp((\text{obj}(Y) - \text{obj}(X))/KT)$ ,  $Y \rightarrow X$ 
  Local Search( $X$ )
If  $T < T_f$  or  $N = N_{\text{non-improving}}$  {Terminate SA}

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Figure 2. Proposed simulated annealing

The problem then solved using Simulated Annealing (SA) algorithm. On this account, the algorithm was implemented using Matlab 2010, and ArcGIS 10.2 was incorporated to visualize the hazard map. The detail of the proposed algorithm can be found in **Figure 2**.

The detail of SA algorithm could be given as follows.

*Step 1 (initialization)* — Set iteration counter  $I = 0$ . Generate an initial feasible solution  $X$  and regard  $X$  as the optimal solution. Set the initial temperature  $T_0$  and the final temperature  $T_f$  are specified. Define the cooling rate  $\alpha$ .

*Step 2 (New solution generation)* — Perform the neighboring function on current solution  $X$ , by swap procedure, insertion procedure, or reverse procedure, and get the new neighboring solution  $Y$ .

*Step 3 (Solution evaluation)* — If the objective function value of the new solution  $Y$  is no less than that of the current solution  $X$ , namely,  $\text{obj}(Y) \geq \text{obj}(X)$ , then proceed to Step 4; otherwise, if  $\text{obj}(Y) < \text{obj}(X)$ , then  $X = Y$ , proceed to Step 5.

*Step 4 (examine metropolis condition)* — Determine the difference ( $\text{obj}(Y) - \text{obj}(X)$ ) between the incumbent solution  $X$  and the neighboring solution  $Y$ . Generate a random number  $r$  from the interval  $(0,1)$ , if  $r < \exp((\text{obj}(Y) - \text{obj}(X))/KT)$ , then  $X = Y$ . Proceed to Step 5.

*Step 5 (local search)* — Perform a local search by shelter's swapping.

*Step 6 (Iteration continuation)* — Set  $I \leftarrow I + 1$ . If  $I \leq I_{\text{iter}}$ , then return to Step 2. Otherwise proceed to Step 7.

*Step 7 (Temperature Adjustment)* — Adjust temperature by the cooling function.

*Step 8 (convergence check)* — If  $T_0 \geq T_f$ , then reset  $i = 1$  and return to Step 2. Otherwise, check the number of non-improving solution found. If  $N = N_{\text{non-improving}}$ , then terminate SA with output the optimal solution  $X$ .

### 3.1. Parameter Selection

Parameter selection may influence the quality of the computational results. Thus, an extensive computational testing was performed to determine the appropriate values of experimental parameters. The following combinations of the param-

eter values were tested. This study uses Taguchi's method with a two-level factorial design to set parameters, including  $N_{\text{non-improving}}$  to terminate the algorithm if after a certain number of iteration, no improvement found; initial temperature, final temperature, number of iteration, Boltzmann constant, and cooling rate. The two-selected-level are as follow:

$N_{\text{non-improving}}$	: N, 2N
$T_0$	: 0, 1
$T_f$	: 0.1, 0.01
$I_{\text{iteration}}$	: $500*N$ , $600*N$
K	: $1/3$ , $1/2$
$\alpha$	: 0.9, 0.99

The result of this design experiment indicates that the best parameter combination for SA is  $N_{\text{non-improving}} = 2N$ , initial temperature  $T_0 = 1$ , final temperature  $T_f = 0.01$ , number of iterations  $I_{\text{iteration}} = 500*N$ , Boltzmann constant  $K = 1/3$ , and cooling coefficient  $\alpha = 0.9$ , where N is the total number of demand nodes.

### 3.2. Algorithm Verification

To ensure the quality of the solution, the proposed SA algorithm was applied to solve three instances for capacitated warehouse location problem that could be downloaded directly from the website: <http://people.brunel.ac.uk/~mastijb/ieborlib/capinfo.html>. All selected instances have been solved by the Lindo software and provide their optimal solutions by the Beasley (Beasley, 1993). As shown in **Table 1**,

**Table 1**, the proposed algorithm can solve up to  $50 \times 50$  problem size with considerably optimal solution and acceptable CPU time (under 1 minute).

## 4. CASE STUDY

Volcanic eruptions can cause losses such as human casualties, property damage, and environmental degradation. These losses are caused by lava flows, ash (tephra) falls, pyroclastic flows, lahars (mudflows), volcanogenic earthquakes, and volcanogenic tsunami (Blong, 1984). Located in rings of fire, Indonesia has nearly 147 volcanoes spread from Sumatra Island to Papua Island, with most active volcano named Mt. Merapi ( $7^{\circ}32'26.99''S$   $110^{\circ}26'41.34''E$ ). Located between two provinces in Java Island, Mt. Merapi slope has a high density of 1901 inhabitants/m<sup>2</sup> with the majority are farmers, stock farmers, and volcanic sand miner (Biro Pusat Statistik, 2010). It poses hazards and risks for inhabitant live near to the mountain.

### 4.1. Evacuation Process during 2010 Eruption

After several increasing seismic activities, the eruption began on late of October 2010. Formerly, Yogyakarta and Central Java Government were employing a hazard map derived from eruption 2006. The map, protruding the maximum lava and pyroclastic flow only reach 5 km to the south and southeast from the peak opening.

Table 1. The SA Algorithm Verification

Name	Size ( $m \times n$ )	Optimal solution	Result	Gap (%)	CPU time (second)
Cap71	$16 \times 50$	932.615.750	932.615.750	0	4.233
Cap101	$25 \times 50$	796.648.440	796.648.440	0	12.552
Cap131	$50 \times 50$	7.934.395.620	7.934.395.620	0	54.688

The evacuation process began on October 25, 2010, and on the first period, resident within radius 8 km was evacuated. Second evacuation order on November 3rd, 2010 suggested clearing the 15 km radius area. Pyroclastic flows traveled up to 10 km away from the summit, forcing the government also to evacuate people from within the shelters set up earlier to accommodate those already dislocated by the volcano. Regardless the sudden alert, unfortunately, the prediction was false as sustained explosive eruption generated an ash column that rose to 17 km altitude and resulted in 353 victims died (Mei et al., 2013). The detail time frame of this disaster illustrates in **Figure 3**.

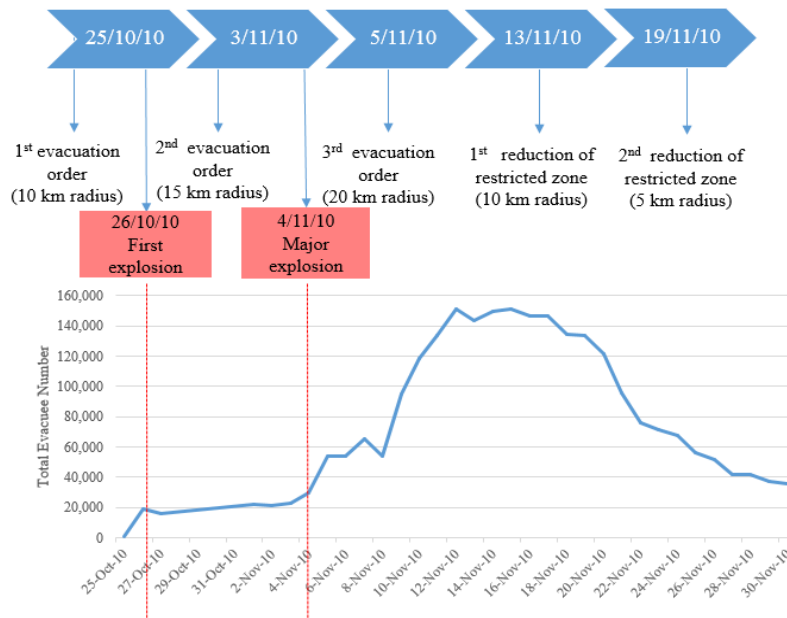
As consequences, 399,403 people reported to be evacuated in Yogyakarta, and Central Java Province and at least 600 shelters were registered to the authority. Due to an insufficient preparation of the evacuee number fluctuation, some evacuees need to move from one shelter to another as no official shelters available out-

side radius 20 km (Maarif Syamsul, 2010; Mei et al., 2013).

**4.2. Hazard Evaluation at Mt. Merapi**

Essentially, Mt. Merapi hazard map can be divided into three zones. Hard hazard zone (impact zone III) prone to not only lava flows but also pyroclastic flows and heavy ash falls. The moderate hazard zone (impact zone II), in which poses a risk from ash falls, and light hazard zone (impact zone I), where prone to mud flood especially during rainy season.

A further analysis between Mt. Merapi history, contingency plan 2009 and hazard evaluation after 2010 eruption highlight several scenarios to be considered for the new hazard assessment map. The frequent eruptions at Mt. Merapi suggests the inevitability of another eruption in the future. By analogy with 2010 eruption, the new evacuation plan of the area would be possible to initiate immediately ahead of the eruption.



**Figure 3. Merapi eruption case 2010 chronology and evacuee number in Yogyakarta province (Badan Penanggulangan Bencana Daerah Sleman, 2011)**

This study will focus on Yogyakarta Province area where the 2010 eruption has higher impact and damage, with detailed map presented in **Figure 4**. The hazard and radius map is prepared using software ArcGIS, based on the data received from the Interview with BPBD Sleman.

The hazard map zoning also divides the area into three zones. Red zone (Zone III) is calculated on radius 8 km from the peak with additional selected areas that cascaded down with river bank prone to lava and pyroclastic flow 10 km far within 1 km wide from a river bank. Zone II (Orange zone), prone to ash fall and heavy dust continued from 8 km until radius 10 km except for village near river bank where the risk area calculated until 12 km far. Village near selected river bank, such as cascaded down the Kuning, Gendol, Woro, Boyong, Krasak and Opak rivers on the slopes of the volcano are included as Zone I (Yellow zone), a flood-prone area,

which can reach to more than 15 km from top, 1 km wide.

Other than that, the only exception is Cangkringan district and the northern part of Ngemplak District where Zone III is stated to be 16 km radius far, and Zone II reach 17 km from the top.

## 5. RESULT AND DISCUSSION

Candidate shelter data was gathered from Regional Disaster Management Agency Sleman District (BPBD Sleman) based on 2010 eruption data and 2012 contingency plan. Transportation cost will be calculated based on distance traveled by evacuee multiplied by gasoline price per liter km per vehicle. In the real condition, most of the evacuee was using a motorcycle, and the priority evacuee is evacuated using car and bus. Thus, by considering ideal condition, this study assumed that each vehicle could carry at most six evacuees at once with some the vehicle is unlimited.

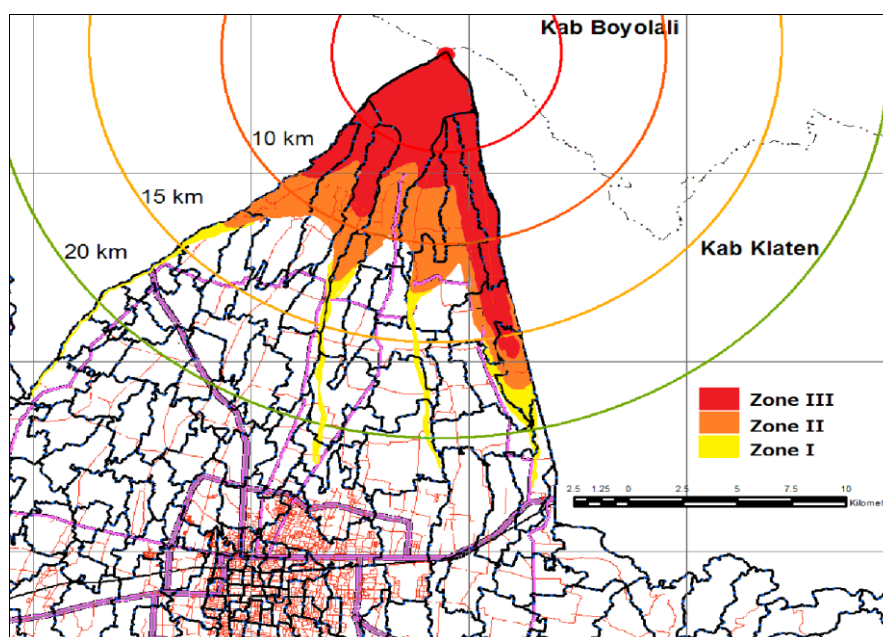


Figure 4. Mt. Merapi new hazard map



### 5.1. Effect on No Capacity Constraint

Based on local government data, the capacity of each shelter is varied from 300-500 people. However, during the actual evacuation, many shelters are used exceed its capacity. This study considers if each shelter has high capacities and set to be able to accept 1,500 evacuees at a time. In this case, regardless the fluctuation of demand, shelters available can carry all of the evacuees. As the cost of relocating to new shelters is also the same, the shelter selection is solely based on the distance and number of evacuees. **Table 2** shows the comparison between different standard for evacuation without capacity constraint in each shelter. Nevertheless, using a hazard map as evacuation guidelines impacted in the number of evacuee. The selected locations are drawn in map using ArcGIS software as shown below.

**Figure 5(a)** and **Figure 5(b)** shows the different location of selected shelters during last period (T=3) without considering capacity constraint. Based on radius based (**Figure 5(a)**), the available number of

shelters cannot accommodate all of the evacuee and the government required to provide unofficial shelters. In opposite, considering evacuation process based on hazard map resulted in an adequate number of available shelters.

### 5.2. Effect on Capacity Constraint

Considering the actual condition where each shelter has different capacities, the shelter choice might differ with some shelters needed increase significantly. **Table 3** shows that by really considering the actual capacity, the shelter number needed is more than the shelter provided by the Government. Many evacuees then choose to stay in places provided other than official shelters but have relatively short distance. The emergent number of evacuees surely become another problem that needs to be solved. Before 2010 eruption, the government has established several numbers of shelters with capacity ranging from 300-500/shelter. In that case, the required number of shelters would be enormous and difficult to monitor.

**Table 2. Total cost comparison between radius based evacuation and hazard assessment based evacuation without capacity constrain**

Hazard Zone	Area	Period	Evacuee	Shelter Needed	Relocation Cost (*1000) (IDR)	Total Cost (*1000) (IDR)
Radius Area	10	1	15,314	11	0	17,022
	15	2	99,166	70	35,000	200,276
	20	3	150,981	100	50,000	251,308
Hazard Map	I	1	16,925	16	0	22,935
	II	2	46,990	35	17,500	80,153
	III	3	75,076	51	25,500	125,600

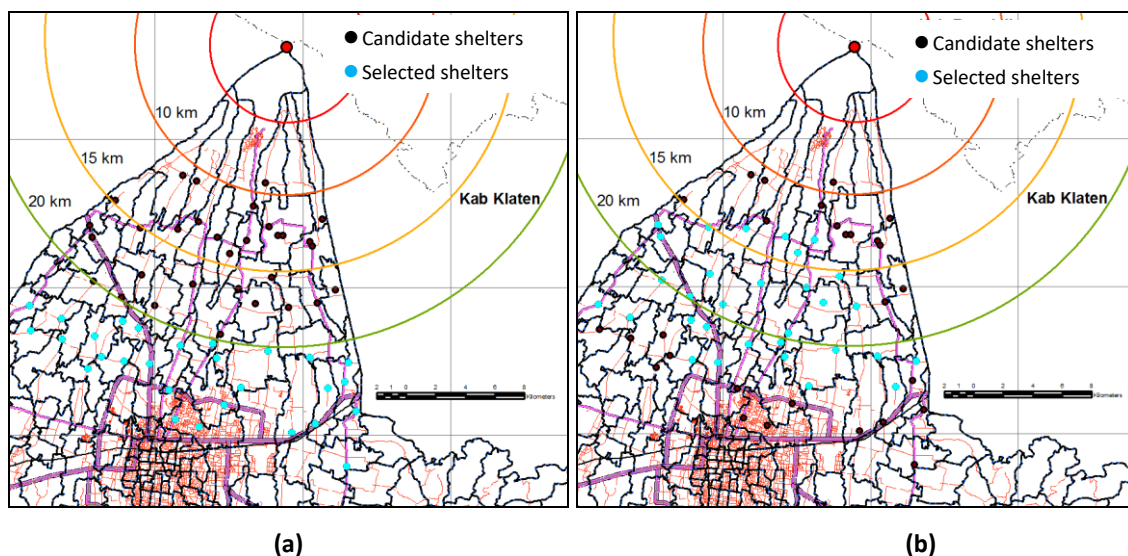


Figure 5. (a) Selected shelter locations based on radius area during Period 3 (b) Selected shelter locations based on hazard map during Period 3

## 6. DISCUSSION

The significance on the establishment of hazard map can be shown in **Figure 6**. It is prominent that by dividing the area based on hazard assessment map, the number of evacuees is less compared to radius based evacuation. Respectively, since the number of evacuees is less than radius based evacuation, the required number of shelters are also decreased.

The decreasing number of shelters affect the total cost for evacuation process.

As stated before, 2010 eruption forced the government to quickly move the risk zone from 10 km to 15 km before expanded it to 20 km radius. In fact, the emergent number of evacuees can be minimized by understanding the hazard prone area. This way, the evacuation process can be done more effectively.

Table 3. Total cost comparison between radius based evacuation and hazard assessment based evacuation with capacity constrain

Hazard Zone	Area	Period	Evacuee	Shelter Need-	Relocation Cost	Total Cost
				ed	(*1000) (IDR)	(*1000) (IDR)
Radius Area	10	1	15,314	30	0	28,938
	15	2	99,166	198	99,000	264,276
	20	3	150,981	335	167,500	419,135
Hazard Map	I	1	16,925	30	0	38,990
	II	2	46,990	90	45,000	123,317
	III	3	75,076	151	75,500	200,626

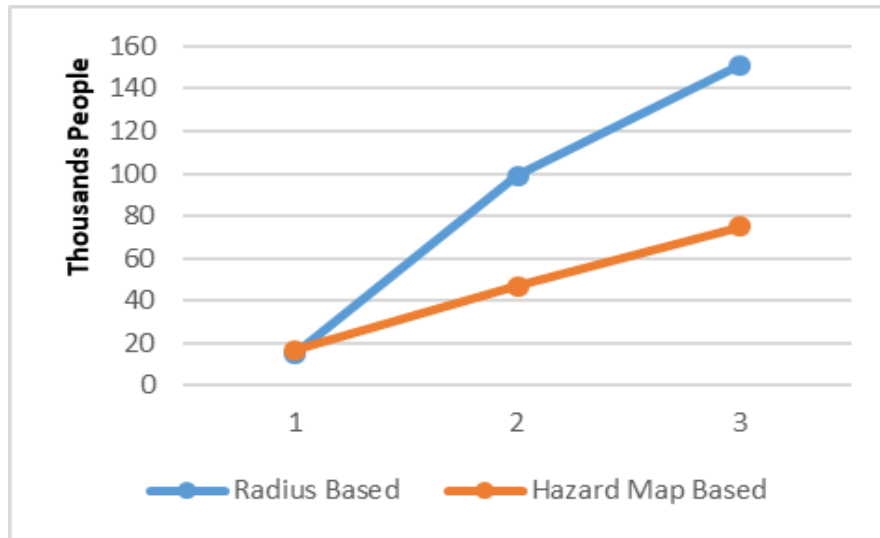


Figure 6. Number of evacuees in each period between radius based evacuation and hazard map based evacuation

## 7. CONCLUSION

This paper makes a key contribution to the literature in disaster management. The model shows the importance of considering the hazard movement scenarios in a certain period when selecting shelter locations. In the case study, rather than prejudice the boundaries based on radius, hazard map gave different subsets of the shelters identified in the first stage to be selected, thereby producing a minimum cost, the number of evacuees, and some shelters used. It is of critical importance

because planning to a single scenario or a small number of “representative” scenarios is common.

The opportunities for future research exist in at least the following two areas. First, this model focuses on the location selection without consideration on the different priority of evacuee. The model may be important for those who are listed as a priority as periodically relocation can be hard. Second, it is important to develop a multi-modal choice expansion of the model so that the transportation needs of priority group can be addressed.

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