Identifying Road Network Vulnerability During Disaster
Cased study: Road Network Evacuation in Merapi Eruption

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(Original Article)

Identifying Road Network Vulnerability During Disaster

Cased study: Road Network Evacuation in Merapi Eruption

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Abstract

The eruption of Mount Merapi in 2010 killed more than 400 people. An optimal evacuation is strongly affected by road network preparedness used as an evacuation route. This study aims at developing a evacuation model from the disaster to identify road network vulnerability in optimizing evacuation route performance. Evacuation modeling employed a user-optimal method to analyze changes in road network performance in the form of flow as a basis for developing a formula to measure road network vulnerability. The results indicated the increased flows on the road network areas of ring 1, ring 2, ring 3, and Sleman outside the ring. By employing the developed vulnerability equation, the road networks identified vulnerable were ring 1, ring 2, ring 3 and Sleman outside the ring indicated by positive index values. Meanwhile, the road
networks in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul were identified invulnerable indicated by negative index values.

**Keywords:** Model, Evacuation, Road Network, Index, Vulnerability.

1. Introduction

The eruption of Mount Merapi that occurred in the administrative area of Yogyakarta inflicted heavy casualties and material losses. Mount Merapi is one of 129 active volcanoes in Indonesia; it has erupted more than 80 times and lastly erupted in 2010 that claimed more than 400 lives (Jousset et al., 2012; Ki, 2016). According by Mei et al. (2013); Wood, Nathan, Jones, Schelling, and Schimidtlein (2014) evacuation is an effective way to minimize casualties. Without good coordination in choosing evacuation routes and time, refugees are frequently caught on road congestion for a long period of time and may cause casualties (Chiu, 2004). Evacuation is a common strategy for dealing with emergency situations. Evacuation is a process in which people from dangerous places are placed to safer places in order to reduce health problems and the lives of vulnerably affected people (Saadatseresht, Mansourian, & Taleai, 2009).

The vulnerability of a road network occurs due to external events resulting in disruption of some road networks or system dysfunction, so that it requires a clear concept of solution (Berdica, 2002). A study conducted by Reggiani, Nijkamp, and Lanzi (2015) state declared that the increased intensity of disasters in recent years is the impact of changes in natural conditions and human hands, some of which have become an interesting object of study, especially regarding the vulnerability of road networks due to disasters. Vulnerability as various events that can reduce service, operability or
even reliability, and accessibility of a transport system defined by (Jenelius, Petersen, & Mattsson, 2006; Taylor, Sekhar, & D’Este, 2006).

The importance of network as an evacuation route makes the identification of vulnerable road networks necessary in order to ensure network preparedness in facing disaster so as to minimize casualties. The process of evaluating the vulnerability or reliability of a road network becomes a standard that can be developed by quantifying the efficiency of performance observed on a network when it gets interrupted (Nagurney & Qiang, 2007). Accordingly, this study aims at modeling the event of evacuation from the eruption of Mount Merapi by developing a user-optimal method to identify vulnerable road network through a new formula.

2. Materials and Methods

2.1 Subject

In making and developing an evacuation model, it is important to know the characteristics of the disaster-affected area, even to the extent to identify an area with high, medium or low vulnerability. Madireddy, Manini, Kumara, Medeiros, and Shankar (2015) classify high risk and low risk area in a disaster area in determining evacuation model scenarios. The model of evacuation from Mount Merapi disaster was developed with the help of SATURN program version 11.3.12W. SATURN program has long been used in transportation modeling because it has a fairly good level of accuracy, in addition to having advantages in easy to operated and having a relatively short time in doing the simulation. Fathoni and Priyanto (2005) developed a modeling using SATURN 9.2 program to estimate the origin-destination matrix and the results indicated good validation.
Evacuation modeling was focused on road networks in Yogyakarta Special Region, involving 140 centroids, consisting of 73 zones based on subdistrict, 6 external zones and 61 evacuation zones. There were 449 buffer nodes, and 851 segments spreading in five regencies/cities in Yogyakarta Special Region. The study area is shown in Figure 1 below. The road networks observed in this study were classified in 8 areas, namely road networks of ring 1, ring 2, ring 3, Sleman outside the ring, Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul. The model of road network is shown in Figure 2 below.

Travel distribution was made using the annual average daily traffic (AADT) data taken from TATRAWIL (Regional Transportation Level) of Yogyakarta Special Region, Indonesia, in 2016. This modeling is a macro-level modeling at a certain time slice, so that the model output is converted into peak hour volume by considering peak hour factor (PHF). The OD matrix of daily travel and evacuation travel was modified in the input of trip distribution. The evacuation matrix was developed to capture the phenomenon of refugees’ travel on the evacuation route. A similar study was developed by Soetomo and Priyanto (2003) in developing OD Matrix to analyze the possibility of public transport routes to and from UGM campus. Therefore, it is expected that this research would be able to analyze optimal evacuation routes in facing the possibility of disaster.

In order to support the analysis, three model scenarios were applied, namely ring 1 scenario, an evacuation route refugees from ring1 (X1) population area with 6 variations of simulation: 50%, 60%, 70%, 80%, 90% and 100%; ring 2 scenario, a combination of variation of refugees from ring 1 (X1) population by 80%, 90%, and 100%, and variation of refugees from ring 2 (X2) population by 50%, 60%, 70%, 80%,
90% and 100% with 18 variations of simulation; and ring 3 scenario, a combination of evacuation route travel variations of ring 1 (X1) population by 90% and 100%, and variations of refugees from ring 2 (X2) population by 80%, 90% and 100%, and variations of refugees from ring 3 (X3) population by 50%, 60%, 70%, 80%, 90% and 100% with 36 variations of simulation.

2.2. Evacuation modeling

Evacuation modeling usually has a wide scope of study area and involves many links and zones, so that the scope of model development falls into macroscopic category. The macroscopic model can be used to assess network performance during emergency disaster evacuation with coverage of large-scale study areas (Hardiansyah, Priyanto, Suparma & Muthohar, 2016; Zhang, Zhao, Parr, Jiang, & Wolshon, 2015). In the SATURN program, the standard model procedure is based on the Wardrop's traffic equilibrium principle (user-optimal), that traffic users manage themselves on a denser network so that the travel costs on all routes used between each pair of OD are equal with the minimum cost of travel and all the unused routes have the same or greater cost. Therefore, the Wardrop's Equilibrium solution makes it possible to capture the effects of congestion (via the cost flow curve) on route options or vice versa. The Wardrop's principle finds a series of flow that minimizes a particular purpose function in the equation 1 as follows.

\[ Z = \sum_{\alpha} \int_{0}^{\lambda} C_{\alpha}(v) \, dv \]  \hspace{1cm} (1)

This equilibrium is useful as one of the ways to build balance by minimizing Z value as a solution to ensure the discovery of balance.
Lastly, the final solution for the algorithm produced the average of each weight of each all-or-nothing travel flow, where the load weight was calculated based on the equation 2 as follows.

\[ \alpha_a = \lambda_j = j + 1 \prod n (1 - \lambda_i) \]  

where \( \alpha_j \) is the proportion of the final solution contributed by the iteration \( j \) and \( \lambda_i \) is the value selected at the first iteration. Therefore, the solution \( j \) is initially loaded a of \( \lambda_j \) fraction, but this is then consistently reduced by factor \((1 - \lambda)\) on each iteration.

Regression analysis to analyze changes in road network performance loaded by evacuation process including flow and travel time as dependent variable and number of refugees in affected area as independent variable is expressed in equation 3 below.

\[ Y = b_0 + b_1 x X_1 + b_2 x X_2 + \ldots + b_n x X_n \]  

Where, \( b_0 \) is a constant and \( X_1, X_2 \) are independent variables.

2.3. Development of vulnerability index

The formula for assessing the condition of a road network has been widely developed and under various conditions, such as a disaster, urban road network density or development plan of a region. Kusumastuti, Dyah, Husudo, Suardi, and Danarsari (2014) have developed a formula for assessing the resilience of disaster-prone areas in Indonesia to natural disasters in the form of indexes, but this study did not specifically include the vulnerability of road networks. Vulnerability is a reaction function of the transport system and ability to adapt the capacity of road network to the exposure of an event (Demirel, Kompil, & Nemry, 2015).

Several studies have developed a road vulnerability index by developing formulae for measuring vulnerability indices. The results study from Scott, Novak, Aultman-Hall, and Guo (2006) introduced the Network Reliability Index (NRI) as a
change in travel time costs associated with route selection. This index is based on the
capacity of each link and considers the route selection for the pair of origin-destination.
A study conducted by Balijepalli and Oppong (2014) introduced the Network
Vulnerability Index (NVI) to assess service and importance of each network on a
network when one of the networks is closed due to flood.

The vulnerability formula developed in this study differs from the previous one,
that is, the formula variable was taken from the results of simulation model when
massive rapid evacuation took place. This study further introduced a new formula as an
important finding, i.e. vulnerability index. Road network vulnerability is measured
based on changes in road network performance due to the implementation of each
scenario and expansion factor of the exposed region. The flow of road network is one of
the model outputs from the SATURN program. Several studies used road network
performance for analyzing traffic problems. Priyanto, Utomo, Soetomo, and
Malkhamah (2004) developed a road network modeling to assess the road network
performance in the future. Road network vulnerability is an increase in the flow caused
by evacuation travel on daily travel. Therefore, if a positive index is obtained, the road
network is considered vulnerable. Otherwise, the road network is considered not
vulnerable. The equation for measuring vulnerability indexes according to the scenarios
is shown in equation 4 below.

\[
INVE_F = \left(\frac{\sum_{i=1}^{\Delta} F_E - \sum_{i=1}^{\Delta} F_D}{\sum_{i=1}^{\Delta} F_D}\right)
\]

(4)

Where, \( INVE_F \) is vulnerability index of the road network during evacuation, \( F_D \)
variable is the total daily flow (pcu/hour), and \( F_E \) is total evacuation flow (pcu/hour).
Equation 4 was used to measure vulnerability when population evacuation occurred
only or stopped at one scenario only.
The road vulnerability formula was then developed to measure the index due to expansion of exposed areas, as shown in equation 5 as follows.

\[
INVE_{Fex} = \left[ \frac{(\sum_{i=1}^{M} F_{E}) - (\sum_{i=1}^{M} F_{D})}{\sum_{i=1}^{M} F_{D}} \right] + \left[ \frac{(\sum_{i=1}^{M} F_{Epre}) - (\sum_{i=1}^{M} F_{Dpre})}{\sum_{i=1}^{M} F_{Dpre}} \right] \quad (5)
\]

Where \(INVE_{Fex}\) is network vulnerability index due to expansion of exposed area, \(F_D\) is total daily flow (pcu/hour), \(F_E\) is total evacuation flow (pcu/hour), \(F_{Epre}\) is previous total evacuation flow (pcu/hour), and \(F_{Dpre}\) is previous daily total flow (pcu/hour).

Different with the previous equation, equation 5 was used to measure vulnerability when the refuge status from one scenario to the next scenario increased within a rapid period of time, so that the effect on road network performance would be greater due to the accumulation of refugees.

3. Results and Discussion

The results of simulation model analysis of each scenario were total network flow values of each observation area. Furthermore, equation model was developed using linear regression to calculate the flow of observation area when the refugee variable changed according to its original condition. The equation model is shown in table 1 below.

Based on the results of interviews with people living in the area affected by the eruption of Mount Merapi, 91% of the population would evacuate using vehicle, consisting of 60% using light vehicle (LV), 8% using heavy vehicle (HV), and 32% using motor cycle (MC). The 91% were then applied into the equation model in Table 1. The results of flow in each observation area based on the above equation model are shown in Table 2 below.
The changes in road network performance in the form of increased flow value of daily travel were the initial identification of the road network vulnerability due to the evacuation from Mount Merapi disaster. The results of the analysis as shown in Table 2 indicates that the evacuation movement of 91% of the population in scenarios of ring 1, ring 2 and ring 3 increased the value of flow. The increased value of the flow due to the implementation of ring 1 scenario occurred in the road networks of ring 2, ring 3 and Sleman outside the ring by 73,319; 198,760; and 517,416 pcu/hour respectively from daily travels. The implementation of the ring 2 scenario increased the flow in the road networks of ring 1, ring 2, ring 3 and Sleman outside the ring by 3,996; 86,829; 205,358; and 515,374 pcu/hour respectively from daily travels. Similarly, the implementation of the ring 3 scenario increased the value of flow in the road networks of ring 1, ring 2, ring 3 and Sleman outside the ring by 5,758; 135,752; 341,393; and 657,659 pcu/hour respectively from daily travels.

The results of the analysis also indicate that the flow of daily travels in the road networks in the areas of Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul decreased after the evacuation scenario model was implemented. The flow significantly decreased when the evacuation was extended to the ring 3 scenario. Based on the initial identification, such decreased value occurred because the catastrophic eruption of Mount Merapi resulted in the delay of some travels.

The average value of VCR (Volume Capacity Ratio) of the observed road networks as a result of the application of the evacuation model is shown in Figure 3. The average VCR value of the ring road networks of ring 1 region decreased when the evacuation scenario of ring 1 was applied to 0.17 from the daily average VCR of 0.20 and increased again when the evacuation scenario of ring 2 and ring 3 was applied to
0.24 and 0.45. The road network in ring 2 observation area indicated that the average
VCR value increased from the daily model by 0.38 to 0.45; 0.54 and 0.87 for the
evacuation scenario of ring 1, ring 2 and ring 3. Then the average VCR value of road
network of ring 3 observation area also increased from daily model by 0.39 to 0.44;
0.47 and 0.77. Similarly, on the road network of Sleman observation areas outside the
ring, the average VCR increased from the daily model by 0.78 to 0.81; 0.81 and 1.06.

Figure 3 also shows that there was no indication of an increase in the average
VCR value in the road networks of observation areas of Yogyakarta City, Bantul, Kulon
Progo and Gunung Kidul. The average VCR value tended to be stable and decreased
when the ring 3 scenario was implemented. For the road networks in Yogyakarta City,
the average VCR value decreased the from the daily model to the evacuation model of
ring 1, ring 2 and ring 3 scenarios by 0.59; 0.58; 0.58 and 0.56 respectively. Then, the
road network of Bantul area decreased by 0.82; 0.82; 0.82 and 0.80, the road network
Kulon Progo area decreased by 0.58; 0.57; 0.56 and 0.52 and the road network of
Gunung Kidul decreased by 0.59; 0.58; 0.58 and 0.54.

Evacuation movement can improve road network performance, which had been
developed by Hobeika and Kim (1998) that evacuation movement model has been able
to identify a traffic jam network, and obtained a high-flow road network and can also
determine the farthest path from the point of origin to the shelter. This is in contrast to a
study conducted by Chiu (2004) stating that the optimization of evacuation time
scheduling can keep the flow of the road network in a stable condition. This study did
not schedule the evacuation time so that the refugee surge significantly has improved
the road network performance in the observation areas.
The road network vulnerability index in the observed areas of each scenario was then analyzed using Equation 4. This index was used to identify the road networks in Yogyakarta Special Region Province that both experienced and did not experience vulnerability due to evacuation process. A positive index value indicates a vulnerable road network, while a negative index value indicates an invulnerable road network. The results of the calculation of road network vulnerability index in the observation area for each scenario are shown in Figure 4 below.

Based on Figure 4, the vulnerability index due to scenario of ring 1 refugees occurred in the observation areas of ring 2, ring 3 and Sleman outside the ring, namely 0.14; 0.10; and 0.02. The implementation of scenario of ring 2 refugees produced road vulnerability indices in the areas of ring 1, ring 2, ring 3 and Sleman outside of ring by 0.24; 0.35; 0.14; and 0.02. Ring 3 scenario produced road network vulnerability indices in the areas of ring 1, ring 2, ring 3 and Sleman outside the ring by 0.78; 1.12; 0.90; and 0.3. The road networks in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul had negative value indices so they were not identified as vulnerable in the results of this index.

Equation 5 was used to measure the vulnerability index due to the expansion of exposed areas because the status changed rapidly. The results of index analysis based on equation 5 are as shown in Figure 5 below.

Figure 5 shows that if the area is exposed in the ring 1 scenario, the road network vulnerability occurs in the observed areas of ring 2, ring 3 and Sleman outside the ring by 0.14; 0.10; and 0.02. If the increased status extended the exposed area to the ring 2 scenario, the road network vulnerability occurred in the areas of ring 1, ring 2, ring 3 and Sleman outside the ring were 0.13; 0.50; 0.25; and 0.05. Similarly, if the
exposed area was re-extended to the ring 3 scenario, the road network vulnerability occurred in the observed areas of ring 1, ring 2, ring 3 and Sleman outside the ring by 1.01; 1.47; 1.04; and 0.32. Similar results are for the road networks in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul that were not identified as vulnerable due to the disaster as evidenced by the negative value indices, although the influence of refugee movement was much greater.

Based on the above vulnerability analysis, road network has been identified to be potentially disrupted during a disaster. This vulnerability index indicates that the road network is an important road network to save many refugees from the exposure of Mount Merapi disaster. Similarly Nagurney and Qiang (2007) developed an index to identify the importance of the road network although not specifically on the evacuation function. The results study from Jenelius, Petersen, and Mattsson (2006) have developed an index of the importance of road links and exposure index based on the increase in general travel costs when the routes are closed. This is different from this study that it did not consider the cost in determining the vulnerability index, but the other result from the model simulation is travel time, which in transportation modeling is called cost, so the vulnerability index in terms of the cost is possible to be developed.

The importance of road networks in ring 1, ring 2 and ring 3 based on the high value of vulnerability index becomes an input to related parties in order to reduce the risk of disaster impact through route preparation and improvement of road network–supporting infrastructure. According by Balijepalli and Oppong (2014) vulnerability index is not only limited to the analysis of index value, but also a reference in the development of the outline of a traffic diversion plan when the road network is closed due to the exposure to a disaster.
4. Conclusions

The results of the study show that not all road networks in the observation area experienced vulnerability resulted from the eruption of Mount Merapi. The road networks identified vulnerable were only located in the areas of ring 1, ring 2, ring 3 and Sleman outside the ring as indicated by the increased flow and proven by positive vulnerability index. Meanwhile, the road networks in Yogyakarta City, Bantul, Kulon Progo and Gunung Kidul were identified not experiencing vulnerability as indicated by the decreased flow and proven by negative index. In addition, the highest vulnerability index value occurred in the road network of ring 1, 2, and 3 so that they needs serious attention, especially for the policy makers in preparing the evacuation route. Furthermore, it is expected that the development of system-optimal model can provide better results than the user-optimal.

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Figure 1. Map of study area

Figure 2. Road network model in SATURN
Figure 3. VCR of road network in the study area

Figure 4. Road network vulnerability index of area observation of each scenario
Figure 5. Index of vulnerability of road network observation due to expansion of exposed areas of each Scenario

<table>
<thead>
<tr>
<th>Road Network Observation Areas</th>
<th>Vulnerability Index due to expansion of the affected area Scenario Ring 1</th>
<th>Vulnerability Index due to expansion of the affected area Scenario Ring 2</th>
<th>Vulnerability Index due to expansion of the affected area Scenario Ring 3</th>
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<tbody>
<tr>
<td>Sleman Inside the ring</td>
<td>1.47</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Sleman Outside the ring</td>
<td>0.13</td>
<td>0.50</td>
<td>0.25</td>
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<td>0.05</td>
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<td>0.02</td>
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<td>-0.03</td>
<td>-0.01</td>
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<td>-0.04</td>
<td>-0.12</td>
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<tr>
<td>Gunung Kidul</td>
<td>-0.11</td>
<td>-0.12</td>
<td>-0.03</td>
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<td>Road Network Observation</td>
<td>Equations measure the volume of the road network</td>
<td>Total volume due to 91% of refugees (pcu/hr)</td>
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<tr>
<td><strong>Scenario ring 1</strong></td>
<td><strong>Equation</strong></td>
<td><strong>X1 = 91%</strong></td>
<td></td>
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<tr>
<td>Ring 1</td>
<td>(Y = 3,163.967 - 2.773 \times X1)</td>
<td>2,912</td>
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<tr>
<td>Ring 2</td>
<td>(Y = 62,795.522 + 115.645 \times X1)</td>
<td>73,319</td>
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<td>Ring 3</td>
<td>(Y = 178,699.163 + 220.444 \times X1)</td>
<td>198,760</td>
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<td>Sleman outside the ring</td>
<td>(Y = 501,562.304 + 174.213 \times X1)</td>
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<td>Yogyakarta City</td>
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<td>128,582</td>
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<td>(Y = 214,892.707 + 4.925 \times X1)</td>
<td>215,341</td>
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<td>91,367</td>
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<tr>
<td><strong>Scenario ring 2</strong></td>
<td><strong>Equation</strong></td>
<td><strong>X1 = 91%; X2 =91%</strong></td>
<td></td>
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<td>Ring 1</td>
<td>(Y = 3166.328 + 7.268 \times X1 + 1.850 \times X2)</td>
<td>3,996</td>
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<td>Yogyakarta City</td>
<td>(Y = 129797.382 - 1.241 \times X1 - 16.488 \times X2)</td>
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<td>Bantul</td>
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<td>Ring 3</td>
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<td>Bantul</td>
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<td>Kulon Progo</td>
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<tr>
<td>Gunung Kidul</td>
<td>(Y = 106397.352 - 75.485 \times X1 - 23.295 \times X2 + 0.778 \times X3)</td>
<td>97,479</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. The equation measures the volume of the road network of observation areas of each scenario
<table>
<thead>
<tr>
<th>Road network observation</th>
<th>Total volume of daily travel (pcu/hr)</th>
<th>Total volume due to 91% of refugees (pcu/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario ring 1</td>
<td>Scenario ring 2</td>
</tr>
<tr>
<td>Ring 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,236</td>
<td>2,912</td>
<td>3,996</td>
</tr>
<tr>
<td>Ring 2</td>
<td>64,184</td>
<td>73,319</td>
</tr>
<tr>
<td>Ring 3</td>
<td>179,913</td>
<td>198,760</td>
</tr>
<tr>
<td>Sleman outside the ring</td>
<td>504,959</td>
<td>517,416</td>
</tr>
<tr>
<td>Yogyakarta City</td>
<td>130,289</td>
<td>128,582</td>
</tr>
<tr>
<td>Bantul</td>
<td>215,626</td>
<td>215,341</td>
</tr>
<tr>
<td>Kulon Progo</td>
<td>93,003</td>
<td>91,367</td>
</tr>
<tr>
<td>Gunung Kidul</td>
<td>107,096</td>
<td>105,526</td>
</tr>
</tbody>
</table>

Table 2. Total volume of observation area due to evacuation movement 91% of the population of each scenario