

Original Article

Identifying road network vulnerability during disaster, a case study of road network evacuation in Mount 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 an evacuation model from the disaster to identify road network vulnerability in optimizing evacuation route performance. The 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 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 vulnerability of 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 as invulnerable indicated by the 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 the last eruption was in 2010 that claimed more than 400 lives (Jousset *et al.*, 2012; Ki, 2016). According to Mei *et al.* (2013) and Wood, Nathan, Jones, Schelling, and Schmidtlein (2014), evacuation is an effective way to minimize casualties. Without good coordination in choosing evacuation routes and time, evacuees are frequently caught in road congestion for long periods of time which 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 displaced to safer places in order to reduce health problems and the lives of vulnerable people (Saadatseresht, Mansourian, & Taleai, 2009).

The vulnerability of a road network occurs due to external events that result in disruption of some road networks or there is a system dysfunction that requires a clear solution (Berdica, 2002). A study conducted by Reggiani, Nijkamp, and Lanzi (2015) stated that the increased intensity of disasters in recent years has an impact on natural conditions and humans. Some disasters have become interesting objects of study, especially the vulnerability of road networks due to disasters. Various events 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 a network as an evacuation route makes the identification of vulnerable road networks necessary in order to ensure network preparedness in facing disaster in order to minimize casualties. The process of

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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 aimed to model the evacuation from the eruption of Mount Merapi by developing a user-optimal method to identify a 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 and identify an area with high, medium or low vulnerability. Madireddy, Manini, Kumara, Medeiros, and Shankar (2015) classified high risk and low risk areas in a disaster area in determining evacuation model scenarios. An

evacuation model from the Mount Merapi disaster was developed with the help of SATURN version 11.3.12W. The SATURN program has long been used in transportation modeling because it has a fairly good level of accuracy, easy to operate, has a relatively short simulation time. Fathoni and Priyanto (2005) developed a model using the SATURN 9.2 program to estimate the origin-destination matrix and the results indicated good validation.

The evacuation modeling focused on road networks in Yogyakarta Special Region that involved 140 centroids of 73 zones based on a subdistrict, 6 external zones, and 61 evacuation zones. There were 449 buffer nodes and 851 segments spread out in five regencies/cities in the Yogyakarta Special Region (Figure 1). 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 (Figure 2).

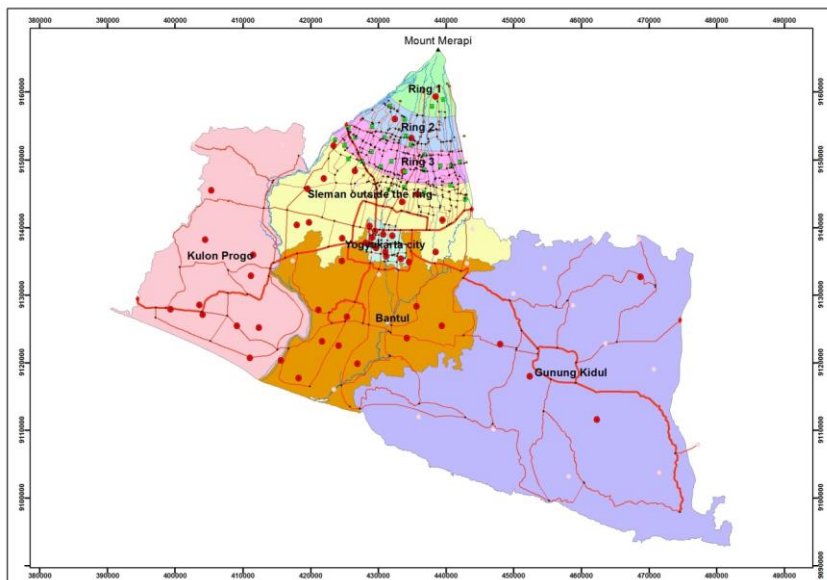


Figure 1. Map of the study area.

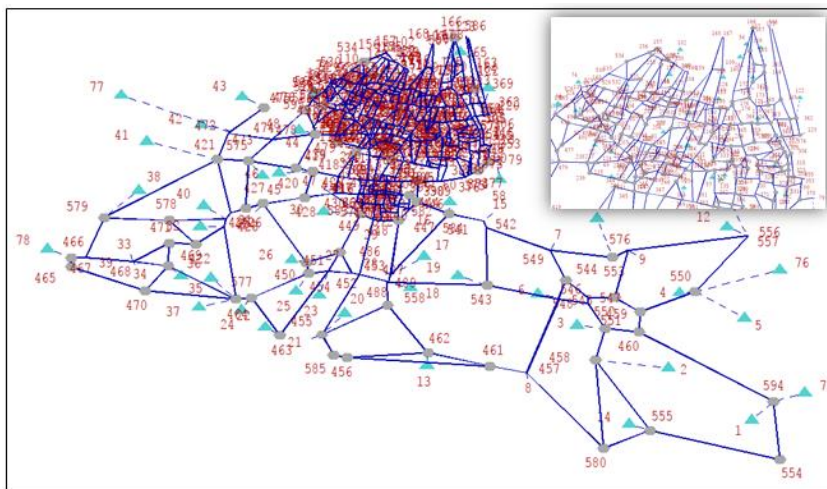


Figure 2. Road network model in SATURN.

Travel distribution was made using the annual average daily traffic data taken from TATRAWIL (Regional Transportation Level) of Yogyakarta Special Region, Indonesia in 2016. This modeling was a macro-level modeling at a certain time slice. Therefore, the model output is converted into peak hour volume by considering a peak hour factor. The origin-destination (OD) matrix of daily travel and evacuation travel were modified in the input of trip distribution. The evacuation matrix was developed to capture the phenomenon of evacuee travel on the evacuation route. A similar study was developed by Soetomo and Priyanto (2003) in developing an OD Matrix to analyze the possibility of public transport routes to and from the campus of Universitas Gadjah Mada. 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 ring 1 (X1) population area with 6 variations of simulation: 50%, 60%, 70%, 80%, 90%, and 100%; ring 2 scenario, a combination of variation of evacuees from ring 1 (X1) population by 80%, 90%, and 100%, and variation of evacuees 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 evacuees 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 study area with a wide scope and involves many links and zones, so that the scope of model development falls into a macroscopic category. The macroscopic model can be used to assess network performance during an 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 to the minimum cost of travel and all 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 flows that minimize a particular purpose function in Equation 1.

$$Z = \sum_a^v \int_0^a C_a(v) dv \quad (1)$$

This equilibrium is useful as one of the ways to build balance by minimizing the 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 Equation 2.

$$\alpha_a = \lambda_{ji} = j + 1 \prod n (1 - \lambda_i) \quad (2)$$

where α_j is the proportion of the final solution contributed by the iteration j and λ_i is the λ value selected at the first iteration. Therefore, the solution j is initially loaded as the λ_j fraction, but this is then consistently reduced by the factor $(1 - \lambda)$ for each iteration.

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

$$Y = b_0 + b_1 x X_1 + b_2 x X_2 + \dots + b_n x X_n \quad (3)$$

where b_0 is a constant and X_1, X_2 are independent variables.

2.3 Development of vulnerability index

The formulae to assess the conditions of a road network have 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) developed a formula to assess 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 the 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 to measure vulnerability indices. The results from Scott, Novak, Aultman-Hall, and Guo (2006) introduced the Network Reliability Index 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 OD. A study conducted by Balijepalli and Oppong (2014) introduced the Network Vulnerability Index 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 a 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 to analyze traffic problems. Priyanto, Utomo, Soetomo, and Malkhamah (2004) developed a road network model 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:

$$INVE_F = \left[\frac{(\sum_{i=1}^{|X|} F_E) - (\sum_{i=1}^{|X|} F_D)}{(\sum_{i=1}^{|X|} F_D)} \right] \tag{4}$$

where $INVE_F$ is the vulnerability index of the road network during evacuation, F_D is the variable for total daily flow (pcu/hour), and F_E is the total evacuation flow (pcu/hour). Equation 4 was used to measure vulnerability when the population evacuation occurred 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:

$$INVE_{F_{ex}} = \left[\frac{(\sum_{i=1}^{|X|} F_E) - (\sum_{i=1}^{|X|} F_D)}{(\sum_{i=1}^{|X|} F_D)} \right] + \left[\frac{(\sum_{i=1}^{|X|} F_{Epre}) - (\sum_{i=1}^{|X|} F_{Dpre})}{(\sum_{i=1}^{|X|} F_{Dpre})} \right] \tag{5}$$

where $INVE_{F_{ex}}$ is the network vulnerability index due to expansion of the exposed area, F_D is the total daily flow (pcu/hour), F_E is the total evacuation flow (pcu/hour), F_{Epre} is the previous total evacuation flow (pcu/hour), and F_{Dpre} is the previous daily total flow (pcu/hour). Equation 5 was used to measure vulnerability when the evacuee status from one scenario to the next scenario increased within a rapid period of

time with a greater effect on road network performance due to the accumulation of evacuees.

3. Results and Discussion

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

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 vehicles that consisted of 60% using light vehicle, 8% using heavy vehicle, and 32% using motor cycle. The 91% was 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.

The changes in road network performance in the form of the increased flow value of daily travel were the initial identification of the road network vulnerability due to the evacuation from the Mount Merapi disaster. The results of the analysis indicated that the evacuation movement of 91% of the population in scenarios of ring 1, ring 2, and ring 3 increased the value of flow (Table 2). 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

Table 1. Equations that measure the volume of the road network of observation areas of each scenario.

Road Network Observation	Equations measure the volume of the road network	Total volume due to 91% of refugees (pcu/h)
Scenario ring 1	Equation	X1= 91%
Ring 1	Y = 3,163.967 - 2.773 X1	2,912
Ring 2	Y = 62,795.522 + 115.645 X1	73,319
Ring 3	Y = 178,699.163 + 220.444 X1	198,760
Sleman outside the ring	Y = 501,562.304 + 174.213 X1	517,416
Yogyakarta City	Y = 129,712.163 - 12.416 X1	128,582
Bantul	Y = 214,892.707 + 4.925 X1	215,341
Kulon Progo	Y = 92,570.859 - 13.229 X1	91,367
Gunung Kidul	Y = 106,773.467 - 13.703 X1	105,526
Scenario ring 2	Equation	X1 = 91%; X2 =91%
Ring 1	Y = 3166.328 + 7.268 X1 + 1.850 X2	3,996
Ring 2	Y = 63112.574 + 188.149 X1 + 72.476 X2	86,829
Ring 3	Y = 177104.773 + 111.053 X1 + 199.425 X2	205,358
Sleman outside the ring	Y = 502668.801 + 64.248 X1 + 75.369 X2	515,374
Yogyakarta City	Y = 129797.382 - 1.241 X1 - 16.488 X2	128,184
Bantul	Y = 215192.971 - 6.305 X1 - 6.469 X2	214,031
Kulon Progo	Y = 92906.276 - 9.713 X1 - 16.029 X2	90,564
Gunung Kidul	Y = 106940.399 - 12.269 X1 - 7.112 X2	105,177
Scenario ring 3	Equation	X1 = 91%; X2 =91%; and X3 = 91%
Ring 1	Y = 3101.357 + 0.716 X1 + 4.597 X2 + 23.882 X3	5,758
Ring 2	Y = 63987.326 + 117.084 X1 + 87.487 X2 + 584.049 X3	135,752
Ring 3	Y = 177983.405 + 104.676 X1 + 62.953 X2 + 1628.080 X3	341,393
Sleman outside the ring	Y = 496034.779 - 410.418 X1 - 6.300 X2 + 2192.804X3	657,659
Yogyakarta City	Y = 128447.795 - 141.633 X1 - 54.416 X2 + 132.961 X3	122,707
Bantul	Y = 213804.088 - 151.268 X1 - 55.926 X2 + 153.412 X3	208,910
Kulon Progo	Y = 92384.347 - 75.769 X1 - 22.916 X2 + 7.300 X3	84,068
Gunung Kidul	Y= 106397.352 - 75.485 X1 - 23.295 X2 + 0.778 X3	97,479

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

Road network observation	Total volume of daily travel (pcu/h)	Total volume due to 91% of refugees (pcu/hr)		
		Scenario ring 1	Scenario ring 2	Scenario ring 3
Ring 1	3,236	2,912	3,996	5,758
Ring 2	64,184	73,319	86,829	135,752
Ring 3	179,913	198,760	205,358	341,393
Sleman outside the ring	504,959	517,416	515,374	657,659
Yogyakarta City	130,289	128,582	128,184	122,707
Bantul	215,626	215,341	214,031	208,910
Kulon Progo	93,003	91,367	90,564	84,068
Gunung Kidul	107,096	105,526	105,177	97,479

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 indicated 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, the decreased value occurred because the catastrophic eruption of Mount Merapi resulted in some delays of traveling time.

The average value of Volume Capacity Ratio (VCR) 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 the 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 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 from the daily model to the evacuation model of ring 1, ring 2, and ring 3 scenarios by 0.59 to 0.58, 0.58, and 0.56, respectively. Then, the road network of Bantul area decreased by 0.82 to 0.82, 0.82, and 0.80, the road network Kulon Progo area decreased by 0.58 to 0.57, 0.56, and 0.52, and the road network of Gunung Kidul decreased by 0.59 to 0.58, 0.58, and 0.54.

Evacuation movement can improve road network performance. Hobeika and Kim (1998) developed an evacuation movement model that was able to identify a traffic jam network and obtained a high-flow road network and could also determine the farthest path from the point of origin to the shelter. This is in contrast to a study conducted by Chiu (2004) that stated 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 evacuee surge significantly 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 experienced or did not experience vulnerability due to the 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 the road network vulnerability index in the observation area for each scenario are shown in Figure 4.

Based on Figure 4, the vulnerability index due to scenario of ring 1 evacuees occurred in the observation areas of ring 2, ring 3 and Sleman outside the ring, namely 0.14, 0.10, and 0.02. Implementation of the scenario of ring 2 evacuees produced road vulnerability indices in the areas of ring 1, ring 2, ring 3, and Sleman outside of ring of 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 of 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; therefore, 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 the index analysis based on equation 5 are shown in Figure 5. 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, 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

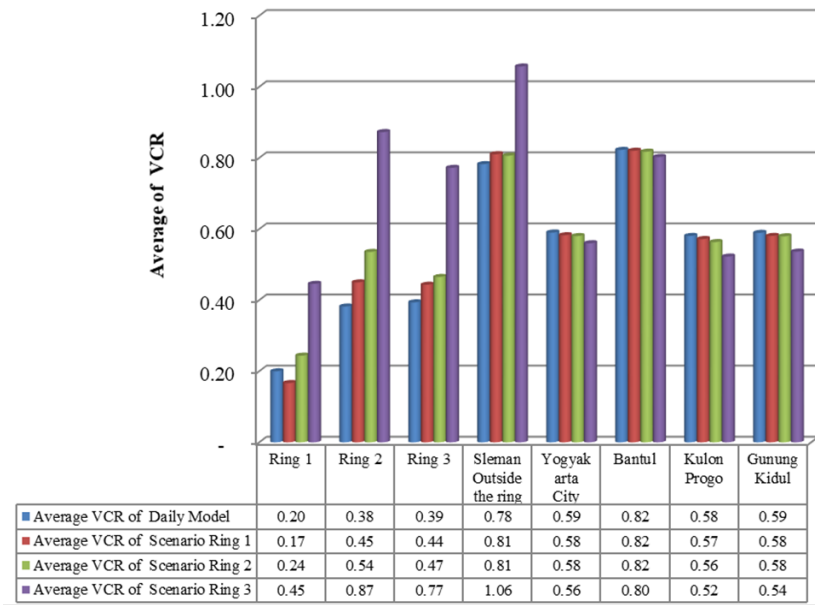


Figure 3. VCR of the road network in the study area.

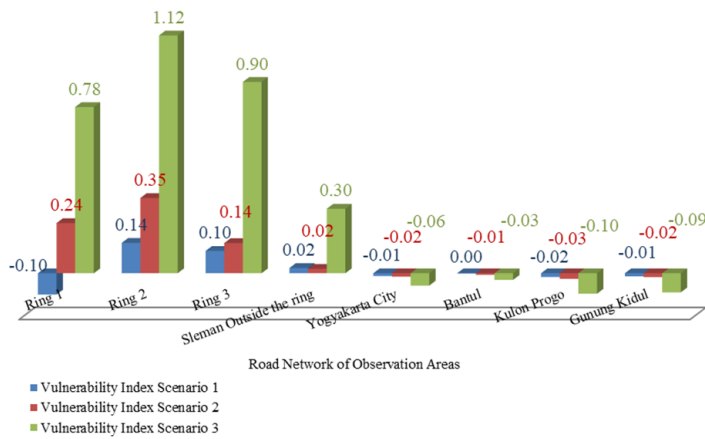


Figure 4. Road network vulnerability index of areas observed in each scenario

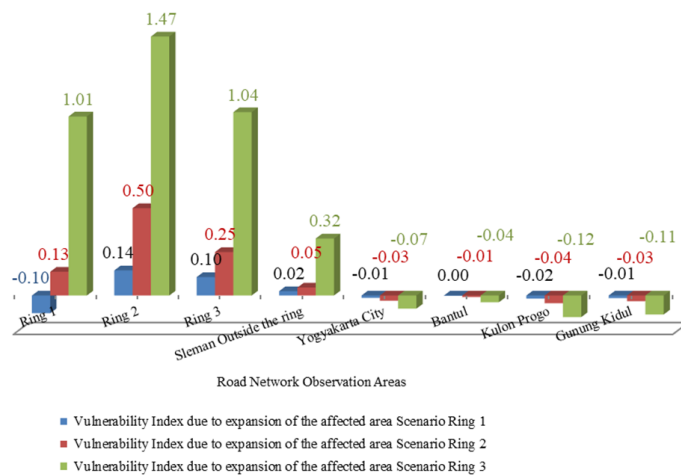


Figure 5. Index of vulnerability of road network observed due to expansion of exposed areas of each scenario.

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, the road network was identified to be potentially disrupted during a disaster. This vulnerability index indicated that the road network is an important road network to save many evacuees from the exposure of another 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. A study by Jenelius, Petersen, and Mattsson (2006) 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. That study was different from this study because it did not consider the cost in determining the vulnerability index, but the other result from the model simulation was travel time which in transportation modeling is called cost. Therefore, the vulnerability index in terms of the cost can 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 to Balijepalli and Oppong (2014), the vulnerability index is not only limited to the analysis of index value, but also as 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 as a result of the eruption of Mount Merapi. The road networks identified as 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 the positive vulnerability index. Meanwhile, the road networks in Yogyakarta City, Bantul, Kulon Progo, and Gunung Kidul were identified as not experiencing vulnerability as indicated by the decreased flow and proven by the negative index. In addition, the highest vulnerability index value occurred in the road network of ring 1, 2, and 3 so that they need serious attention, especially for the policy makers in preparing an evacuation route. Furthermore, it is expected that the development of a system-optimal model can provide better results than the user-optimal.

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