Analysing vulnerability of road network and guiding evacuees to sheltered areas: Case study of Mt Merapi, Central Java, Indonesia

Hardiansyah[1,2], Imam Muthohar[2], Chandra Balijepalli[3,4] and Sigit Priyanto[2]

Abstract

Historically people traded the risk of living in dangerous places such as volcanic slopes for the benefit of farming in rich soils. Road network around risk prone area plays a key role in saving lives when evacuation is required in an emergency, and thus needs to be in full preparedness to face the eventuality. This will need analysing vulnerability to disruption and identifying critical network links of the evacuation routes. It is also crucial to ensure that the evacuees are aware of recommended routes to sheltered areas. Traffic models to assess road network performance due to natural disasters have been developed in the past. But few researchers investigated whether the evacuees are aware of the recommended routes to sheltered areas and whether they are willing to use them indeed. This paper adopts a vulnerability index and identifies network links to improve, by mapping them to a simple 'traffic light style' congestion scale. A special mobile phone application software was developed to guide the residents to reach sheltered areas which takes account of the fact that a third of the residents living around Mt Merapi are not aware of evacuation routes to sheltered areas.

Keywords: Vulnerability, Evacuation, Disaster, Mt Merapi Eruption, App-based route guidance

1. Introduction

Land around volcanos becomes highly fertile in the long run due to very high concentration of minerals. In fact, volcanic soils are the richest on the earth. This is why people risk their lives and live on volcanic slopes, as seen in various countries including Indonesia, Italy, Japan and Philippines (Fisher et al 1997). However in the short run, volcanic ash and lava bring misery to people living in the vicinity as well as to others located further afield. Generally, it is true even in case of rivers where the fertile land around river banks is attractive to live, despite the flooding risks involved. Thus, this kind of situation creates a tension between peoples' desire to live in/around dangerous places and the societal commitment to keep them safe. It is this tension that is the focus of this paper, and it addresses the question of how to be prepared for a natural disaster like a volcanic eruption, prioritising roads to improve as well as raising the awareness of evacuees concerned.

Three solutions can be effectively pursued to minimise the risks involved: (i) through land-use planning by prohibiting the future development in high-risk areas, (ii) relocating current residents

[1] Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Jalan WR. Supratman Bengkulu, Bengkulu, Indonesia

[2] Department of Civil and Environmental Engineering, Faculty of Engineering, University of Gadjah Mada, Jalan Grafika No.2, Yogyakarta, 55281, Indonesia

[3] Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT England, United Kingdom
[4] Corresponding author's e-mail: n.c.balijepalli@leeds.ac.uk

with a resettlement on a permanent basis, and (iii) temporary displacement of residents for a period (Tyas et al., 2016). Whilst the land use control and permanent displacement approaches take several years to produce positive outcomes, temporary displacement approach remains the most effective solution to ensure safety of people residing around. The temporary displacement approach, however, relies heavily on using road network around the affected area as a means to facilitate the evacuation process. Utilising region's road network to evacuate the traffic in emergency situation becomes a difficult proposition when the road network is not in readiness to deal with the altered flows. The importance of having adequate network capacity to handle the evacuation traffic makes it necessary to identify the set of critical road links to improve, which will ensure a high degree of preparedness to face the eventuality.

There has been a growing body of research on identifying critical links in a network since the introductory work by Berdica (2002). Many researchers e.g. Taylor et al (2006), Jenelius et al (2006), Scott et al (2006), Knoop et al (2012), Balijepalli & Oppong (2014), El-Rashidy & Grant-Muller (2014) have contributed to the work, and looked at ways to identify critical links of a network predominantly by simulating a degraded network to compare the performance against network intact. The research on critical links grew further by considering the impact of degrading multiple links of a network – see for example, Wang et al (2016), Bagloee et al (2017) and Peñafiel Mera & Balijepalli (2020). Whether seeking to identify a single or multiple critical links, the focus of research largely stayed centred around altering network characteristics implementing full/partial link closures. A few others e.g. Chen et al (2012) looked at the uncertainty in demand, risk taking behaviour of travellers, yet, their focus too revolved around network link closures although in a reduced search space associated with the 'impacted area'. A common feature of the papers reviewed is that they characterise the functioning of a road network *after* a disaster strikes, but, in contrast with others, our paper is concerned with network performance associated with the evacuation activity carried out *before* the disaster strikes.

There is also a large body of research on evacuation planning and modelling too, which considers various aspects of evacuation, such as, willingness/behaviour of the affected people to evacuate (Yang et al 2018, Otani et al., 2018), evacuation destination (Yuan et al., 2006), mode of travel (Miller et al., 2008, Yuan & Puchalsky, 2014) and evacuation route choice (Pel et al., 2012). (See Murray-Tuite & Wolshon 2013, for a comprehensive review). In contrast with the above works, our research focuses on developing a practicable approach aimed at improving the compliance to evacuation, potentially reducing the casualties. This paper innovates in developing a mobile phone application to guide the evacuees to sheltered areas. We analyse the network performance during the evacuation and identify road sections that need capacity augmentation. We also investigate the level of awareness of residents, their knowledge of evacuation routes/ location of sheltered areas, and develop an innovative app-based route guidance advice to reach the evacuees to sheltered locations.

The paper is divided into six sections including this one. Section 2 reviews the literature, section 3 sets out the method followed, section 4 introduces the case of Mt Merapi and section 5 discusses the results. An app-based route guidance system developed as part of the research is also discussed in Section 5. Section 6 concludes the research.

2. Literature review

According to Berdica (2002) and Reggiani et al (2015) vulnerability of a transportation system is defined as the susceptibility of network to rare, big risks such as earthquakes, volcanic activity etc. which is measured by the impact of disruption created on the accessibility. The term resilience is defined as the opposite of vulnerability which means the ability to withstand major incidents. Accessibility itself is defined as the ease of reaching a place which is measured in units of time/distance or even money. Route selection models have been used by researchers to assess the performance of road networks due to major/minor disruptions. Vulnerability analysis typically involves simulating a degraded network and comparing performance against the network intact. Balijepalli and Oppong (2014) developed a model to identify critical links of a road network with partially/fully closed roads due to incidents such as flooding. Their research produced an index of vulnerability called Network Vulnerability Index (NVI) which accounts for the serviceability of roads based on relative loss of capacity. Likewise, there are many other indices developed – e.g. change in generalized cost measure (Taylor et al 2006), network efficiency measure (Nagurney & Qiang 2007), importance measure (Jenelius et al 2006), network robustness index (Scott et al 2006) among others. Recently, Hardiansyah et al (2018) developed a simple index suitable for comparing network performance based on the difference in traffic flow (travel time) on each road between normal day operations and evacuation operations. This paper adopts Hardiansyah's index and enhances the analysis further by mapping the results to a simple 'traffic light style' congestion scale to aid prioritising road works.

Assessing network performance involves assigning traffic to routes either by User Optimal (UO) or System Optimal (SO) principles (Wardrop 1952). UO is achieved when all used routes in a congested network have equal travel time and no driver can change routes to reduce their travel time. In contrast, SO is achieved when the total travel time is minimised for all network users put together. It is arguable that in an evacuation scenario whether affected people are willing to follow the advice given by the local authorities (aimed at leading to normative SO) as it requires ensuring complete compliance by all evacuees (Yang et al 2018). Thus, in this research we analysed the network performance with both UO and SO assignments to consider both types of route choice behaviour.

In contrast with many other works in literature, we assume the network is intact during the evacuation process as the activity will take place *before* the incident and thus the main difference between normal day and emergency day operations is the change in travel pattern. In particular, during the evacuation process, we assume that all persons are destined to reach one of the sheltered areas and it is this change in travel pattern that makes certain links more congested than the usual. The case that road links are already congested even on a normal day, is also accounted for in the analysis by benchmarking the vulnerability index relative to daily congestion levels. Network vulnerability index computed thus will need to be mapped to congestion level to which it is associated with, to facilitate identifying links in need of urgent attention, prioritising links for budgetary allocation. We then worked out budgetary needs to address the prioritised works in consultation with local authorities in Yogyakarta. Finally, a mobile phone based application has been developed to guide the evacuees to follow the suggested routes to sheltered areas.

3. Methods

Let us consider a network of roads represented as a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{A})$ where $\mathcal{N}$ is the set of nodes and $\mathcal{A}$ is the set of directed arcs containing ordered pairs of nodes in $\mathcal{N}$. A subset of nodes is associated with origin/destination of travellers where the critical mass of trips is located within each traffic zone. Each road link $a \in \mathcal{A}$, is associated with a monotonic travel time function $t_a(x_a)$, where, x_a is the flow on link *a*. The travel time function is assumed to follow the standard Bureau of Public Roads (1964) function, $t_a(x_a, q_a) = \alpha_a \left[1 + \beta_a \left(\frac{x_a}{q_a}\right)^{\theta}\right]$ where, q_a is the capacity of link a, and α, β and θ are parameters which depend on the type of road, length of the road which need to be calibrated to observed flows/travel times.

3.1 Vulnerability indices

The vulnerability index is based on the relative difference between traffic flow (travel time) due to evacuation travel compared to normal daily travel. Thus, if the resulting index value is positive, the road network is considered to be vulnerable, but on the contrary if the index produced is negative, the road network is declared not vulnerable. Road network vulnerability index based on traffic volume is as shown in Equation 1.

$$INVE_F = \left[\frac{(\sum_{a=1}^{|\mathcal{A}|} x_a^E) - (\sum_{a=1}^{|\mathcal{A}|} x_a^D)}{(\sum_{i=1}^{|\mathcal{A}|} x_a^D)}\right] \quad (1)$$

where,

$INVE_F$ = Index of road network vulnerability due to traffic flow

x_a^D = Traffic flow (pcu/hour) on link *a* on a normal day

x_a^E = Traffic flow (pcu/hour) on link *a* on an evacuation day

Road network vulnerability index based on travel time is shown in Equation 2.

$$INVE_T = \left[\frac{(\sum_{a=1}^{|\mathcal{A}|} t_a^E) - (\sum_{a=1}^{|\mathcal{A}|} t_a^D)}{(\sum_{a=1}^{|\mathcal{A}|} t_a^D)}\right] \quad (2)$$

where,

$INVE_T$ = Index of road network vulnerability due to travel time

t_a^D = Travel time (second) on link *a* on a normal day

t_a^E = Travel time (second) on link *a* on an evacuation day

Furthermore, in this paper, the vulnerability index computed is mapped to a performance scale based on congestion level to identify the particular set of links that needs improvement. Vulnerability index mapped to volume capacity ratio (VCR) divides the network into three categories. The first category is the combination of VCR values of up to 0.85, in conjunction with *negative* vulnerability index, resulting in a road segment identified in *green,* where the traffic condition is very smooth. The second category is defined by the combination of VCR values of up to 0.85, but associated with a *positive* vulnerability index, resulting in a *yellow* road segment, which means the road is busy but operating smooth. While the third category is the combination of VCR values > 0.85 with a *positive* vulnerability index, resulting in a road segment identified by *red* colour, which means the road is congested even under normal traffic conditions. Roads placed in the third category are the most critical as their performance during an evacuation is extremely critical to minimising the death toll, hence requiring an urgent attention. There is also one more possibility that road links have VCR > 0.85, but associated with negative vulnerability index values, which means that these roads are congested even under normal conditions, but, as they do not contribute to the evacuation activity, they may form the lowest priority as far as the disaster related road maintenance plan is concerned. The classification is summarised Table 1.

Table 1: Classification of roads based on vulnerability

VCR Value	Vulnerability Index	Colour of road segment	Remark
0 – 0.85	Negative value	Green	Free flowing
0 – 0.85	Positive value	Yellow	Busy but flowing
> 0.85	Positive value	Red	Congested

3.2 Development of mobile phone application

Mobile phone application or simply an app, is a piece of software downloaded to a mobile device which performs a specific set of functions and runs within the operating system until the user closes it. Mobile apps have gathered momentum as they open up the opportunity to direct marketing. They became attractive to users as they are very convenient. Mobile apps may access content/data from the internet or download the information and work off-line, either way, they have proved to improve the access. Mobile apps can be developed using Integrated Development Environment (IDE) in Android Studio. Other app builders or even native programming methods for larger bespoke applications could be used too. There are a number of internet based sources advising how to build a mobile app. The following describes the steps involved in developing an app which have been summarised from Anurag (2020).

Step1: Define the problem to resolve
Step2: Identify target users and mobile platforms to deliver
Step3: Design the app with a focus on user interface
Step4: Identify the approach to develop the app – native or web/app builders
Step5: Develop a prototype and test
Step6: Release the app, monitor and upgrade

App development starts with defining the problem to resolve which should clearly identify the benefits to users. Target users need to be clearly identified and a good user interface is essential for the success of an app. Mobile platforms need to consider hardware devices, battery life, device support etc. Web based app builders provide a quick/easy option to developing an app, but significant applications will need bespoke programming, which could be expensive though they are able to deliver high quality user experience. Developing a prototype will be very useful to test the functioning of an app as well as allowing the checking of user interface. Finally, one will need to monitor the usage of an app overtime, and upgrades may become necessary to meet the arising user needs and/or the fast changing hardware/software environment.

4. The case of Mt Merapi evacuation planning

Mt Merapi situated within the Pacific Ring of Fire is the most active volcano in Central Java, Indonesia. The volcano is located 28km to the North of the city of Yogyakarta. Mt Merapi erupted more than 70 times since the records began in year 1548, with the eruption in year 2010 claiming more than 400 lives (Ki, 2016 and Jousset et al., 2012). With a peak height of nearly 3,000 meters above the sea level, 'hot cloud', that is, high density mixture of hot volcanic debris, ashes, sands, and rocks produced during the eruption poses the main risk. Hot cloud can glide at speeds of up to 100 km/h over to areas as far as several dozens of kilometers away from the mountain making the area around Merapi a high-risk region. There is a continuous monitoring of the volcano by the Indonesian Centre for Volcanology and Geologic Hazard Mitigation to anticipate the eruption and alert the authorities to start the evacuation when required. However, it is crucial to maintain the surrounding network to facilitate evacuation especially by those roads falling directly on the identified evacuation routes. General map of Yogyakarta region is shown in Figure 1.

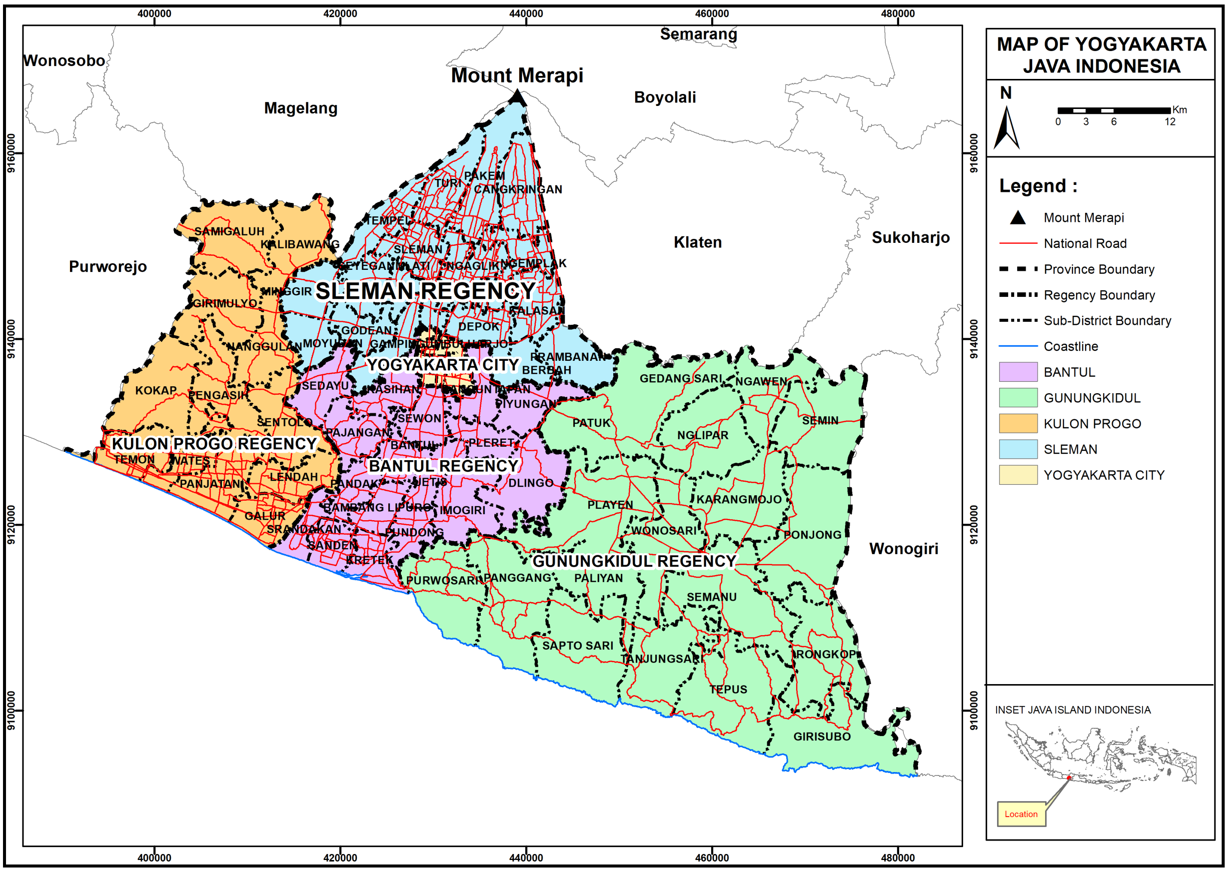

Figure 1: Special region of Yogyakarta, Central Java, Indonesia

Local government of Yogyakarta in consultation with the National Disaster Management Agency (known as BPBD in Indonesia) has divided the region into three concentric areas – viz., Ring 1, Ring 2 and Ring 3 depending on the proximity to Mt Merapi, and then into five radial sectors A, B, C, D, E based on river boundaries (See Figure 2). The division of area into sectors is done along the five rivers viz., Krasak River, Boyong River, Yellow River, Opak River, and Gendol River flowing radially in the disaster prone area. The course of each river acts as a natural path to pyroclastic flow from the eruption, it will be too dangerous for the refugees to cross a river during the evacuation. The objective of this research is to assess the evacuation routes in sectors A to E which are located across, in Rings 1, 2, 3, and develop an easy to follow route guidance system to reach sheltered areas. The research also considers extended areas outside of the hazard prone zone including Sleman area outside of Ring 3, Yogyakarta city, Bantul, Kulon Progo and Gunung Kidul (shown in Figure 1).

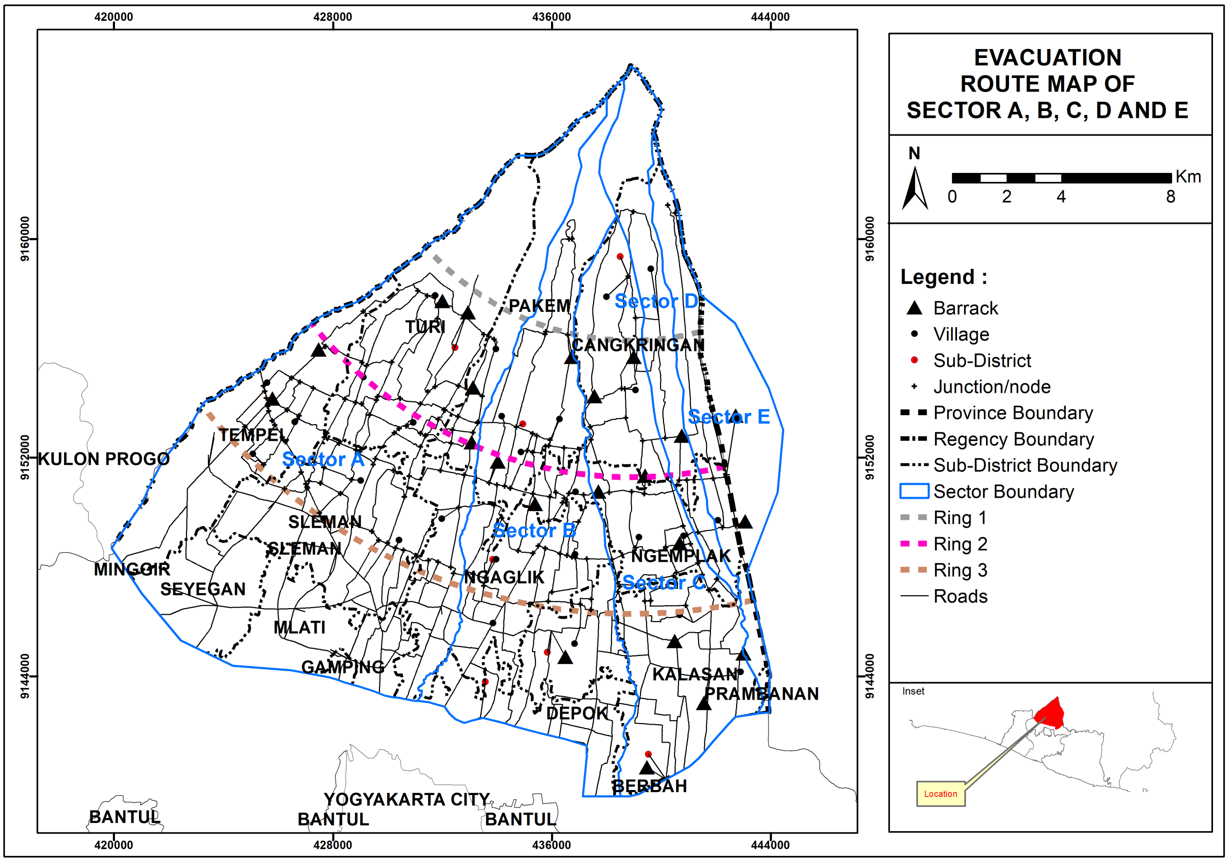

Figure 2: Road network prone to disruption near Mt Merapi

As part of this research we developed a network model of the region using SATURN software (Van Vliet 2015). The modelling exercise requires road network data (characteristics of each road segment such as length, number of lanes, type of road, capacity, free flow speed, speed at capacity etc) and travel patterns viz., a demand matrix of trips between origins and destination. The road network data is based on a Ministerial Decree of the Ministry of Public Works & Housing No. 248/KPTS/M/2015, Decree of Yogyakarta Governor No. 118/KEP/2016, Decree of Sleman Regency No.105/Kep.KDH/A/2013, and Yogyakarta Local Regulation No. 2/2010. We have adopted the capacity values for different types of roads based on the Indonesian Highway Capacity Manual, Binkot (2017).

In 2013, the Regional Disaster Management Agency of Yogyakarta developed a set of evacuation routes in anticipation of further eruptions of Mt Merapi. In this study, we used their baseline demand and evacuation route data. The baseline travel demand data includes trips organised as an O-D matrix under normal day conditions and an O-D matrix of trips when evacuation is needed.

Daily trip matrix is the data set of travel patterns among 73 sub-districts in the Special Region of Yogyakarta and six external areas. Meanwhile, evacuation trip matrix is the data set that contains travel patterns between sub-district areas affected by the disaster and the evacuation barracks as determined by BPBD.

SATURN network model of the region has been developed with 140 zones, 449 nodes (junctions) and 851 links (roads) to evaluate the network performance. The trip matrices were obtained from Yogyakarta's Regional Transportation Board (known as Tatrawil in Indonesia) for the year 2012 and then updated to 2016 as the new base year for the model. A vehicle growth rate of 9% per year was used to predict the number of vehicles in the base year of the model. The growth rate of vehicles adopted is as per the advice of the Integrated Road Management System developed by the Yogyakarta National Road Implementation Center. Figure 3 shows the modelled SATURN network of the area for this research.

In this research we simulate three scenarios of evacuation as below:

S1: Evacuation of all residents within Ring 1
S2: Evacuation of all residents within Ring 2
S3: Evacuation of all residents within Ring 3

In each of the three scenarios we report two possible routing choices i.e. User Optimal - UO (individuals get to choose routes to minimise their travel time, selfishly) and System Optimal – SO (individuals follow routes recommended by the authorities).

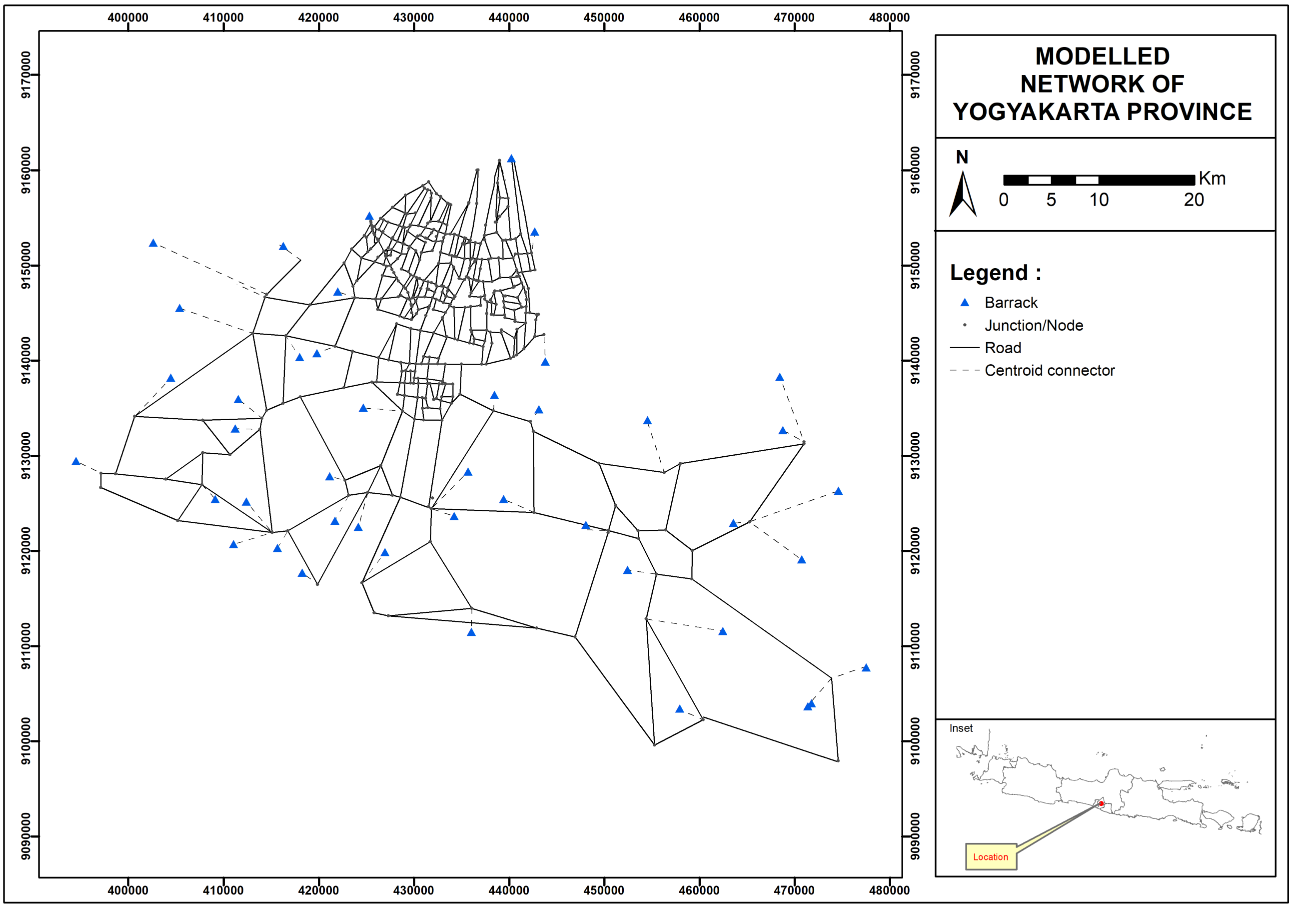

Figure 3: Modelled network for evaluating the evacuation routes

We ran SATURN model for normal day situation, and also for each of the three scenarios S1, S2 and S3. All model runs were carried out for both UO and SO assignments. We then extracted link flows and link travel times and computed the two indices $INVE_F$ and $INVE_T$. The ensuing section analyses the results obtained.

5. Results and discussion

5.1 Analysis of results

Table 2 compares values of the $INVE_F$ index computed for UO and SO evacuation models for the road network of observation areas in each scenario. Looking at various parts of the modelled network, it is clear that SO routing is better than UO routing especially within the three areas of Ring 1, Ring 2 and Ring 3. This is evident from lower $INVE_F$ values between SO and UO routing choices. This means, the authority concerned needs to focus on advising the routes to follow by the affected people when a disaster strikes. Secondly, the road network within Ring 1 is not as prone to disruption as the roads within Ring 2 or Ring 3. Although this might seem counter-intuitive due to its proximity, it is noted that $INVE_F$ values are sensitive to capacity of road links and traffic flow. Thus, the road improvement programme needs to prioritise roads within Ring 2 and Ring 3 over Ring 1. Thirdly, the road network outside of Ring 3 in Sleman appears to be prone to disruption in any of the evacuation scenarios (from S1, S2, S3). It is particularly severely prone to disruption, if the evacuation of Ring 3 is required. This means the road network around Sleman is, in general, quite congested, and if a disaster strikes, it will be even more seriously affected thus requiring urgent attention. Roads within Yogyakarta city are, in general, not prone to disruption due to Mt Merapi eruption, but, if evacuating residents up to Ring 3, then the road network in the city gets seriously congested. Thus some contingency plans will be essential to minimise the danger to life. Similarly, the road network within Bantul also needs some minor improvement in general, as the roads are prone to disruption as indicated by positive values of $INVE_F$. Finally, Kulon Progo and Gunung Kidul are not prone to disruption in any of the evacuation scenarios, thus may attract the lowest priority.

Table 2: $INVE_F$ evacuation model with UO and SO assignments

Scenario/Sector	S1		S2		S3	
	UO	SO	UO	SO	UO	SO
Ring 1	-0.13	-0.22	0.07	-0.48	0.93	-0.72
Ring 2	0.14	0.11	0.46	0.02	1.37	-0.14
Ring 3	0.10	0.10	0.25	0.38	0.99	0.80
Sleman outside of Ring 3	0.02	0.03	0.05	0.08	0.32	0.71
Yogyakarta city	-0.01	-0.01	-0.03	-0.02	-0.07	0.06
Bantul	0.00	0.00	-0.01	0.00	-0.04	0.03
Kulon Progo	-0.02	-0.02	-0.04	-0.04	-0.12	-0.11
Gunung Kidul	-0.01	-0.01	-0.03	-0.03	-0.11	-0.10

Table 3 shows values of time-based vulnerability index $INVE_T$ which appear to follow the same trends as the flow based index discussed earlier. In general, $INVE_T$ values are larger than the corresponding $INVE_F$ values indicating that the roads are more prone to disruption when time is considered as the basis. In other words, this would mean the roads are more congested than indicated by the flow-based index. Moreover, in case of volcanic eruption obviously time to reach a safe sheltered place is more important, thus the time-based vulnerability indicator is highly relevant to the analysis. Thus, we use the time-based index to prioritise the links needing attention. Moreover, from these results, it is also clear that SO routing instructions will need to be provided to maximise the safety of evacuees.

Table 3: $INVE_T$ evacuation model with UO and SO assignments

Scenario/Sector	S1		S2		S3	
	UO	SO	UO	SO	UO	SO
Ring 1	-0.18	-0.20	0.37	-0.40	1.91	-0.75
Ring 2	0.17	0.14	0.61	0.11	1.90	0.06
Ring 3	0.15	0.15	0.36	0.55	1.45	1.15
Sleman outside of Ring 3	0.03	0.04	0.05	0.10	0.44	0.94
Yogyakarta City	-0.01	-0.01	-0.03	-0.02	-0.09	0.07
Bantul	0.00	0.00	-0.01	0.00	-0.04	0.03
Kulon Progo	-0.02	-0.02	-0.05	-0.04	-0.13	-0.11
Gunung Kidul	-0.02	-0.01	-0.04	-0.03	-0.12	-0.11

5.2 Prioritising road improvement works

In the ensuing, we identify the sections of roads which need immediate attention based on vulnerability index values computed from the network assignment, and then map them to the colour coding scale as introduced earlier (see Table 1). Figure 4 shows the resulting colour coded roads based on a mapping of the $INVE_T$ to VCR scales. The following paragraphs summarise the results.

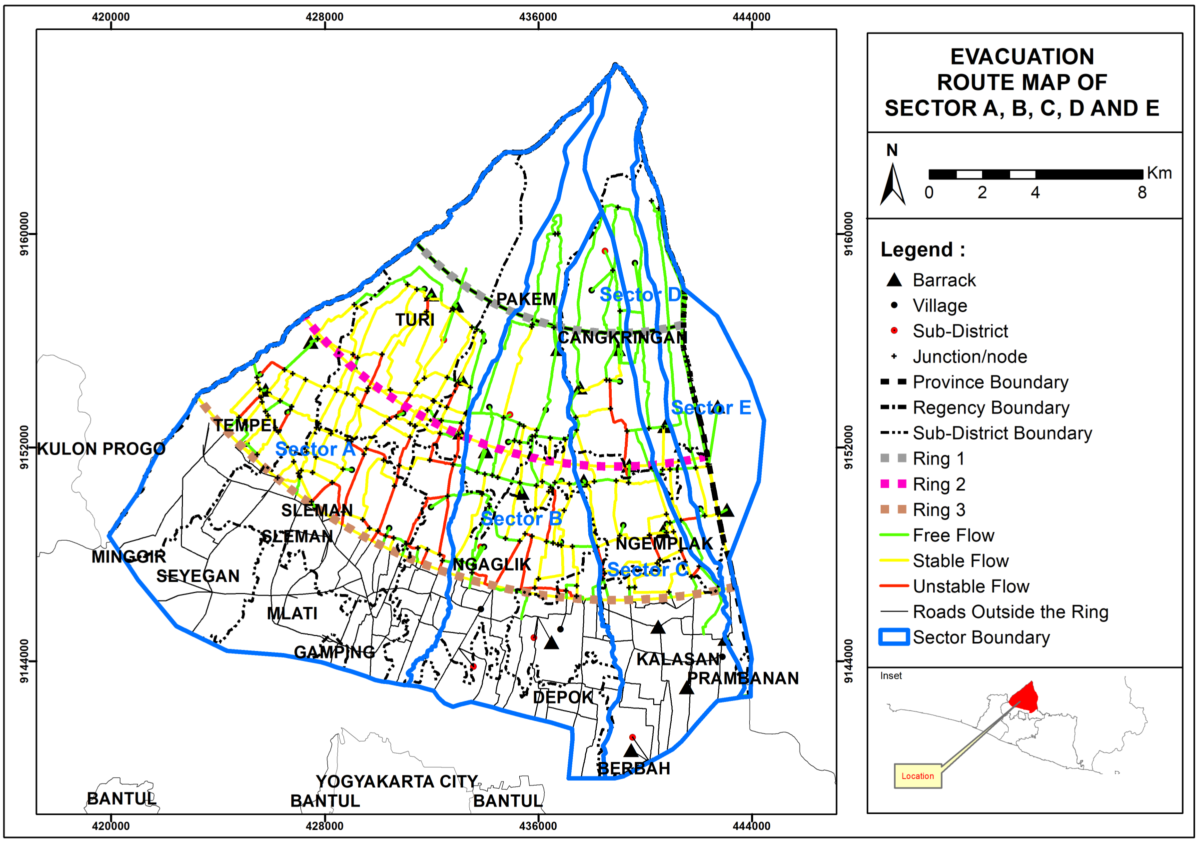

Figure 4: Road network map of evacuation routes

Sector A is the affected area that lies between the Boyong and Krasak Rivers. In this area, 158 road sections were identified as constituting the evacuation routes. It is noted that 10% of the road sections are running smooth, but 67% of roads are busy, but flowing. That means 23% of roads are extremely busy and congested, requiring immediate attention. It is noted that 37 roads were classified as congested (red) and are in need of urgent capacity improvement.

Sector B lies between the Boyong River and Yellow River. A total of 75 roads are used as a means of evacuation during an eruption. In Sector B, 46% roads have been classified as running smooth, 39% busy but flowing and 15% highly congested. The results indicate that 11 segments of the road network in Sector B are highly critical and need to add capacity as soon as possible.

Sector C is the disaster-prone area between the Yellow River and the Opak River. Sector C evacuation road network has 45 segments which are a parts of evacuation routes. 15% roads are classified as very smooth, 58% busy but flowing and 27% as congested. Based on the results of the evacuation modelling analysis we identified 11 segments of the network that need capacity increases.

Sector D lies between Opak River and Gendol River. The evacuation routes in sector D have a network of 8 segments in all. Road network of evacuation routes of Sector D has been classified as 50% very smooth, 37% busy and 13% congested. Only one segment of the road network in Sector D is classified as red which needs to add capacity on an immediate basis.

Sector E is the area bounded by the Opak River and Gendol River and has nine segments of which 43% have been classified as smooth and 57% as busy. In this sector no roads were identified as critical, as none of the roads are highly congested thus not in need of increase in road capacity.

5.3 Budgeting for road network improvement

The previous section identified critical road links in each of the sectors which need capacity improvement and also prioritised them on the basis of level of congestion. This section works out the budget requirements for the proposed capacity improvement programme. The higher the evacuation traffic volume, the more important the road to increase capacity through widening. We have worked out the possible road widths in case of each of the identified critical links in consultation with local authorities of public works in Sleman, Yogyakarta and then computed the amount of money needed to improve the road capacities. The unit price for one square metre of road improvement is taken as IDR 571,428.57 (= US $ 39.00) as per the prevailing standard schedule of rates in Indonesia. Finally, the proposed schedule of network enhancement and its associated costs for each priority are shown in Tables A1 to A4.

Table 5 summarises the total cost of implementing the proposed road capacity improvement programme through road widening. As seen in Table 9, the total amount needed for improvement is IDR 264.26 Billion (US $ 17.62 Million). Based on the budgeting system followed by the government, the total sum required is distributed over seven fiscal years. Thus, this case study proposes an annual allocation of IDR 40 Billion (US $ 2.67 Million) as shown in Table 6.

Table 5: Required cost for implementing the proposed improvement

Suggested Improvement	Total estimate (IDR)	Total estimate (US $)
Priority 1	48,681,151,429.00	3,245,410
Priority 2	77,982,274,286.00	5,198,818
Priority 3	126,540,211,429.00	8,436,014
Priority 4	11,060,225,714.00	737,348
Total	**264,263,862,857.00**	**17,617,591**

Table 6: Proportion of budget allocated as per priority in each fiscal year

Year	Priority 1	Priority 2	Priority 3	Priority 4
Year 1	83%			
Year 2	17%	41%		
Year 3		52%		
Year 4		7%	25%	
Year 5			32%	
Year 6			32%	
Year 7			11%	100%

Note: Year 7 will have spare budget

As indicated by Table 6, for the first fiscal year, the majority of budget is allocated to the road network of priority 1. The second year's budget would be allotted for both priority 1 and 2, and so on. It is expected that the road capacity improvement will result in a reduction of the percentage of VCR values for 93 roads along evacuation routes. We ran the network model once again in the end with all improved capacities and note that indeed the VCR values will reduce, as shown in Figure 5.

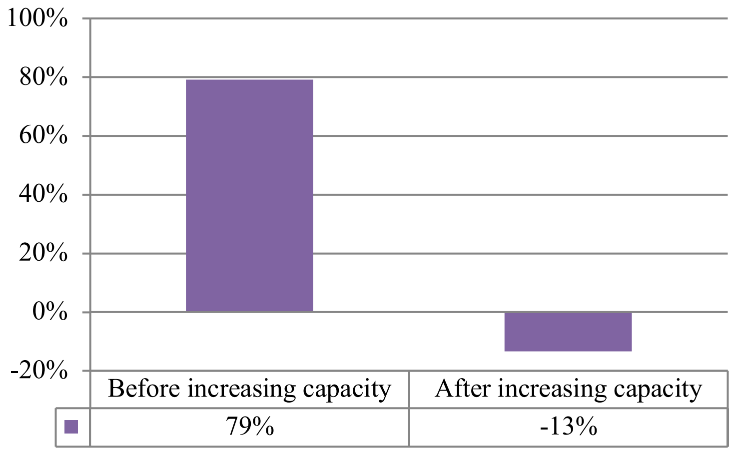

Figure 5: Percentage change in VCR value before and after capacity building

Prior to capacity building, the VCR value of the road network will have increased on an average by 79% during evacuation. However, after building additional capacity for the identified roads, the average VCR value under the evacuation situation is likely to reduce by 13% from the daily situation. Figure 6 shows the reduction of travel time on evacuation route network after road widening.

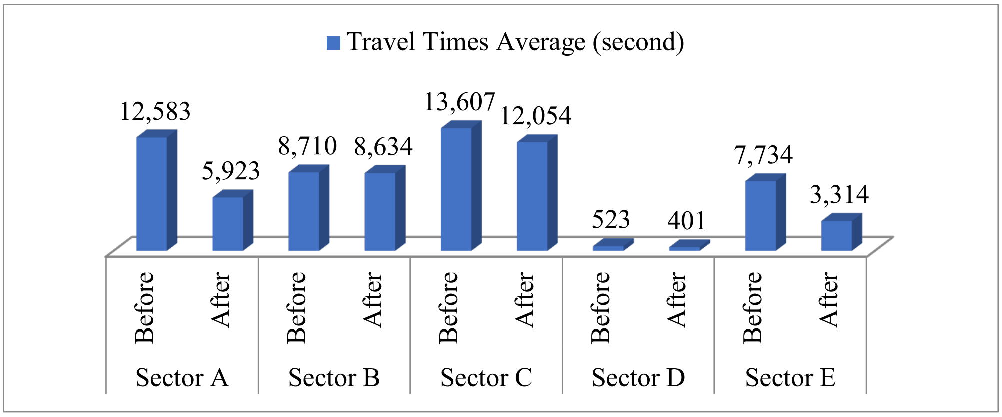

Figure 6: Average travel time by sector – before and after network improvement

5.4 Development of app-based route guidance system

From the analysis presented above, it is clear that SO routing is better than UO routing for the greater good. However, it is worth asking the following key questions as we aim to reduce the danger to life:

(i) Are the residents in disaster prone area aware of the location of sheltered areas?
(ii) Do they know how to reach sheltered areas?
(iii) Are they willing to follow the route guidance, if made available?

To address these questions we have undertaken a survey of respondents in the disruption prone area to find out the characteristics of trips during evacuation. There are 4 sub-districts with 12 villages directly affected by the Merapi eruption in Sleman. We followed the standard as set out by the Directorate General of Highways, Ministry of Public Works and Housing of Indonesia, which recommends a sample size of 2.5% of the total population. In the affected villages, there are 30,453 residents in total, thus the number of samples obtained was 761 persons (@2.5% of 30,453) which were distributed among the villages on a pro-rata basis (See Table 7). The interviews were conducted at homes of randomly selected respondents in each village. From the survey it was noted that 98% of the respondents were exposed to the eruption in 2010, and thus, the sample is deemed to be representative of the realistic response of the population in the affected area.

Table 7: Number of residents in Sleman District

Sub-district	Village	Population	Sample
Pakem	Purwobinangun	3249	81
	Hargobinangun	3200	80
	Candibinangun	2158	54
	Pakembinangun	2303	58
Tempel	Merdikorejo	2321	58
Cangkringan	Argomulyo	2792	70
	Wukirsari	3934	98
	Glagaharjo	1544	39
	Kepuharjo	1216	30
	Umbulharjo	1681	42
Turi	Girikerto	2740	69
	Wonokerto	3315	83
	Total	**30453**	**761**

The survey revealed that 91% residents have access to a motorised vehicle (personal/public), while the remaining 9% rely on walking/cycling. Amongst the motorised modes of transport, 58% use motorcycles, 22% use cars and about 20% use other modes (public transport). On the question, whether the residents are aware of location of the shelters, it is noted that 88% responded positive. However, it is concerning to note that only 67% said they know how to reach sheltered areas, meaning 33% revealed no knowledge of evacuation routes though many of them are aware of their existence. We also learnt from the survey that 69% of the residents are willing to follow the recommended routes to shelters. This means, effectively only 46% (=67% × 69%) residents are aware of the routes to shelters and are willing to follow the advice.

The above survey has major implications to the evacuation planning. It is clear that less than half of the residents are aware of the shelters/evacuation routes, and are willing to follow the advice. Thus, it is extremely important to raise the awareness of location of the shelters to a target population of 12% (=100-88). Secondly, 33% (=100-67) of the population needs to learn about the routes to sheltered areas. Finally, we need to raise the willingness of 31% (=100-69%) of the population to follow the advice provided. It is understood that, in general, the location of shelters is well publicised through posters, display boards located at prominent public places which has resulted in a high awareness of 88%. But, the difficulty with lack of awareness of routes and poor willingness to follow the advice, still persists. While the awareness of location of shelters can be improved by periodic campaigning, raising the awareness of routes and willingness to follow the advice need innovation in our approach. Thus, we came up with the idea of developing a route guidance application to run on mobile phones which can advise them the location of shelters and the routes to reach them as described below.

We aim to develop a route guidance system to deliver via smart phones directly to users which underpins the fact that 66% of the residents in affected area use smart phones. To facilitate the motorcycle users receiving route guidance while driving, the proposed solution includes voice instructions too. This study designed and developed a new piece of software using the Android Studio application on the Jelly Bean version of android operating system. This software is named MEVA, abbreviated as 'Mount MErapi EVAcuation', which aims at informing safe areas such as evacuation shelters, simultaneously providing navigation services. MEVA app is available to download for free via Google Playstore. MEVA application requires 3.91 MB of memory space and is thus quick/easy to download. The smartphone display will show the application installed as in Figure 7. The next step after installing the app on smartphone, is to activate the GPS service (Global Position System). GPS function, in general, determines the location, speed, direction and time of an object on the surface of the earth with the help of satellite signals. It should be ensured that the smartphone device used has this feature turned on, because, MEVA needs GPS support to identify the location of an individual and also the nearest sheltered area. After the GPS service is activated, then the software is ready to use.

Figure 7: App display on smartphone

To obtain the route guidance, the first step is to open the application and the display will appear as in Figure 8. The app will automatically detect an individual's location via GPS activated device and will provide a marker on the map. Furthermore, MEVA will detect nearby shelter locations and recommended routes with estimated time to reach, will be displayed. At the bottom of the display, there is a description of shelter in the form of shelter name, address and distance between the user and shelter. The next step is to press the 'Navigation' button that is the red box at the bottom left of the display to guide the user to the recommended shelter. The final step in running the MEVA app is initiated by pressing the 'start' button on the screen as shown in Figure 13, then MEVA will guide the user to the recommended evacuation shelter by the chosen route option. The navigation function at the end of this app adopts the functionality that runs on the Google Maps app, so that users who have been accustomed to using the service will be able to run MEVA application with ease. This application can be downloaded for free by anyone including the residents of the disaster affected area, as well as tourists visiting the area of Mount Merapi.

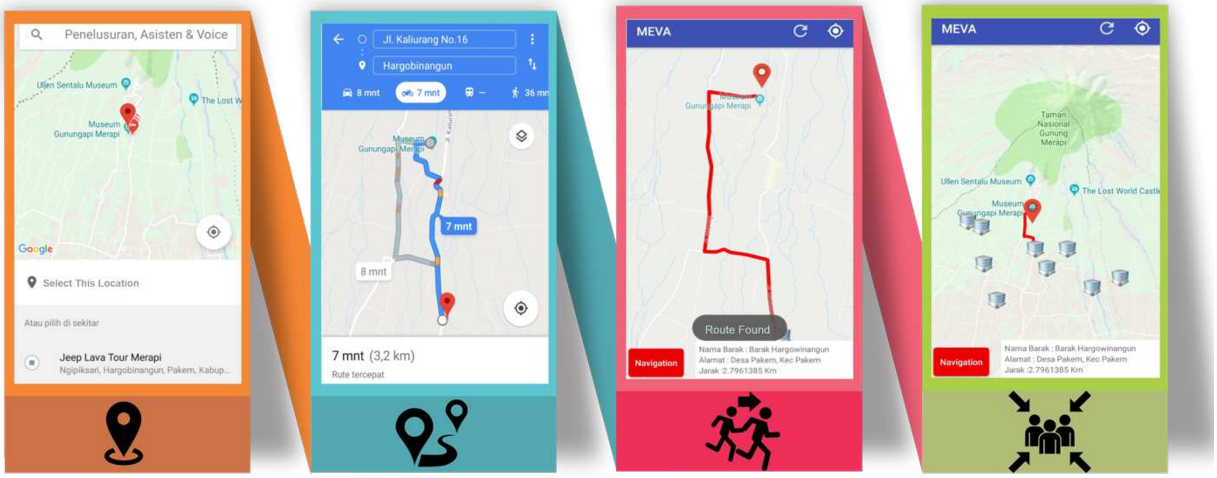

Figure 8: View of MEVA application

6. Concluding remarks

Research on resilience (the opposite of vulnerability) is a growing body of work involving identifying critical network links and preparing evacuation plans. Critical link identification methods assign traffic to network intact, and then, to degraded network to compare the effects. Literature developed a number of indices to identify critical network links which can be improved and/or maintained to ensure a good degree of preparedness in the event of a disaster striking. This research adopted a simple approach to identify critical network links, and enhanced the outcomes by mapping them to a three level congestion scale to prioritise road works involved. This research also notes that only about half of the residents living near Mt Merapi, are aware of, and are willing to follow the evacuation routes to safe locations. An innovative mobile phone application software MEVA has been designed and developed as part of the project to guide the residents to safe areas via the evacuation routes. The main conclusions from this work are as below:

- The SO loading method has a smaller vulnerability value (compared to the UO method), indicating that the evacuation of refugees will be more efficient, if the refugees are directed to shelters than leaving them to find their own way. It is noted that SO envisages some refugees accepting longer travel times for the greater good, though UO assumes travelers to have perfect knowledge of route costs and that they choose routes which minimise their individual travel time. It is also recognised that the willingness of residents to follow the advice is critical to minimise the casualties.
- Based on the classification of road network performance results, 11% of the total number of roads are in need of increasing the capacity. In the affected area, nine roads are in the prime priority, 19 roads in the second priority, 53 roads in the third priority, and 12 roads in the fourth priority category requiring capacity augmentation. Overall, in order to ensure safe evacuation of residents, Yogyakarta needs IDR 264.3B (=US $17.6M) which can be scheduled over seven years by spending a sum of IDR 40B per year.
- 88% of the population is aware of the location of shelters, but only 67% know how to reach them. It is also understood that about 69% of the population is willing to follow the route advice. This implies that less than half the population are aware of, and are willing to follow

the recommended routes to shelters indicating a huge scope to make a significant improvement, if combined with an innovative approach to engage the population.

To mitigate the lack of awareness, there will be a need to educate the residents from time to time informing them the location of shelters and the benefits of following the advice on evacuation routes recommended by the authorities. Short training programmes of using MEVA app may be delivered to increase the compliance of residents, which significantly improves the engagement of the affected persons. The percentage of smartphone users in the affected areas is 66%. Thus, it may not be adequate to rely entirely on the app-based route guidance. The local authorities also have been advised to distribute maps identifying evacuation routes and also to conduct refresher sessions to maintain a good level of compliance. In general, using a motorcycle is very common in Indonesia and to help with this further, the app has been designed to deliver voice instructions too. The simulation model developed in this research drew largely from the experience of the eruption in 2010, however, the findings are still subject to a few limitations. As the information obtained from the interviews is limited by the sample size, any future work should consider a wider sample, perhaps, by using social media.

Acknowledgements

The authors wish to express their gratitude to the Ministry of Research, Technology and Higher Education of the Republic of Indonesia for sponsoring this research (Dikti Grant #22097608, Letter# 0299/E3/2016). Furthermore, the authors thank the Regional Disaster Management Agency of Yogyakarta for providing the information on the 2013 road network of evacuation route plans for Mt Merapi eruption and 2014 scenario of the study of evacuation routes for the vulnerable area in Sleman. The authors also thank Yogyakarta Department of Transportation for providing the daily O-D matrix and evacuation O-D matrix for 2012.

Appendix: Road link improvement schedule

Table A1: Road network enhancement schedule: priority 1

Name	Area (m^2)	Unit Price/m^2	Total Cost (IDR)	Total Cost (USA $)
Jalan Ngentak - Glagahombo	4,353.92	571,428.57	2,487,954,285.71	165,863.62
Jalan Kapitu - Rejodani	3,514.80	571,428.57	2,008,457,142.86	133,897.14
Jalan Karangasem - Kayunan	22,044.96	571,428.57	12,597,120,000.00	839,808.00
Jalan Yogya - Pulowatu	18,151.80	571,428.57	10,372,457,142.86	691,497.14
Jalan Medari - Karanglo	10,127.12	571,428.57	5,786,925,714.29	385,795.05
Jalan Klelen - Kadisono	10,756.48	571,428.57	6,146,560,000.00	409,770.67
Jalan Karanggawang - Soprayan	430.48	571,428.57	245,988,571.43	16,399.24
Jalan Ngentak - Glagahombo	8,357.52	571,428.57	4,775,725,714.29	318,381.71
Jalan Denggung - Kandanen	7,454.94	571,428.57	4,259,962,857.14	283,997.52
Priority 1 Total Cost			**48,681,151,428.57**	**3,245,410.10**

Table A2: Road network enhancement schedule: priority 2

Name	Area (m^2)	Unit Price/m^2	Total Cost (IDR)	Total Cost (USA $)
Jalan Madas - Turi	1,465.23	571,428.57	837,274,285.71	55,818.29
Jalan Madas - Turi	15,026.83	571,428.57	8,586,760,000.00	572,450.67
Jalan Kapitu - Rejodani	2,251.76	571,428.57	1,286,720,000.00	85,781.33
Jalan Yogya - Pulowatu	4,338.60	571,428.57	2,479,200,000.00	165,280.00
Jalan Yogya - Pulowatu	8,101.73	571,428.57	4,629,560,000.00	308,637.33
Jalan Klelen - Kadisono	5,304.48	571,428.57	3,031,131,428.57	202,075.43
Jalan Klelen - Kadisono	1,205.76	571,428.57	689,005,714.29	45,933.71
Jalan Kadisobo - Tepan	4,021.36	571,428.57	2,297,917,142.86	153,194.48
Jalan Mulungan - Karangasem	15,339.94	571,428.57	8,765,677,142.86	584,378.48
Jalan Denggung - Beran	5,083.85	571,428.57	2,905,054,285.71	193,670.29
Jalan Kapitu - Rejodani	3,701.60	571,428.57	2,115,200,000.00	141,013.33
Jalan Beran - Balong	6,303.57	571,428.57	3,602,040,000.00	240,136.00
Jalan Medari - Jogokerten	14,123.20	571,428.57	8,070,400,000.00	538,026.67
Jalan Yogya - Pulowatu	15,629.60	571,428.57	8,931,200,000.00	595,413.33
Jalan Besi - Jangkang	1,611.60	571,428.57	920,914,285.71	61,394.29
Jalan Gentan - Tonggalan	16,569.67	571,428.57	9,468,382,857.14	631,225.52
Jalan Gentan - Tonggalan	7,756.52	571,428.57	4,432,294,285.71	295,486.29
Jalan Rejodani - Ngaglik	7,392.00	571,428.57	4,224,000,000.00	281,600.00
Jalan Ngemplak	1,241.70	571,428.57	709,542,857.14	47,302.86
Priority 2 Total Cost			**77,982,274,285.71**	**5,198,818.29**

Table A3: Road network enhancement schedule: priority 3

Name	Area (m^2)	Unit Price/m^2	Total Cost (IDR)	Total Cost (USA $)
Jalan Tawangharjo - Gondoarum	2,903.28	571,428.57	1,659,017,142.86	110,601.14
Jalan Wonokerto - Jrakah	1,790.46	571,428.57	1,023,120,000.00	68,208.00
Jalan Yogya - Pulowatu	1,560.52	571,428.57	891,725,714.29	59,448.38
Jalan Pelem - Kembangarum	4,298.64	571,428.57	2,456,365,714.29	163,757.71
Jalan Kadisobo - Krandon	3,815.40	571,428.57	2,180,228,571.43	145,348.57
Jalan Gondang - Kembangarum	5,989.45	571,428.57	3,422,542,857.14	228,169.52
Jalan Kadisobo - Krandon	5,133.00	571,428.57	2,933,142,857.14	195,542.86
Jalan Kapitu - Rejodani	2,387.64	571,428.57	1,364,365,714.29	90,957.71
Jalan Kapitu - Rejodani	1,200.81	571,428.57	686,177,142.86	45,745.14
Jalan Kapitu - Rejodani	1,029.66	571,428.57	588,377,142.86	39,225.14
JalanKapitu - Rejodani	1,512.30	571,428.57	864,171,428.57	57,611.43
Jalan Yogya - Pulowatu	1,336.36	571,428.57	763,634,285.71	50,908.95
Jalan Ngentak - Glagahombo	4,545.68	571,428.57	2,597,531,428.57	173,168.76
Jalan Morangan - Ngablak	4,253.16	571,428.57	2,430,377,142.86	162,025.14
Jalan Medari - Kendal	693.40	571,428.57	396,228,571.43	26,415.24
Jalan Pakem - Sedogan	908.00	571,428.57	518,857,142.86	34,590.48
Jalan Ngentak - Ngelo	5,460.84	571,428.57	3,120,480,000.00	208,032.00
Jalan Cungkuk - Ngabean	3,800.28	571,428.57	2,171,588,571.43	144,772.57
Jalan Sedogan - Tunggularum	5,318.73	571,428.57	3,039,274,285.71	202,618.29
Jalan Dadapan - Gondanglegi	6,364.96	571,428.57	3,637,120,000.00	242,474.67
Jalan Ngaglik - Selorejo	10,012.08	571,428.57	5,721,188,571.43	381,412.57
Jalan Dadapan - Gondanglegi	1,044.60	571,428.57	596,914,285.71	39,794.29
Jalan Dadapan - Gondanglegi	3,971.36	571,428.57	2,269,348,571.43	151,289.90
Jalan Ngentak - Glagahombo	1,971.72	571,428.57	1,126,697,142.86	75,113.14
Jalan Yogya - Pulowatu	1,762.84	571,428.57	1,007,337,142.86	67,155.81
Jalan Turi - Gondoarum	1,514.34	571,428.57	865,337,142.86	57,689.14
Jalan Denggung - Beran	7,239.24	571,428.57	4,136,708,571.43	275,780.57
Jalan Ngaglik - Selorejo	6,270.04	571,428.57	3,582,880,000.00	238,858.67
Jalan Ngablak - Toragan	6,569.84	571,428.57	3,754,194,285.71	250,279.62
Jalan Pelem - Kembangarum	2,590.12	571,428.57	1,480,068,571.43	98,671.24
Jalan Medari - Kendal	5,658.88	571,428.57	3,233,645,714.29	215,576.38
Jalan Pakem - Sedogan	1,634.88	571,428.57	934,217,142.86	62,281.14
Jalan Ngablak - Toragan	5,634.32	571,428.57	3,219,611,428.57	214,640.76
Jalan Kembangarum - Pambregan	4,874.20	571,428.57	2,785,257,142.86	185,683.81
Jalan Cungkuk - Ngabean	497.68	571,428.57	284,388,571.43	18,959.24
Jalan Pakem - Sedogan	5,370.76	571,428.57	3,069,005,714.29	204,600.38
Jalan Klangon - Tempel	5,739.40	571,428.57	3,279,657,142.86	218,643.81
Jalan Pelem - Kembangarum	3,285.60	571,428.57	1,877,485,714.29	125,165.71
Jalan Kapitu - Rejodani	1,456.65	571,428.57	832,371,428.57	55,491.43
Jalan Drono - Jabung	5,790.00	571,428.57	3,308,571,428.57	220,571.43
Jalan Kaliurang	1,339.44	571,428.57	765,394,285.71	51,026.29
Jalan Kaliurang	7,929.44	571,428.57	4,531,108,571.43	302,073.90
Jalan Klidon - Dongkelsari	8,782.56	571,428.57	5,018,605,714.29	334,573.71
Jalan Candi - Kopatan	9,000.92	571,428.57	5,143,382,857.14	342,892.19
Jalan Prambanan - Pakem	5,344.55	571,428.57	3,054,028,571.43	203,601.90
Jalan Rogobangsan - Brongkol	9,779.60	571,428.57	5,588,342,857.14	372,556.19
Jalan Grogolan - Kebunan	5,345.70	571,428.57	3,054,685,714.29	203,645.71
Jalan Balong - Kowang	9,990.25	571,428.57	5,708,714,285.71	380,580.95
Jalan Prambanan - Pakem	6,512.95	571,428.57	3,721,685,714.29	248,112.38
Jalan Plataran - Kragilan	3,026.82	571,428.57	1,729,611,428.57	115,307.43
Jalan Ngemplak	1,961.67	571,428.57	1,120,954,285.71	74,730.29
Jalan Rogobangsan - Brongkol	2,445.55	571,428.57	1,397,457,142.86	93,163.81
Jalan Koroulan - Kejambon	2,794.80	571,428.57	1,597,028,571.43	106,468.57
Priority 3 Total Cost			**126,540,211,428.57**	**8,436,014.10**

Table A4: Road network enhancement schedule: priority 4

Name	Area (m^2)	Unit Price/m^2	Total Cost (IDR)	Total Cost (USA $)
Jalan Madas - Turi	2,484.80	571,428.57	1,419,885,714.29	94,659.05
Jalan Madas - Turi	748.03	571,428.57	427,442,857.14	28,496.19
Jalan Madas - Turi	549.05	571,428.57	313,742,857.14	20,916.19
Jalan Prambanan - Pakem	76.66	571,428.57	43,805,714.29	2,920.38
Jalan Cungkuk - Ngabean	2,853.93	571,428.57	1,630,814,285.71	108,720.95
Jalan Madas - Turi	3,215.43	571,428.57	1,837,385,714.29	122,492.38
JalanKomplek Ibu Kota	1,584.28	571,428.57	905,302,857.14	60,353.52
Jalan Babadan - Mindi	964.93	571,428.57	551,385,714.29	36,759.05
Jalan Gentan - Tonggalan	1,289.78	571,428.57	737,014,285.71	49,134.29
Jalan Dayu - Pajangan	2,539.65	571,428.57	1,451,228,571.43	96,748.57
Jalan Prambanan - Pakem	921.04	571,428.57	526,308,571.43	35,087.24
Jalan Besi - Jangkang	2,127.84	571,428.57	1,215,908,571.43	81,060.57
Priority 4 Total Cost			**11,060,225,714.29**	**737,348.38**

References

Anurag (2020) 10 Steps: How to create a successful mobile app https://www.newgenapps.com/blog/10-steps-to-create-a-successful-mobile-application/ website accessed 26 May 2020

Bagloee, S.A., Sarvi, M., Wolshon, R., Dixit, V., (2017). Identifying critical disruption scenarios and a global robustness index tailored to real life road networks. Transportation Research Part E 98, 60-81.

Balijepalli, C., & Oppong, O. (2014). Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography*, *39*, 145–155. http://doi.org/10.1016/j.jtrangeo. 2014.06.025

Beckmann, M.J., McGuire, C.B. and Winsten, C.B. (1956) Studies in the Economics of Transportation. Yale University Press, New Haven.

Berdica, K. (2002). An Introduction To Road Vulnerability: What Has Been Done, Is Done And Should Be Done. *Transport Policy*, 9(2), 117–127. http://doi.org/10.1016/S0967-070X(02)00011-2

Bilova, M., Bíl, M., Vodák, R., & Kubec, J. (2015). Evaluating Road Network Damage Caused By Natural Disasters In The Czech Republic Between 1997 And 2010, 80, 90–103. http://doi.org/10.1016/j.tra.2015.07.006

Bureau of Public Roads, (1964). *Traffic Assignment Manual,* Washington, DC: US Department of Commerce.

Chen, B, Lam, W.H.K., Sumalee, A., Li, Q. and Li, Z-C. (2012) Vulnerability analysis for large-scale and congested road networkswith demand uncertainty, *Transportation Research Part A*, 46, 501-516.

Directorate General Bina Marga & Directorate of Urban Road Development (Binkot). (1997). Indonesian Highway Capacity Manual (IHCM) 1997. Jakarta.

El-Rashidy, R.A., Grant-Muller, S., (2014). An assessment method for highway network vulnerability. *J. Transp. Geogr*. 34, 34–43.

Fisher, R.V., Heiken, G., and Hulen, J.B., 1997, Volcanoes; Crucibles of Change. Princeton, Princeton University Press.

Hardiansyah, Priyanto S, Muthohar I, Suparma BS. (2018). Identifying Road Network Vulnerability During Disaster Cased study: Road Network Evacuation in Merapi Eruption. *Songklanakarin Journal of Science and Technology SJST-2017-0428.R2*

Jenelius, E., Petersen, T., & Mattsson, L.-G. (2006). Importance And Exposure In Road Network Vulnerability Analysis. *Transportation Research Part A: Policy and Practice*, 40(7), 537–560. http://doi.org/10.1016/j.tra.2005.11.003

Jenelius, E., & Mattsson, L. (2012). Road Network Vulnerability Analysis Of Area-Covering Disruptions : A Grid-Based Approach With Case Study. *Transportation Research Part A*, 46(5), 746 – 760. http://doi.org/10.1016/j.tra.2012.02.003

Jousset, P., Pallister, J., Boichu, M., Buongiorno, M. F., Budisantoso, A., Costa, F., Lavigne, F. (2012). The 2010 Explosive Eruption Of Java's Merapi Volcano — A “100-Year” Event. *Journal of Volcanology and Geothermal Research*, 241 – 242, 121 – 135.

Ki, S. J. (2016). Social Vulnerability At A Local Level Around The Merapi Volcano. *International Journal of Disaster Risk Reduction*, 20(October), 63–77. http://doi.org/10.1016/j.ijdrr.2016.10.012

Knoop, V. L., Snelder, M., Zuylen, H. J. Van, & Hoogendoorn, S. P. (2012). Link-Level Vulnerability Indicators For Real-World Networks. *Transportation Research Part A*, 46(5), 843–854. http://doi.org/10.1016/j.tra.2012.02.004

Miller, D.L., et al., (2008). The Role of Transit in Emergency Evacuation. Transportation Research Board of the National Academies, Washington, D.C.

Murray-Tuite, P., Wolshon, B., (2013). Evacuation transportation modeling: an overview of research, development, and practice. *Transp. Res. Part C* 27, 24–44.

Nagurney, A., & Qiang, Q. (2007). A Transportation Network Efficiency Measure That Captures Flow, Behavior And Cost With Applications To Network Component Importance Identification And Vulnerability. Proceeding of the POMS 18th Annual Conference, 83(2), 447 – 478. http://doi.org/http://dx.doi.org/10.1016/0304-405X(86)90051-6

Otani, K., Legono. D., Darsono, S., & Suharyanto. (2018). Effects of Disaster Management Programs on Individuals' Preparedness in Mount Merapi. Journal of the Civil Engineering Forum, 4 (1), 79-90. https://doi.org/10.22146/jcef.29580

Pel, A.J., Bliemer, M.C.J., Hoogendoorn, S.P., (2012). A review on travel behavior modelling in dynamic traffic simulation models for evacuations. *Transportation* 39 (1), 97–123.

Penafiel Mera, A.W. and Balijepalli, N.C. (2020) Towards improving resilience of cities: an optimisation approach to minimising vulnerability to loss of road network capacity due to natural disasters under budgetary constraints, *Transportation*, 47(4), 1809-1842. https://doi.org/10.1007/s11116-019-09984-8

Reggiani, A., Nijkamp, P., & Lanzi, D. (2015). Transport Resilience And Vulnerability : The Role Of Connectivity. *Transportation Research Part A*, 81, 4–15. http://doi.org/10.1016/j.tra.2014.12.012

Scott, D. M., Novak, D. C., Aultman-Hall, L., & Guo, F. (2006). Network Robustness Index: A New Method For Identifying Critical Links And Evaluating The Performance Of Transportation Networks. *Journal of Transport Geography*, 14(3), 215–227. http://doi.org/10.1016/j.jtrangeo.2005.10.003

Taylor, M. a P., Sekhar, S. V. C., & D'Este, G. M. (2006). Application Of Accessibility Based Methods For Vulnerability Analysis Of Strategic Road Networks. *Networks and Spatial*

Economics, 6 (3–4), 267 – 291. http://doi.org/10.1007/s11067-006-9284-9

Tyas, E., Mei, W., Fajarwati, A., Hasanati, S., & Meilyana, I. (2016). Resettlement following the 2010 Merapi volcano eruption. Procedia - Social and Behavioral Sciences, 227 (November 2015), 361 – 369. http://doi.org/10.1016/j.sbspro.2016.06.083

Van Vliet, D. (2015). *SATURN 11.3.12: User Manual.* Leeds, UK: Institute for Transport Studies, University of Leeds.

Wang, D. Z. W., Liu, H., Szeto, W. Y. & Chow, A. H. F., 2016. Identification of critical combination of vulnerable links in transportation networks – a global optimisation approach. *Transportmetrica A: Transport Science,* 12(4), p. 346–365.

Wardrop, J. G. 1952. Some theoretical aspects of road traffic research. ICE Proceedings: Engineering Divisions, Thomas Telford, 325-362.

Yang, X., Ban, X. and Mitchell, J. (2018) Modeling multimodal transportation network emergency, evacuation considering evacuees' cooperative behavior, *Transportation Research Part A*, 114, 380-397

Yuan, F., Han, L., Chin, S.M., Hwang, H., (2006). Proposed Framework for Simultaneous Optimization of Evacuation Traffic Destination and Route Assignment. *Transportation Research Record: J.* Transp. Res. Board 1964, 40–48.

Yuan, F., Puchalsky, C.M., (2014). Multimodal evacuation simulation and scenario analysis in dense urban area: a Philadelphia case study. Transp. Res. Record: J. Transp. Res. Board 2532, 91–98.