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METHODOLOGY

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Integrating criticality concepts into road network disruption assessments for volcanic eruptions

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Abstract

Road networks in volcanically active regions can be exposed to various volcanic hazards from multiple volcanoes. Exposure assessments are often used in these environments to prioritise risk management and mitigation efforts towards volcanoes or hazards that present the greatest threat. Typically, road exposure has been assessed by quantifying the amount of road network affected by different hazards and/or hazard intensity. Whilst this approach is computationally efficient, it largely fails to consider the relative importance of road segments within the network (i.e., road criticality). However, road criticality is an important indicator of the disruption that may be caused by an eruption. In this work, we aim to integrate road criticality concepts to enhance typical volcanic eruption road exposure assessments into road disruption assessments. We use three key components to quantify disruption: a) road criticality, b) impact severity, and c) affected road quantity. Two case study eruptions: Merapi 2010 and Kelud 2014, both in Java, Indonesia, are used to demonstrate the usefulness of integrating road criticality into road disruption assessments from volcanic eruptions. We found that disruption of the road network from the Kelud 2014 case study was an order of magnitude greater than the Merapi 2010 case study. This is primarily driven by the more widely dispersed tephra fall from the Kelud 2014 event, which affected nearly 28% of Java's road network length, compared to Merapi 2010, which affected 1.5%. We also identified potential disruption hotspots that were affected by both of these case study eruptions. At Merapi, roads that carry traffic directly away from the summit, those that cross major valleys, and the major Yogyakarta-Magelang highway were key disruption hotspots, which has implications for moving large volumes of traffic efficiently, such as in an evacuation. The Kelud case study highlighted the potential impacts of widespread tephra falls on socio-economic activity and connectivity of large urban centres. Our approach has been designed such that it can be applied entirely using open-sourced datasets. Therefore, the approach to integrating road criticality in this paper can be used, applied, and adapted to assess road network disruption at any volcano in the world.

Keywords: Functionality loss, Impact assessment, Exposure assessment, Criticality assessment, Infrastructure

Introduction

Road networks contain important links that enable the movement of people and goods between and within geographically dispersed communities. Disruptions to road networks can occur when either nodes (e.g., road intersections) or links (i.e. the road connecting the nodes) within the network have to operate under a reduced functionality and/or become completely inoperable (Zhu and Levinson 2012; Diakakis et al. 2020). This introduces inefficiencies such as route changes to avoid congestion, or barriers to movement within the network such as bridge failures (Zhu and Levinson 2012; Diakakis et al. 2020). Disruptions of various levels of severity can

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manifest through mechanisms such as accidents, maintenance works, or impacts from natural hazard events (e.g., earthquakes, severe weather and flooding, tsunami, or volcanic eruptions) (Zhu and Levinson 2012). Due to the importance of roads to society, cascading effects from disruption to road networks can then flow onto other infrastructure and socio-economic systems (Rinaldi et al. 2001; Kotzanikolaou et al. 2013; Sword-Daniels et al. 2015). Road disruption and the corresponding cascading effects can also be detrimental during emergencies and disasters as it can exacerbate the negative consequences by delaying emergency access and inhibit recovery operations (Little 2002; Boin and McConnell 2007; Xie et al. 2014; Alexander 2018). Thus, evaluating the exposure of road networks to potential disruptions is an important aspect of mitigating the impact of disasters and identifying long-term resilience initiatives.

Performance of road networks under disruptive conditions is an active area of research within the transportation risk assessment and resilience literature, for both non-specific disruptions (Sullivan et al. 2009, 2010; Zhu and Levinson 2012; Jenelius and Mattsson 2012; Bhavathrathan and Patil 2015), and frameworks for specific hazards such as earthquakes (Costa et al. 2020) and flooding (Lu et al. 2015). A wide variety of metrics such as travel cost, accessibility, traffic flow, and quality of service have been used to measure network performance under normal and disruptive conditions (see the following for detailed review of existing approaches: Sullivan et al. 2009; Zhu and Levinson 2012; Nakat et al. 2015; Mattsson and Jenelius 2015; Hardiansyah et al. 2019; Jafino et al. 2020). Such metrics are often computed using detailed attribute data of the road network under consideration (e.g., topology, travel speed, capacity, traffic flow, and traffic lights), but these analyses are often impeded by two aspects. Firstly, detailed datasets required for such analyses are often proprietary and time-consuming to produce and maintain (Brovelli et al. 2017). Open- and crowd-sourced road network datasets (e.g., OpenStreetMap; OSM) are increasingly more up to date than proprietary ones, but in many parts of the world lack the quantity and quality of attributes needed to run detailed analyses (Haklay 2010; Ludwig et al. 2011; Brovelli et al. 2017). Secondly, these types of analysis are often computationally intensive to run at larger than local scales (e.g., regional or global) (Bagloee et al. 2017). This makes evaluating potential disruption in data limited contexts challenging.

Volcanic eruptions can disrupt road networks through multiple different mechanisms, both direct (e.g., physical damage) and indirect (e.g., implementation of evacuation/exclusion zones) (Blong 1984; Wilson et al. 2014; Blake et al. 2017a, 2018). A complicating factor when assessing the potential impacts to roads is that volcanic eruptions are intrinsically multi-hazard events, and these different volcanic hazards can manifest at different times through an eruption sequence, spatially around a volcano, and to differing degrees of intensity (Kappes et al. 2012; Hayes et al. 2020; Selva et al. 2020). Thus, the resulting severity of impacts on the road network can be heterogenous in space and time (Blake et al. 2017b). For example, for the same eruption some areas may only be subject to minor nuisance impacts (e.g., reduced visibility), whilst others may have roads completely impassable due to burial from deposits (Wilson et al. 2014; Blake et al. 2018). Further, in volcanically active regions, it is common that exposure of road networks to volcanic hazards can come from multiple different source volcanoes spread across a large region. For example, Java, Indonesia contains 36 volcanoes that exhibit varying eruption styles and frequency (Global Volcanism Program 2013; Whelley et al. 2015; Jenkins et al. 2018), which could affect the road network. National Route 1, which forms part of the Asian Highway Network (Abdul Quium, 2018), is approximately 1,300 km in length and spans the entire length of the island, linking many of the major metropolitan areas of Java (Fig. 1). Jakarta is potentially exposed to tephra fall from at least 19 different volcanoes, each with differing hazard characteristics (Jenkins et al. 2018). Therefore, it is challenging to prioritise research initiatives to investigate resilience or vulnerability of road networks in such environments, particularly given the intensive computational and data requirements to run such analyses.

One typical approach to evaluate the relative impact different volcanoes or eruption scenarios may pose to society is to conduct an exposure assessment. In this context, an exposure assessment is where the type and number of assets (e.g., buildings or roads) likely to be affected by volcanic hazards are evaluated. Volcanoes or scenarios can then be ranked by a given exposure metric (Brown et al. 2015; Osman et al. 2019). For road networks, quantifying the length of road affected by a volcano or an eruption scenario, often characterised by road hierarchy and hazard intensity, has previously been applied (Biass et al. 2017; Osman et al. 2019). However, the length of road affected is just one component that contributes towards the overall disruption of a road network and the flow-on effects to society. The criticality of different road links (i.e. how important each is to overall functionality of the system) and the degree to which they are affected (e.g., quantitative measure of functionality loss) is also of importance (Balakrishnan and Zhang 2020). A measure of road criticality is important because the more critical the road segment (i.e. a link between two or more nodes within a road network data model) the more severe the resulting consequences to society can be (Jenelius et al.

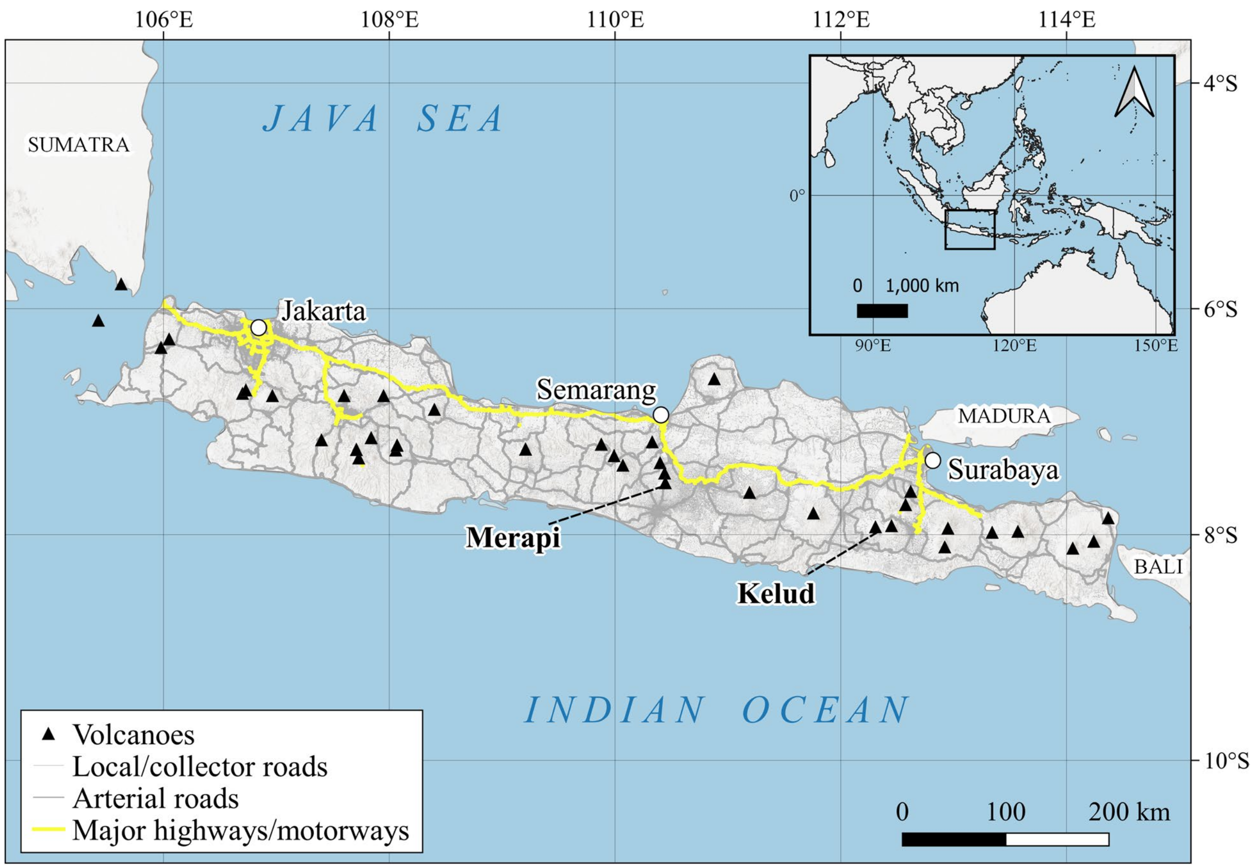

Fig. 1 Roads and Holocene volcanoes of Java, Indonesia. Roads data from OpenStreetMap (OSM) and volcano location from (Global Volcanism Program 2013). The two case study volcanoes of Merapi and Kelud are highlighted, as are major cities. Inset: Location of Java (within box) relative to southeast Asia

2006; Jafino et al. 2020). For example, disruption of a road segment that is the only route for evacuation for a community may result in fatalities if people are unable to exit high hazard/risk zones or if responders are unable to access an affected area in an emergency (Kim et al. 2019). This was an issue of consideration following the 2015 Calbuco eruption, Chile, where responding authorities made specific arrangements to maintain a key evacuation route to ensure connectivity between communities that may have needed to evacuate in the event of further eruptions (Hayes et al. 2019). Similarly, roads that lead to critical infrastructure facilities such as power plants, are important to ensure workers are able to access the site and minimise electricity service disruption (Comes and Walle, 2014; Dong et al. 2019).

Road segment criticality has previously been used to evaluate the potential consequences of disruptive events such as traffic accidents or natural hazards (Sullivan et al. 2010; Rupi et al. 2015; Togia et al. 2019; Kumar et al. 2019; Jafino et al. 2020). However, relatively few studies have considered this concept for volcanic eruptions (Blake et al. 2017b; Mossoux et al. 2019). Blake et al. (2017b) utilised stakeholder engagement as a method to dynamically explore the level of service roads would be able to sustain during and following an eruption. Whilst this is an effective approach to evaluate potential disruption, the intensive stakeholder engagement component makes this difficult to apply on a large scale or to large numbers of volcanoes. Mossoux et al. (2019) evaluated how important segments are within a road network by removing each segment iteratively from the network to investigate the effects of a complete blockage due to lava flow inundation. This approach could be applied across a wide area, but road segments might not always be completely blocked by the spectrum of different volcanic hazards, and instead exhibit a reduced level of service (e.g., reduced speed limits). Therefore, there is a need for an approach that can balance computational costs and resource requirements whilst integrating concepts of criticality to obtain a more robust indication of disruption to road networks from volcanic eruptions.

In this work, we have developed a generic and widely applicable approach that quantifies potential disruption using globally available open- and crowd-sourced data sets. Our approach can be used to evaluate and rank the severity of road disruption from volcanic eruptions. There are two applications we suggest this approach could be used for. The first approach is to evaluate the severity of disruption within a given scenario to consider roads likely to be heavily disrupted. The second is to compare overall disruption scores for an entire road network can be ranked and compared across scenarios, eruptions and volcanoes. This allows the analyst to identify particularly disruptive scenarios or volcanoes, or compare the disruption from historic eruptions.

We use two case studies to demonstrate the utility of the approach, based on the Merapi 2010 and Kelud 2014 eruptions in Indonesia (volcano locations shown in Fig. 1). In what follows, we present an overview of the rationale that underpins our approach. We then evaluate the criticality of Java's roads, and examine how the two case studies differ in their modelled disruption and reported impacts. Finally, we discuss the implications for road disruption on Java, the limitations of the approach developed in this paper and where future research could build upon it.

Method

Conceptual overview of road network disruption analysis

Our intention was to develop a road disruption assessment framework that produces first-order estimates of disruption that can be used to rank different volcanoes, volcanic hazards, and/or eruption scenario-sets, and identify potential disruption hotspots. To do so, we structured our analysis around three indicators that characterise different components of road disruption: a) road criticality, b) impact severity, and c) length of road affected. We characterise each of those components for each road segment. A length of road can be segmented in a number of ways (e.g., equal length segmentation), but we use the segmentation within OpenStreetMap, which are the links between nodes and intersections. Road criticality was used to provide an indication of the level of importance of each road segment, under the assumption that more disruption to society will occur if important road segments suffer a reduced functionality. This is because high criticality roads may have a high degree of: a) interdependencies for other critical infrastructure systems (e.g., maintaining access to electricity supply sites), b) dependence for every-day socio-economic activities (e.g., education, security, shopping), and c) the efficient movement of people and goods. The impact severity defines the level of service loss for a road segment. This is important because volcanic eruptions can affect road networks in different ways with different levels of severity (Wilson et al. 2014; Blake et al. 2017c). For example, some segments may only require speed restrictions, whilst others may require complete closure (Blake et al. 2017c). Finally, the length of road affected was used to provide an indication of the spatial extent of disruption and the level of resources and/or time required to restore functionality. This indicator was used under the assumption that—all other aspects being equal—larger quantities of road will take more resources and/or time to restore. The road criticality indicator was evaluated across the entire road network under consideration, whilst the impact and length of road indicators were evaluated at the scale of each individual scenario, hazard, or volcano. This approach allows scenarios, hazards, or volcanoes to be compared across a consistent road criticality dataset. We elaborate on each of these three indicators and how they were assessed in the subsections that will follow.

We used an amalgamated scoring system assessing each of these three indicators (Fig. 2). For each eruption scenario, scores were assigned to each affected road segment based on criteria outlined in the subsections below. Road criticality, impact severity, and length of road scores for each road segment were equally weighted and multiplied together to produce a Road Segment Disruption Score (RSDS). We kept each facet of the RSDS equally weighted to so that we can explore how each influences the RSDS. All RSDS values were summed to produce an overall Road Network Disruption Score (RNDS) for the affected road network under consideration. Each disruption scenario or volcano can then be ranked using this common measure of disruption. The scoring system for each of the three RNDS components is described below. Python code used in this analysis is available at: www.github.com/vharg/RNDS.

Road criticality score

In this work, we sought to obtain a measure of criticality that can fully utilise open-source datasets and can be applied for large-scale analysis. To do so, we built upon the road criticality framework presented in Rebello et al. (2019), with some modifications outlined in the sections below. There are three elements to the criticality framework:

1. Road hierarchy (e.g., motorway, arterial road, residential road)
2. Access to important sites (e.g., international border entry points, power stations)

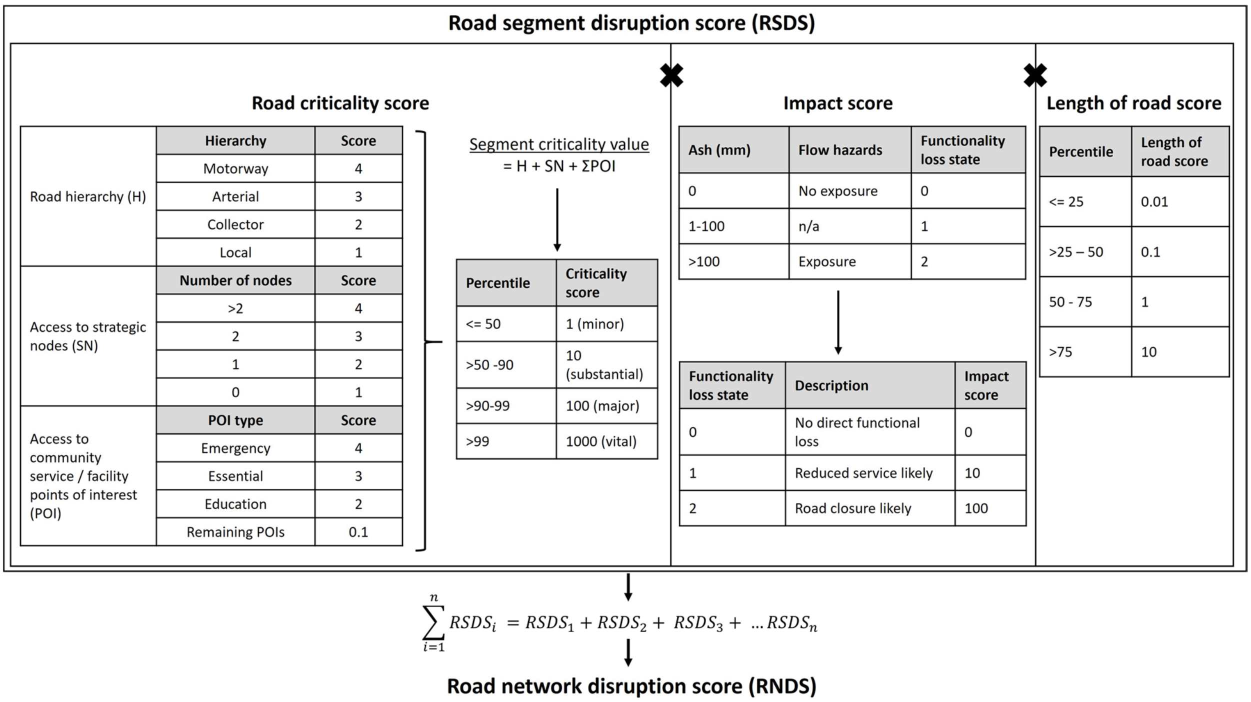

Fig. 2 Approach to calculate the RNDS. Scores are assigned based on criteria described in the Methods section

Table 1 Data types and sources used in this study to conduct road criticality assessment

Data type	Data Source	Date obtained
Airports	https://ourairports.com	3 June 2020
Amenities and roads	OSM: https://download.geofabrik.de/asia/indonesia.html	26 November 2020
Border crossings	World Food Programme, Logistics Cluster: https://data.humdata.org/dataset/global-border-crossing-points	4 June 2020
Power plants	Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. 2018. Global Power Plant Database. Published on Resource Watch and Google Earth Engine; http://resourcewatch.org/ https://earthengine.google.com/	7 February 2020
Sea ports	World Port Index from OCHA: https://data.humdata.org/dataset/world-port-index	4 June 2020

3. Access to community facilities and services (e.g., hospitals, supermarkets)

To determine the criticality of a road segment, each of the above three components were weighted and then summed to produce a road segment criticality value. For simplicity, in this work we assumed equal weighting for all criticality components. Road segment criticality values were then classified by the percentile that each road segment criticality value falls within, across the entire road network (Fig. 2). Road segment criticality was scored using percentile bins and assigned a criticality score (1, 10, 100, 1,000) and classification (minor, substantial, major, vital) (Fig. 2). We chose to use percentile bins rather than absolute scores because we wanted to weight the relative criticality of each road segment into an order of magnitude scale. The percentile bins were chosen based on the assumption that road networks will contain many more roads of minor criticality than vital criticality in the overall system. Whilst different weighting systems for each criticality component could be used (e.g., relatively higher weighting towards access to important sites) the effect of the weighting is not likely to be influential given that each segment is subsequently scored based on the percentile range it falls within. Since percentile bins are used, the criticality of any given road is relative to the spatial scale of the analysis being undertaken. For instance, a road may be of little or moderate importance at a regional or national scale, but of high criticality at a local village scale if it is the only ingress/egress route.

Table 2 Road network hierarchy scoring system used in this study

Hierarchy classification	OSM classification	Score
Motorway	Motorway; Motorway link	4
Arterial	Trunk; Trunk link; Primary; Primary link	3
Collector	Secondary; Secondary link; Tertiary; Tertiary link;	2
Local	Unclassified; Residential; Living street; Service; Road; Unknown	1

Our analysis undertaken here considered criticality at the scale of Java, Indonesia, but the approach can be applied at any scale.

We used OSM data, supplemented by specialised open-source geospatial datasets, to conduct our road criticality assessment for Java, Indonesia (Table 1). The reason for restricting our analysis to data that can be openly obtained was to ensure the methodology is transferable across study areas and does not rely upon proprietary datasets. Whilst additional critical infrastructure sites could be used in this analysis (e.g., waste water treatment plants, electricity substations), we opted to restrict ourselves to global datasets that are actively being maintained to limit the potential for geospatial biases to enter the analysis.

Road hierarchy

A road hierarchy describes how road objects are defined based upon their function and capacity within a road network, broadly inferring a degree of criticality (Rebello et al. 2019). Motorways/highways are designed to provide high-speed and high-volume traffic flow, and typically occupy the top of a road hierarchy. Local roads on the other hand are usually low traffic volume and designed to provide access to housing, and typically occupy the lower portion of a road hierarchy. This structure provides a useful indicator of number of road users that could be affected. Thus, an assumption we made in this work was that the number of road users affected is related to road hierarchy class. For example, loss of service on a motorway will disrupt more road users than roads occupying lower levels of the road hierarchy (e.g., a local road). The OSM road classification system includes 17 different road types, and it can be challenging to make a specific distinction between the importance of each of these classifications. Therefore, we simplified the OSM road classification into four categories of road hierarchy (Table 2). We used an ordinal scale to assign scores to each hierarchy class, with a value of four being the highest score and occupying the top of the road hierarchy (Table 2). We excluded roads classified as pedestrian from the analysis to avoid classifying many walking tracks that are common on volcanoes.

Access to important infrastructure sites

There are a number of important infrastructure sites that need to maintain functionality before, during, and after disasters to facilitate socio-economic activities and ensure disaster response and recovery is efficient. Roads that lead to these sites need to be functional to allow access for activities such as maintenance and repairs or their continued use. For example, maintaining the supply of electricity during a volcanic eruption may require cleaning of components at power supply sites (Wardman et al. 2012). International border entry sites (e.g., seaports and airports) are important for maintaining trade and providing entry points for foreign humanitarian aid to flow into affected areas and evacuation for small island settings. Thus, we considered access to important infrastructure sites as an indicator of road segment criticality. To do so within our framework, we treated each critical infrastructure utility site (power station, airport, seaport) as points within the road network and assigned a score to each segment of road depending on the number of these critical infrastructure points that fall along that road segment. To assign a point to any given road segment, each point is automatically moved to its nearest road segment. We limited movement of points to a maximum of 500 m, this meant that if a point was more than 500 m from its nearest road it was excluded from the analysis. The reason for this is that some of the datasets we use are global, and so we wanted to prevent clearly inaccurate assignment of points that were very far away from road segments in our analysis (i.e., in other countries). Our choice of 500 m as a limit was to ensure that points such as airports or seaports, which may have their point geospatially located hundreds of metres from the nearest road, are still captured within the analysis.

Access to community services and facilities

Access to community services and facilities is an important component contributing to the liveability of an area and the wellbeing of its inhabitants (Guite et al. 2006; Leby and Hashim 2010). Further, maintaining access to essential services during a disaster is important for public health (e.g., healthcare facilities), emergency response (e.g., police and fire stations), and sustenance (e.g., local marketplaces, supermarkets) (Sword-Daniels et al. 2015). OSM contains a large database of community facilities such as those described above. Thus, we used the full OSM dataset for Indonesia and filtered using the command line Java application, 'Osmosis',[1] for 'nodes' (as characterised in the OSM data structure) that have the key: "Amenities".

[1] Details of the Osmosis application can be found at: https://wiki.openstreetmap.org/wiki/Osmosis and the GitHub repository: https://github.com/openstreetmap/osmosis

Table 3 Priority scores for different amenities used in this study

Service class	OSM features included in class	Score
Emergency	Hospital; Fire station; Police; Rescue station	4
Essential	Supermarket; Prison; Waste transfer station; Lighthouse; Social facility; Bank; Shelter; Pharmacy; Water well; Dentist; Doctors; Embassy; Town hall; Public building; Water tower; Nursing home; Courthouse; Fuel; Consulate; Chemist; Veterinary	3
Educational	Kindergarten; School; Library; College; University	2
Non-essential	All remaining	0.1

Different community services and facilities may hold different levels of priority for an affected community. For example, access to a medical facility may be considered more critical than access to a restaurant. Therefore, we assigned amenities to one of four service classes and assigned different scores to each (Table 3). The priority scores were chosen to reflect a simple ordinal scale from facilities that are likely to have a high priority during an emergency or disaster (e.g., emergency services) compared to non-essential services. Amenities are then assigned to their nearest road segment that falls within a 50 m radius. We have chosen a smaller radius here than for the strategically important sites because amenities are not likely to be located on large property lots that extend hundreds of metres from the nearest road in the same way an airport or seaport might be. This also aids computational efficiency. An overall priority score for a given road segment was then calculated by summing all priority scores along that road segment. For example, a road segment with a hospital (priority score = 4), supermarket (priority score = 3), and kindergarten (priority score = 2) would result in an access to community services/facilities value of nine.

Impact score

The impacts from volcanic eruptions on ground transportation networks are diverse. Proximal volcanic hazards such as lahars, lava flows, and pyroclastic density currents (PDCs) cause severe damage to roads, often with the consequence that an affected road becomes impassable for a period of time due to thick sediment deposition, flow inundation, scouring and/or bridge damage (Blong 1984; Wilson et al. 2014; Dagá et al. 2018). Cracks and fissures in roads can also occur due to thermal effects from the flows or from ground deformation associated with volcanism (Blong 1984; Wilson et al. 2014), whilst ballistic impacts can cause irregular depressions in the road surface (Blong 1984; Wilson et al. 2014; Blake et al. 2015). The impacts from tephra fall on roads are not typically destructive, but are disruptive and widespread, even at relatively modest thicknesses of a few millimetres (Blong 1984; Wilson et al. 2012; Blake et al. 2017c). Visibility can be severely reduced during tephra fall or as a consequence of remobilisation of tephra (Blake et al. 2018). Tephra deposits can obscure road markings and reduce skid resistance of the road surface, which can contribute to increased accident rates (Blong 1984; Wilson et al. 2012; Blake et al. 2017a). Roads can also become impassable at high and unconsolidated deposit accumulations (Blong 1984; Blake et al. 2017c). Thus, the diversity of impacts and their severity meant that it was important to include a grading of severity in our analysis.

We classified impact severity by considering three levels of functionality loss state (FLS): no direct functionality loss likely (FLS 0), reduced service likely (FLS 1), and road closure likely (FLS 2) (Fig. 2). No direct functionality loss means that the road can largely operate as usual. Reduced service means that the road may require speed restrictions whether they be enforced formally, by authorities, or informally, by drivers self-moderating their speed due to hazardous driving conditions. These roads might be expected to have higher incidence of traffic jams and accidents until full functionality is restored. Road closure means that the road is likely to require closure for debris clearance or consolidation and/or cooling of the material before it is able to be driven on again. Note, these functionality loss states do not consider how long the functionality loss will remain. This is because functionality loss will be conditional on the efficiency of road maintenance activities and decision-making from authorities, which we did not consider in this analysis.

To assess functionality loss, we used a framework that links hazard intensity thresholds with functional loss states (FLS) (Fig. 2). Impact scores were then mapped to road segments as per the schema in Fig. 2. For tephra, we used the thresholds outlined in Jenkins et al. (2015b) with some modifications based upon Blake et al. (2017c). We assumed a binary impact threshold for flow hazards, where no exposure means the FLS is 0, and where exposure occurs the FLS is 2. For consistency, if a road segment was co-incident with a hazard layer, the entire road segment was assigned the appropriate FLS, even if it is only a partial overlap. When hazards overlap in space, we adopted the highest FLS. Functionality loss was only assigned from direct exposure to a hazard and not from indirect functionality loss due to impacts or inefficiencies elsewhere within the road network (i.e. our analysis did not operate as a graphical network).

Length of road score

The length of road affected will play a role in how fast disruption can be reduced through clean-up and/or repairs. More resources will be required to restore functionality where large quantities of road are affected because impacts will be more widely distributed. To determine a length of road score, we again classified road segments by percentiles based on their length, with each increasing percentile class being scored as an order of magnitude greater than the previous class (Fig. 2). We chose this percentile-based scoring system rather than using the absolute length of road to avoid the length of road having an undue influence on the overall disruption score. For example, a road that is very long but is low criticality and experiences a low level of impact may become high disruption if absolute lengths are used. The scoring system was designed so that relatively vast road segments (likely time- and resource-intensive to restore) had a multiplicative effect, but small lengths (likely quicker and less resource intensive to restore) reduced the overall disruption score for that segment.

Selected case studies

We selected two volcanic eruptions within Southeast Asia to demonstrate the applicability of the approach: 1) Merapi 2010, and 2) Kelud 2014. To select these case studies, we opted to consider eruptions for which we could obtain either quantitative or qualitative information relating to road network disruption so we could compare modelled disruption with reported disruption. Both eruptions were Volcanic Explosivity Index (VEI) 4 and caused significant damage to the built environment (Jenkins et al. 2013; Williams et al. 2020). Published maps detailing the hazardous phenomena were digitised to obtain hazard footprints and intensity (Fig. 3).

Merapi 2010

The November 5 paroxysm phase of the 2010 eruption of Merapi produced southward-directed PDCs from dome explosion and collapse, and a 14–17 km-high plume that dispersed tephra to the SW (Jenkins et al. 2013; Komorowski et al. 2013; Pallister et al. 2013). Soon after this paroxysm, rainfalls started remobilising loose pyroclastic material into lahars that have affected roads and settlements (de Bélizal et al. 2013; Jenkins et al. 2015a).

National Route 14 connecting Yogyakarta with Magelang and Semarang was affected by tephra fall in 2010 and lahars in 2011 (de Bélizal et al. 2013; Solikhin et al. 2015; Jenkins et al. 2015a). Reported impacts from the eruption indicated that most of the roads affected by PDCs were covered with deposits a few cm to tens of cm thick (Jenkins et al. 2013). Lahars were reported to be a large driver of road network disruption by damaging roads and bridges, with 21 bridges and 14 Sabo dams being destroyed during the rainy season following the eruption (de Bélizal et al. 2013). National Route 14 (N14 on Fig. 7) in particular was affected by lahar activity for months following the eruption, each time requiring debris clearance and traffic diversions through a narrow mountain road, which caused substantial traffic jams in the area (de Bélizal et al. 2013). Unfortunately, we were unable to find any source material indicating the severity of disruption caused to roads leading into Yogyakarta from tephra.

Kelud 2014

The February 13 2014 eruption of Kelud volcano was a Plinian eruption with a VEI of 4. PDCs ran out to 4.7 km from the vent (Goode et al. 2019), and the eruption developed a strong plume with the top of the umbrella cloud reaching an elevation of 18–19 km asl (Kristiansen et al. 2015). One key characteristic of the 2014 Kelud eruption was the bilobate tephra deposit that resulted from wind shear, with southerly winds at an elevation of ~6 km and the easterly winds above (Kristiansen et al. 2015). The elevation of the main tephra emission was estimated at ~17 km, where strong easterly winds drove tephra accumulations of up to 2 cm thick in Yogyakarta, more than 200 km away from the volcano (Kristiansen et al. 2015; Maeno et al. 2019).

In Yogyakarta it was reported that the government advised people to remain off the roads unless travel was necessary due to the tephra fall (Blake et al. 2015). Bus operations also completely ceased within the city for four days, and it took ~10 days before service was fully restored (Blake et al. 2015). We also identified Surabaya and National Route 1 as disruption hotspots, although we were unable to identify literature that reports on road network disruption specifically for these locations. However, given that a few centimetres of tephra fell on these locations and Surabaya airport was closed for two days (Blake et al. 2015; Maeno et al. 2019), we anticipate that road disruption was evident.

The 2014 Kelud eruption was reported to have severely damaged roads close to the volcano through lahars, ballistic impacts, and heavy tephra fall (Blake et al. 2015). Damage to the road network in proximal areas disrupted access to the Kelud crater and local villages, with about 1 km of road reportedly closed for several months. Four bridges were destroyed by lahars in Kali Konto due to sporadic lahar activity up to several months following the eruption (Dibyosaputro et al. 2015). Major clean-up operations were reportedly required in the Kediri regency and thousands of buildings collapsed/were damaged due to the heavy tephra deposition (IFRC 2014; Blake et al. 2015; Williams et al. 2020).

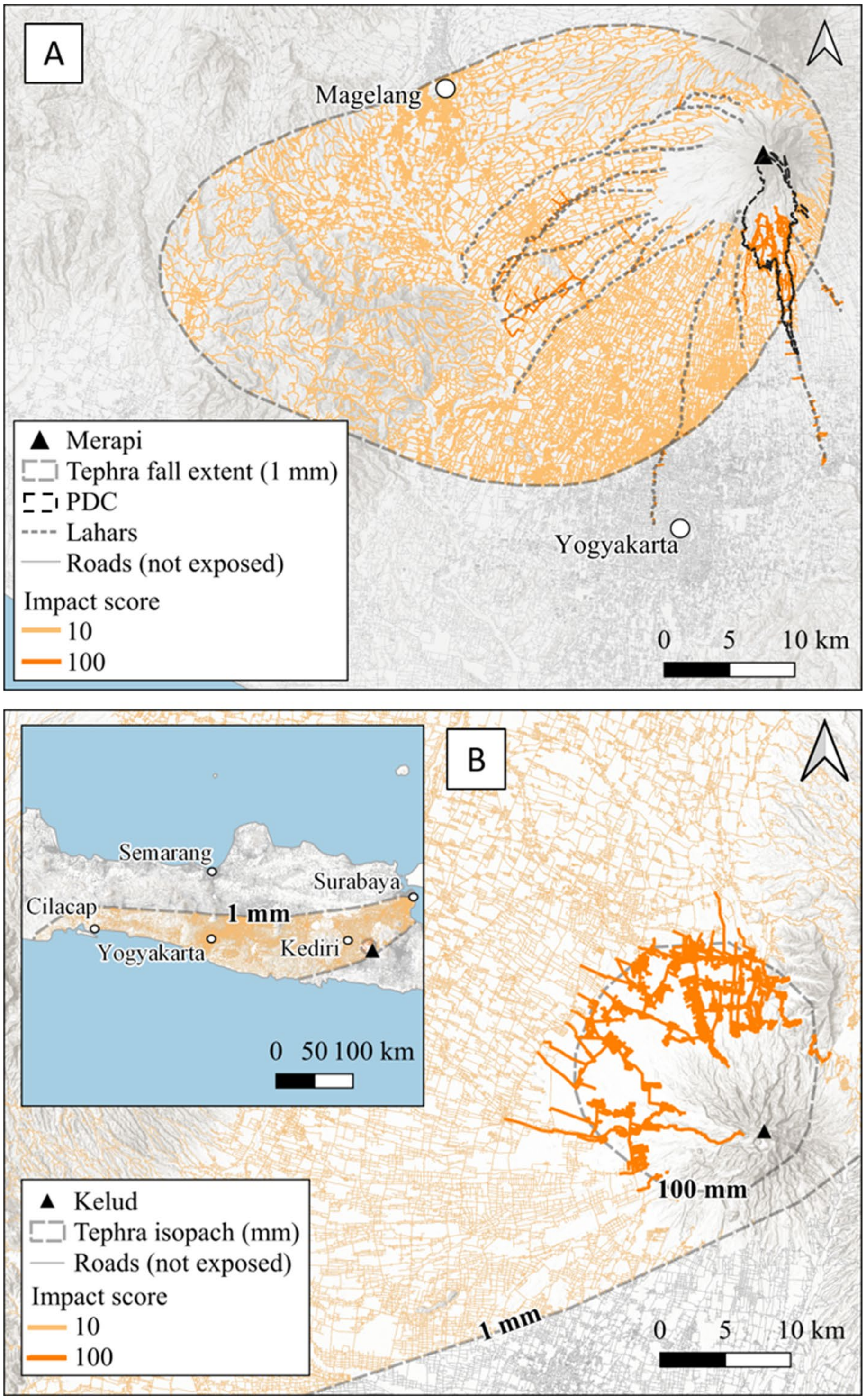

Fig. 3 Map of hazard extent and impact scores for each case study: **A**) Merapi 2010, and **B**) Kelud 2014. Derived from published tephra isopach maps and lahar/PDC footprints for the eruptions of **A** Merapi 2010 (de Bélizal et al. 2013; Jenkins et al. 2013; Komorowski et al. 2013; Solikhin et al. 2015) and **B** Kelud 2014 (Maeno et al. 2019). Note that for Merapi 2010, no tephra accumulation > 100 mm impacted the road network

Table 4 Criticality classification of the Java road network, following the 'Road criticality score' approach outlined in Fig. 2

Criticality class	Criticality score	Number of segments	Length (km)	% total road network length
Minor	1	2,039,369	396,419	86
Substantial	10	0	0	0
Major	100	85,840	60,599	13
Vital	1,000	11,925	6,685	1
All	-	2,137,134	463,704	100

Results

Road criticality in Java, Indonesia

There is approximately 460,000 km of road in Java based upon the OSM data set we have used in this analysis. Of this total road length, our approach classified 86% of roads as having minor criticality, 0% as substantial criticality, 13% as major criticality, and 1% as vital criticality (Table 4). The reason 0% of roads were scored as substantial criticality was because 95% of individual road segments obtained the same road criticality value (0.33). In this instance the 25th, 50th, and 75th percentiles were the same value and so obtain the same criticality score (criticality score = 1 = minor criticality) (Fig. 2).

Using kernel density estimation for the location of important site points unsurprisingly yielded major urban centres such as Jakarta, Yogyakarta, and Surabaya, as major hotspots (Fig. 4A). In addition, other smaller cities (Cilegon, Cirebon, and Cilacap) where ports are located that feature a relatively dense distribution of important infrastructure sites (Fig. 4A). Cilegon is a major industrial city and is one of the largest producers of steel in Southeast Asia (Yeoh 2021). The city also contains the Port of Merak, which is a key transport link between Sumatra and Java. Cirebon is the only coastal city within the West Java province and contains a port that primarily receives goods from other Indonesian ports. Cilecap is a sea port town, and one of only a few that service the southern coast of Java. Taking the same approach for access to community facilities and services, and weighting for priority score, we also found these concentrated within the major urban centres (Fig. 4B). However, the port cities barely registered using this metric, indicating the usefulness of considering access to important infrastructure sites in the analysis. The geographical distribution of the road hierarchy across Java also highlights the important links between population centres and port cities (Fig. 4C). Thus, whilst the major population centres are obvious hotspots of system level disruption, strategically important locations and the roads that link them together could be the cause of considerable flow-on effects for wider disruption on Java, which is why these cities and the roads that link them together were scored as high criticality (Fig. 4D). In particular, the vital route (National Route 1) linking Jakarta to Semarang and on to Surabaya is prominent (Fig. 4C-D). Sporadic and isolated high criticality roads are seen across the map and often associated with main roads of smaller cities, towns, and villages (Fig. 4D).

The similarity between road hierarchy and road criticality can be seen by comparing Fig. 4C and Fig. 4D, where there appears to be similarity between motorways and high criticality values, but this does not translate through to roads lower on the road hierarchy (e.g., arterial/collector/local roads). This perhaps supports the rationale of using road hierarchy as a proxy for road criticality at large scales. However, road hierarchy alone may not capture the same level of detail as using explicitly defined criticality indicators, such as those used in this study, and the same comparability may not be evident for other locations around the world.

Modelled disruption

Case study one: Merapi 2010.

Our approach calculated that the Merapi 2010 case study affected ~ 7,000 km of road (~ 1.5% of total road length) and ~ 29,000 road segments (~ 1.4% of all road segments) on Java (Table 5). We obtained a RNDS for the Merapi 2010 case study of 1.5×10^7. Of the affected road segments, only a small proportion (~ 0.4% of segments or ~ 1% by length) were classed as vital criticality within our criticality framework (Fig. 5A-B), but the disruption of these vital road segments contributed to around a quarter of the RNDS value (Fig. 6A). Most of the affected roads (98% of the affected segments or 97.1% of the affected road length) were affected by small accumulations of tephra, and so were classed as FLS 1 (Fig. 5C-D). Despite only ~ 2% of affected road segments (~ 2.9% by length) being assigned FLS 2, these roads contribute to approximately ~ 26% of the total RNDS value (Fig. 6C). A largely even proportion of all road segment length classes were affected by this case study (Fig. 5E-F). Of the total RNDS, 91% was made up of road segments with a RSDS

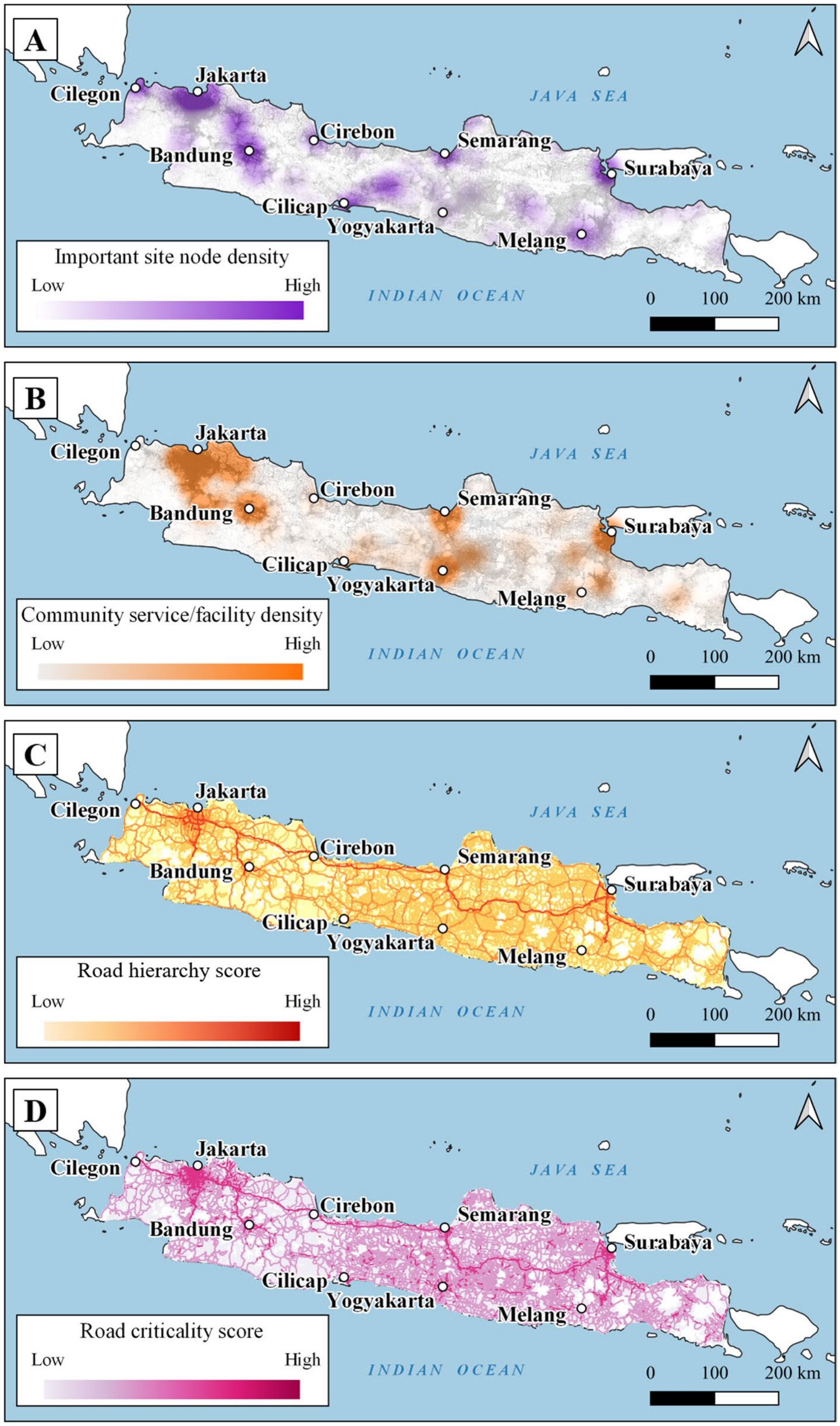

Fig. 4 Road importance characteristics on Java. A) kernal density heat map of important sites, **B**) kernal density heat map of community services/facilities weighted by priority score, **C**) road hierarchy on Java, and **D**) Road criticality map for Java. Note: grey lines on A and B are roads, which are displayed for context

Table 5 Quantification of affected road segments and length for each disruption metric

Metric	Score	Segments		Length (km)	
		Merapi	Kelud	Merapi	Kelud
Criticality[a]	1 (Minor)	28,249 [1.4]	505,900 [24.8]	6,071 [1.5]	108,808 [27.4]
	100 (Major)	1,092 [1.3]	20,869 [24.3]	969 [1.6]	17,300 [28.5]
	1,000 (Vital)	50 [0.4]	1,904 [16]	67 [1.0]	1,275 [19.1]
Impact[b]	10 (FLS 1)	28,888 [1.4]	526,647 [24.6]	6,915 [1.5]	126,780 [27.3]
	100 (FLS 2)	503 [0.02]	2,026 [0.1]	193 [0.04]	603 [0.1]
Length of road[c]	0.01	5,770 [1.1]	114,516 [21.4]	174 [1.2]	3,197 [21.4]
	0.1	7,275 [1.4]	123,165 [23.1]	525 [1.4]	8,907 [23.1]
	1	7,616 [1.4]	133,788 [25]	1,073 [1.4]	18,915 [24.3]
	10	8,730 [1.6]	157,201 [29.4]	5,322 [1.6]	96,364 [28.7]
All[c]	-	29,391 [1.4]	528,673 [24.7]	7,094 [1.5]	127,383 [27.5]

[a] Numbers in square brackets are the percentages of the total road network that has been assigned that criticality score.

[b] Numbers in square brackets are the percentage of the total Java road network.

[c] Numbers in square brackets are the percentages of the total road network that has been assigned that length of road score.

of ≥ 10,000 (Fig. 6D). However, these high RSDS roads made up only 2% of all affected road segments (~ 14% of the affected road length) (Fig. 5G-H).

A map of RSDS for the Merapi 2010 eruption is presented in Fig. 7, which can be used to identify potential road network disruption hotspot locations. Modelled disruption was concentrated in areas of PDC inundation to the south of Merapi, roads leading into Yogyakarta, and National Route 14 connecting Yogyakarta with Magelang and Semarang. Our modelling suggests roads leading to Yogyakarta could also be a disruption hotspot. We note the disruption may be inflated on the road segments denoted by the 'a' and 'b' labels on Fig. 7. This is because our approach automatically assigned amenity or important site points to road segments based on the closest road within a given threshold distance, but the closest road to the point is not always the best road to assign the point to. Thus, model outputs should be carefully interpreted at this level of detail.

Case study two: Kelud 2014

We estimated that ~ 127,000 km of road (~ 27.5% of total road length) and ~ 529,000 road segments (~ 24.7% of all road segments) were affected by the eruption (Table 5). The RNDS for the Kelud 2014 case study was calculated as 2.3×10^8. Of all affected road segments for this case study, ~ 0.4% were classed as vital (~ 1% of affected road length) (Fig. 5A-B). Disruption of vital road segments contributed to ~ 45.5% of the total RNDS value (Fig. 6A). Roads assigned an impact score of 10 (FLS 1) amounted to 99.6% of all affected road segments (99.5% of the total length of affected roads) (Fig. 5C-D), and account for approximately 98% of the RNDS value (Fig. 6C). A largely even proportion of all road segment length classes were affected by this case study (Fig. 5E-F). Approximately 2.2% of road segments (14.2% of affected road length) had an RSDS of ≥ 10,000 (Fig. 5E-F), which contributed to over 90% of the total RNDS (Fig. 6D).

Modelled disruption for the Kelud case study indicated widespread disruption across Java (Fig. 8A). This disruption appears to be particularly evident in the port city of Cilacap (Fig. 8B), major urban centres of Yogyakarta (Fig. 8C), and Surabaya (Fig. 8E), and the motorways that connect them. We also found that roads within 10–20 km of Kelud were hotspots for disruption (Fig. 8D), which is indicative of the heavy tephra fall and impact severity that occurred within this area (Maeno et al. 2019).

Case study comparison

Whilst the proportionality for each of the disruption indicators for both case studies were similar (Fig. 5), there was an order of magnitude difference in RNDS between the two case studies. This indicates that the Kelud 2014 case study was considerably more disruptive to the wider road network than the Merapi 2010 case study. This is in agreement with the eruptive styles of both eruptions, with Merapi 2010 being the magmatic paroxysm of a sequence of dome growth and explosions and Kelud 2014 being a Plinian eruption that was sufficiently intense to develop an umbrella cloud. As a result, the Kelud 2014 case study affected more roads overall, and a greater proportion of vital road segments than the Merapi 2010 case study (Fig. 5A), which are major drivers of disruption within our framework. The Kelud 2014 case study affected ~ 16% of vital road segments on Java, compared to just 0.4% for the Merapi

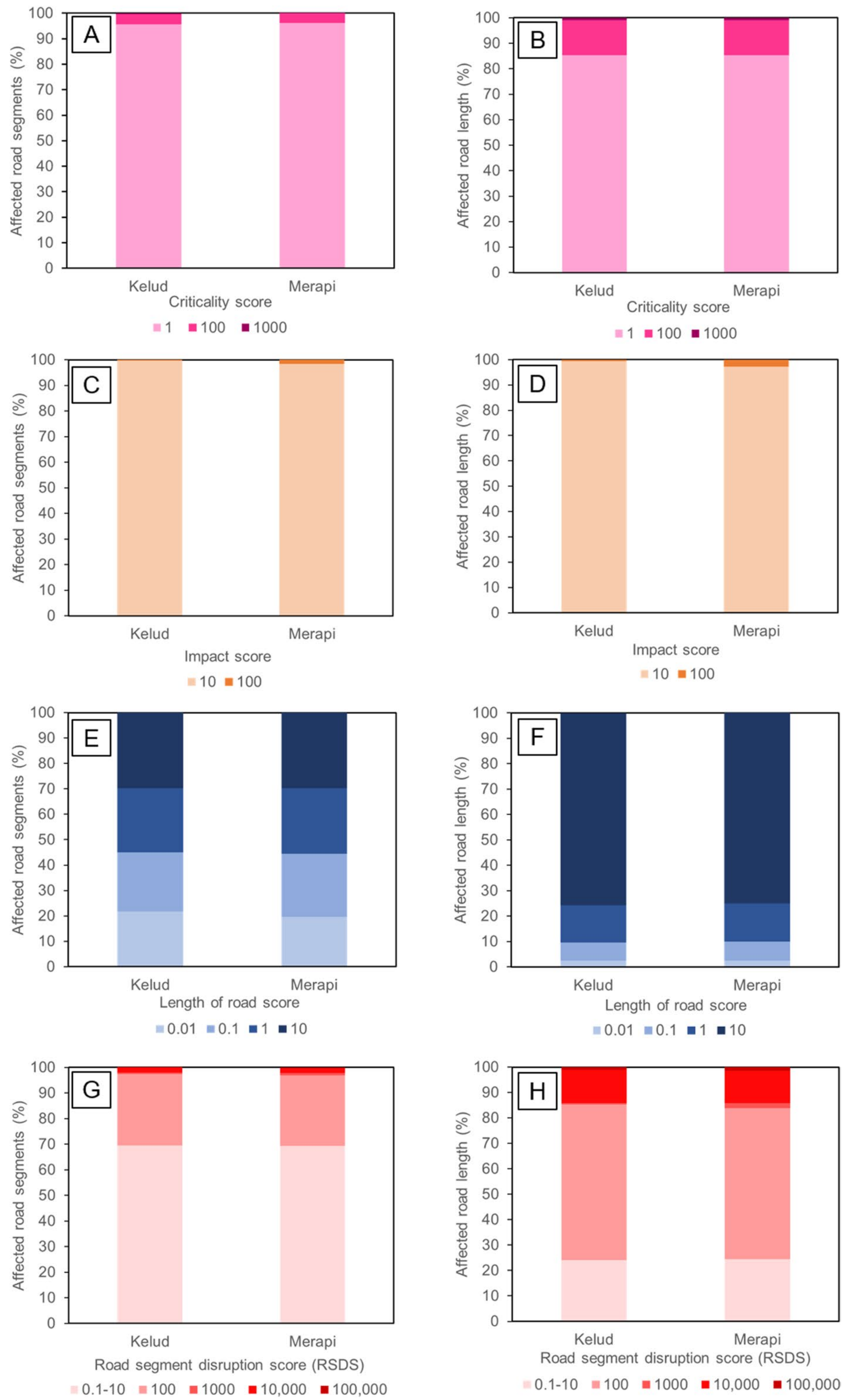

Fig. 5 Percentage of affected road segments and lengths assigned scores for **A**-**B**) Criticality, **C**-**D**) Impact, **E**-**F**) Length of Road, and **G**-**H**) Road Segment Disruption Score (RSDS)

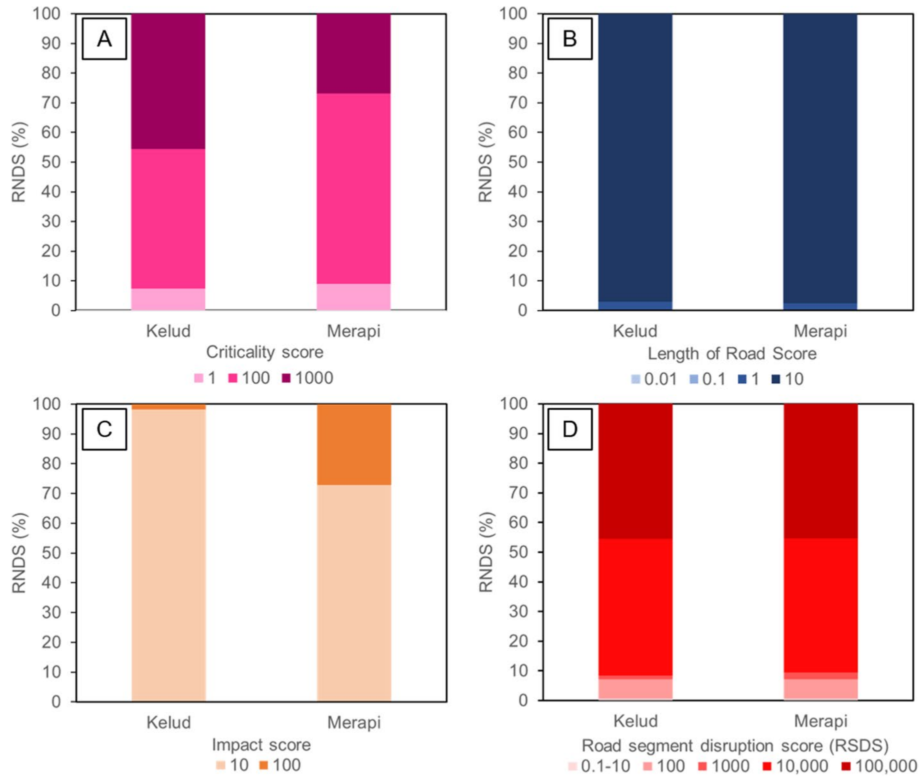

Fig. 6 Percentage of the total RNDS value for **A**) Criticality, **B**) Length of road, **C**) Impact, and **D**) Road Segment Disruption Score (RSDS)

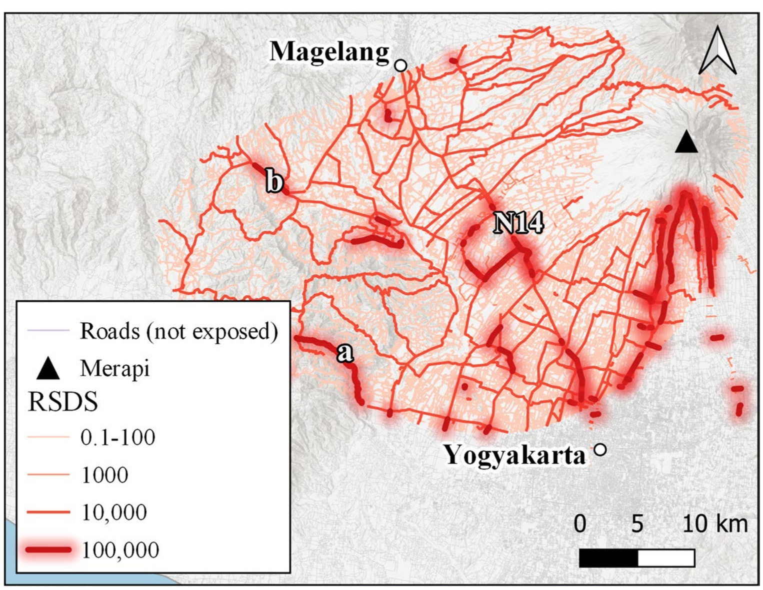

Fig. 7 RSDS results using the Merapi 2010 event as hazard input. See text for explanation of points a and b, and N14 (National Route 14). RNDS value = 1.5×10^{7}

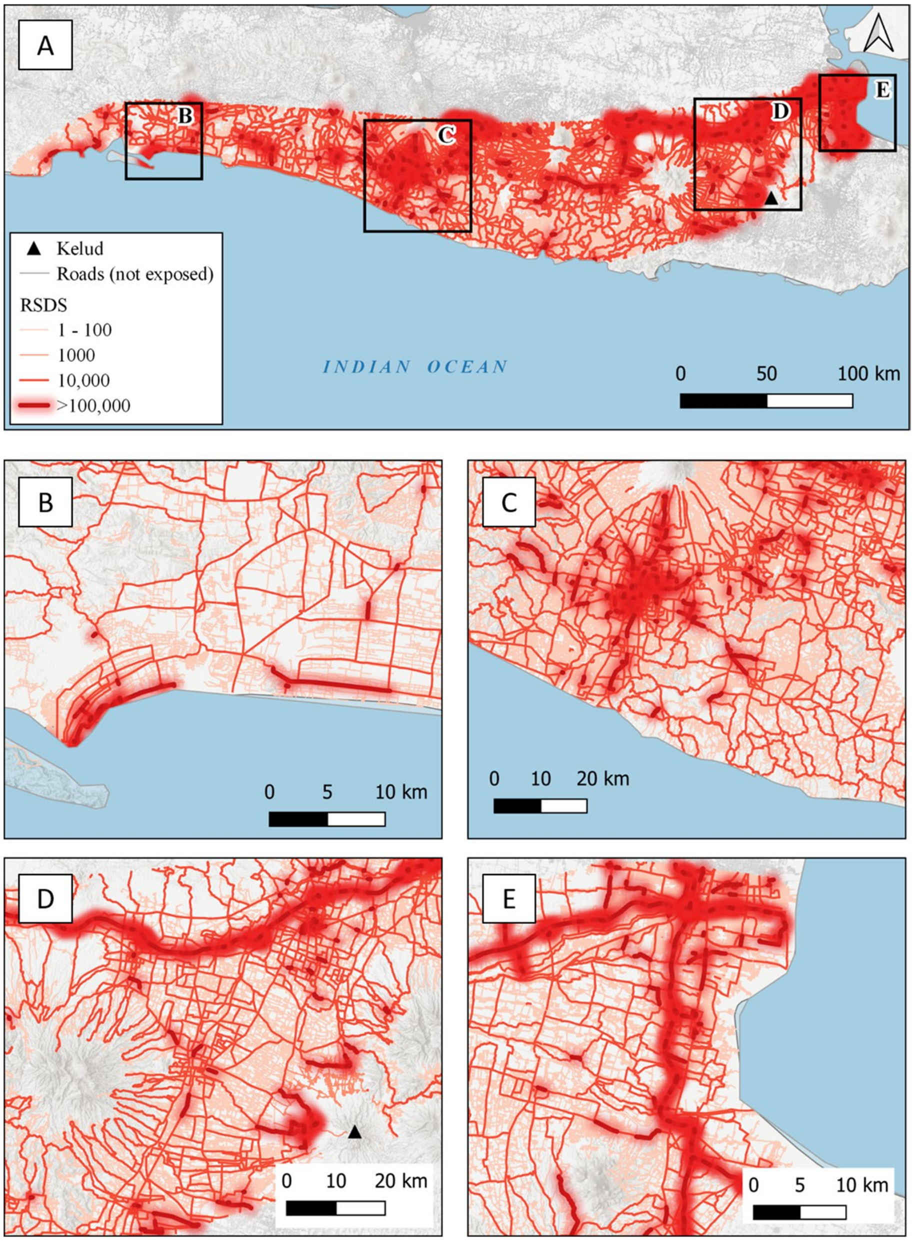

Fig. 8 RSDS results using the Kelud 2014 event as hazard input. RNDS value = 2.3 × 10.[8]. **A**) Overview map of RSDS spanning West, Central and East Java; **B**) Cilicap; **C**) Yogyakarta. **D**) Kediri, and **E**) Surabaya

2010 case study. Both case studies had the vast majority of the total RNDS value coming from roads at functionality loss state one, which is indicative of the wide spread disruptive nature of tephra fall. However, for the Merapi 2010 case study, a larger proportion of the disruption was driven by the proximal effects from PDCs and lahars compared to proximal hazards from the Kelud 2014 case study (26% compared to 2% of RNDS respectively).

Discussion

Using and adapting the RNDS

The approach presented in this paper provides a structured method to quantify potential road network disruption from volcanic eruptions. Of importance was the inclusion of road segment criticality, an element that has received limited attention in road network exposure assessments for volcanic eruptions (Mossoux et al. 2019). The fundamental purpose of this approach is to identify priority areas for further research, disaster and long-term resilience planning using more detailed road vulnerability or resilience analysis techniques. Thus, it is not intended to provide an absolute quantitative estimate on disruption, but rather assess the relative potential for volcanoes, eruptions, or scenarios to cause differing levels of disruption to socio-economic activities.

In this study we used open-source data relating to services and infrastructure important for societal functionality across Java. However, other studies could also be undertaken that investigate potential disruption at a finer grained resolution (e.g., individual city or community) and the criticality indicators and scoring system may differ from those used in this study. For example, a community that is likely to require a full evacuation during an eruption may incorporate key emergency egress routes and score these highly, whilst access to other community amenities may be considered inconsequential due to this evacuation and scored lower (or even omitted). Therefore, our intention with the framework presented here is to highlight the utility of including criticality metrics within road disruption assessments, and any number of indicators could be used.

Whilst the scoring system used in this study was based on subjective estimates, we consider this superior to the commonly used practice of solely using length of road affected as a measure of road exposure. This is because the decision to omit other characteristics about the importance of the road is a subjective choice usually taken without explicitly defined justification. Specific scoring values do not necessarily need to be implemented exactly as we have done so in this work, but the broad overarching principles of using criticality, impact, and length of roads affected is a simple, adaptable, and transferrable method to obtain an estimate of disruption for purposes of ranking of disruptive scenarios, hazard types, or volcanoes. Therefore, what is important is that the subjectivity is contextualised by transparent rationale that underpins the choices in the scoring system. To moderate the effect of subjective values in this work, we have used order of magnitude scales and assign scores based on percentiles. This is advantageous in this use-case as we were assessing relatively high-level/coarse-grained characteristics of disruption from different eruptions. Other studies may opt to take a community-driven approach where stakeholder's views regarding the importance of different attributes are incorporated via various community-based participatory methods.

The two case studies used in this paper demonstrate some of the varying characteristics that can occur when volcanic hazards affect road networks. The widespread nature of the Kelud 2014 tephra fall meant that disruption was also widespread, affecting several large cities. The implications of this were sizable, but temporary, reductions in urban functionality and socio-economic activities in these cities. Whilst for the Merapi case study, the disruption was more concentrated due to the nature of the eruptive activity. At the scale of the entire road network this meant that the Kelud 2014 eruption caused island-wide disruption that amounted to an order of magnitude greater RNDS than for the Merapi case study. However, the disruption caused by tephra fall is typically concentrated to the immediate aftermath of the eruption (excepting remobilisation), while lahars can continue over many years (as in the case of Merapi). This illustrates the differing spatial, temporal and disruptive scale of consequences that can be produced by volcanoes to the road network. Java contains 36 volcanoes, each with the potential to affect the road network in a number of ways. Identifying the volcanoes that are most likely to cause disruption, and the manner that they may cause disruption would be of value to informing emergency planning and research priorities. For example, identifying and differentiating between the volcanoes likely to cause substantial disruption due to widespread tephra deposition on large urban areas (e.g., Jakarta) and those volcanoes that might cause severe but relatively localised disruption. This would provide insights into the different approaches that could be taken for disaster risk reduction. In the case of volcanoes producing widespread urban disruption, considering the implications to supply chains and conducting tephra clean-up planning will be useful planning exercises for how to manage road network disruption caused by an eruption from a given volcano (Wilson et al. 2012; Hayes et al. 2015). On the other hand, locally specific hazard and risk studies will be of value for volcanoes that are assessed as likely to produce severe but localised disruption. As an example, a volcano identified as having the potential to cause severe localised disruption from lahars may warrant further analysis that refines lahar hazard and risk assessments to identify specific risk mitigation options. Risk mitigation in this situation could include incorporation of anticipated road disruption within community outreach, disaster planning programmes, and, where appropriate, specific engineered solutions and land-use planning (Lavigne 1999; Pierson et al. 2014; Andreastuti et al. 2015; Cho et al. 2016; Lestari et al. 2018). These analyses may also identify underappreciated risks, which could be particularly important for volcanoes that have not been active for hundreds of years, but have the potential to cause substantial disruption.

The approach is also well suited to be applied within a long-term resilience planning framework that aims to inform long-term infrastructure investment and asset management strategies. We have shown how using this approach can assist in identifying volcanoes, hazards, or even criticality hotspots likely to be the cause or source of considerable disruption during natural hazard events. Ranking of volcanoes, hazards, or specific scenario event sets by the corresponding RNDS value then facilitates identification of priority research areas. In addition, particular road segments that have high disruption scores across many different scenarios may indicate areas of particular concern for long-term resilience enhancement. More in-depth investigation of these areas using typical road vulnerability and resilience methodologies that are more computationally intensive can then be confidently undertaken to confirm initial results and identify potential asset redundancy and investment options.

Indirect disruption

In this analysis we demonstrated that the RNDS value was being driven by relatively few high RSDS road segments. It is important to recognise that these high RSDS road segments could cause disruption to propagate further through the road system. Asset redundancy may also reduce potential disruption as it reduces reliance upon any given road segment due to the potential for multiple road segments to be used for the same purpose. The analysis undertaken here does not capture potential propagating impacts within the road system, nor potential redundancy within the road network, because both would require graphical models to be used. However, potential disruption hotspots can be identified, which allows for triaging of research efforts to focus in-depth and resource intensive analysis (e.g., using graph theory or agent-based modelling) on these hotspot locations. These hotspots would be defined as areas that will suffer severe disruption with the potential to propagate regionally. Such areas may be at risk from several different volcanoes and different volcanic hazards. Thus, a transparent approach to prioritising in-depth investigations is particularly important in regions with high numbers of source volcanoes, such as Java, Indonesia.

Disruption can also be caused by decisions that are made by authorities. For example, the establishment of evacuation and/or exclusion zones will have substantial disruptive effects on road networks within and near the affected areas. In this work, we have not implemented any decision-derived disruption. Consideration of evacuation and exclusion zones in impact or exposure assessments has typically been undertaken at an individual community scale and in collaboration with emergency managers and local communities or using pre-established evacuation policies (Zuccaro et al. 2008; Deligne et al. 2017). Whilst decision-derived effects are likely to cause substantial disruption to road networks, the criteria they rely upon requires detailed analysis of the volcano and the social context of the affected community (Blake et al. 2017c), which can make generic and widely applicable criteria difficult to produce for regional assessments. Wild et al. (2021) recently put forward a methodological approach to assess population exposure to evacuation areas across a large number of potential vents for a volcanic field using pre-existing evacuation policies. These policies were based upon concentric circles of a given radius from a potential vent opening position, and were derived from the likely extent of hazardous phenomena. However, when defining evacuation zones, it is important to also consider additional factors not directly associated to hazard exposure. For example, some areas might not necessarily be directly exposed to eruption hazards, but could have access to and from them cut off by either the hazard or evacuation zone extent. Thus, when defining decision-derived disruption it is important to focus on the decision-making criteria and key decision-drivers in addition to hazard extent, both of which will require localised input and knowledge.

Duration of disruption

A commonly acknowledged characteristic of volcanic eruptions is that the effects they have on communities can be relatively short-lived (e.g., hours to days) or very long-lasting (e.g., years). For example, lahars or lava flows can disrupt road networks over a period of months to years following a volcanic eruption. A road segment that is blocked and then cleared within a few hours is likely to be less disruptive than if that same road segment is unpassable for months (Kim et al. 2018). Thus, duration of disruption would be a useful indicator for overall disruption. A complicating factor is that the disruption caused by volcanoes can occur sporadically or continuously throughout the eruption duration. Lulls in volcanic activity can also allow for mitigation efforts to be undertaken to reduce societal impacts, assuming it is safe to do so. Hazard intensity is also likely to be a relevant factor that will influence disruption duration. For example, a dense PDC deposit is likely to cause thermal damage and potential scouring to bridges and roads, but a surge deposit could be removed by the next rainfall having caused relatively little long-lasting damage to road infrastructure (Jenkins et al. 2013). Here, we have adopted a conservative approach in our assignment of hazard intensity for PDCs and assume that any inundation and deposition is likely to require road closures for a period of time. This is because it will take time for authorities to undertake impact and risk assessments to determine whether it is safe to travel within PDC affected areas, due to either eruptive hazards or secondary road hazards caused by the eruption (e.g., fallen electricity poles). Further, decisions on long-term recovery of areas that suffer large scale damage and thick depositions of volcanic material within the built environment may also take time to resolve (e.g., whether to clean-up/remove deposited material or to consolidate and/or build on top) (Sword-Daniels et al. 2014; Jenkins et al. 2017; Hayes et al. 2021).

Both of the case study eruptions used in this study had road segments that were sporadically affected for months following the start of the eruption. We have not explicitly incorporated any time sensitive metric into the analysis of this study, although length of road affected will incorporate some elements of disruption duration related to the amount of work required to restore the road segment. That is to say, all other aspects being equal, an extensive length of road takes longer to restore than a small amount of road. However, we highlight that the approach taken in this work was to assume that if a road segment was affected by a hazard, the entire segment was assigned the same impact score regardless of the proportion of that segment that was directly affected by the hazard. This was to ensure consistency and repeatability of the methodology across case studies and also to factor in that even if a small section of a road segment is affected, the entire segment would likely reach the same loss of functionality. For example, a lahar that destroys a bridge will result in an entire road segment being impassable. But this also means that for those segments that are only partially affected (e.g., at the periphery of the tephra deposition area) would probably be restored quicker in practice that those segments that are wholly affected. Overall, we suspect this affect is minimal and consider adopting the consistent treatment of these segments to be advantageous compared to individually assigning impact based on specific context, which would be time consuming and would be unaligned with the aim of the approach to provide an efficient assessment of road disruption. Consideration of dynamic exposure throughout an eruption as a result of the sporadicity and duration of an eruption would be a useful area of future research to build upon the methodological approach developed in this paper.

Conclusions

There are multiple factors involved in defining the severity of disruption caused by a volcanic eruption, such as criticality of the road affected, severity of physical impact, and length of road affected. Previous studies of road exposure from volcanic eruptions have omitted road criticality from this analysis. In this study we proposed an approach to incorporate road criticality concepts into road disruption assessments. By combining criticality scores with impact and length of road scores, we were able to obtain a common measure of disruption that is comparable across case studies. Our approach is widely applicable and utilises open-data sets, and can be applied in a range of different contexts globally. We evaluated criticality as a function of three components: road hierarchy (as a proxy for number of road users), access to community services and facilities, and access to important infrastructure sites. Incorporating road criticality concepts can enhance insights into the potential drivers of disruption and identify potentially unexpected high disruption areas. Thus, examining road disruption in this manner facilitates identification of key disruption hazards, hotspots, and volcanoes.

In this paper, we used two case studies based on the Merapi 2010 and Kelud 2014 eruptions to demonstrate how this approach can be used, and its limitations. We found that the Kelud 2014 case study resulted in an order of magnitude greater disruption to the road network compared to the Merapi 2010 case study. Our modelling results found for both case studies that disruption to the road network was largely driven by tephra fall, but for the Merapi 2010 case study, a sizable proportion was due to lahar and PDC inundation. We demonstrated how potential disruption hotspots can be identified, but that caution should be observed when interpreting these results due to the automated nature of our criticality score assignment. Whilst we have used real world case study eruptions in this work to retrospectively examine disruption, we suggest that utilising our methodology with probabilistic hazard assessment methodologies or hypothetical scenario sets could also be valuable for assessing and planning for potential future disruption.

Abbreviations

RSDS: Road Segment Disruption Score; RNDS: Road Network Disruption Score; PDC: Pyroclastic Density Current; OSM: OpenSteetMap; FLS: Functional loss state; VEI: Volcanic Explosivity Index.

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Authors' contributions

JLH conceptualised the project, developed the methodology, carried out formal analysis, and wrote the original draft. SB, SFJ, ESM, and GTW provided feedback on the methodology, and reviewed/edited the manuscript. The authors all read and approved the final manuscript.

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Availability of data and materials

Python code for producing the road criticality file used in this analysis can be found at: https://github.com/vharg/RNDS/.
The geospatial datasets used to assess disruption from the two case studies can be obtained from: https://researchdata.ntu.edu.sg/privateurl.xhtml?token=d3f9145b-ba2c-4394-b7a9-3054f0880cde.

Declarations

Competing interests
The authors declare that they have no competing interests.

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