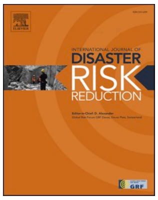
International Journal of Disaster Risk Reduction 114 (2024) 104997

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Quantifying systemic vulnerability of interdependent critical infrastructure networks: A case study for volcanic hazards

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ARTICLE INFO

Keywords:
Volcanic multi-hazards
Impact assessment
Disaster risk assessment
Interdependencies
Criticality
Volcanic risk management

ABSTRACT

Infrastructure networks are vital for the communities and industries that rely on their continued operation. Disasters stress these complex networks and can provoke systemic disruptions that extend far beyond the spatial footprint of hazards. An enduring challenge for assessing infrastructure networks within disaster impact assessment frameworks has been to adequately quantify the high spatial interdependence of these networks, and to consider risk management interventions through time. This is of particular importance for volcanic eruptions, which can produce multiple hazards over highly variable spatiotemporal extents. In this study, we present a methodology for the quantification of systemic vulnerability of infrastructure networks, which can be coupled with physical vulnerability models for the purpose of impact assessment. The two-part methodology first quantifies the haard-agnostic criticality of infrastructural components, inclusive of interdependencies, and then incorporates representative hazard spatial footprints to derive the systemic vulnerability. We demonstrate this methodology using the case study of volcanic eruptions from Taranaki Mounga volcano, Aotearoa New Zealand, where there are many industrial sites of national importance, and a high likelihood of a complex multi-hazard volcanic eruption. We find a considerable increase in the systemic vulnerability of electricity and natural gas network components after incorporating infrastructure interdependencies, and a further increase in the systemic vulnerability of these critical components when cross-referenced with potential volcanic hazard spatial extent. The methodology of this study can be applied to other areas of interest in both its hazard-agnostic or hazard-dependent form, and the systemic vulnerability quantification should be incorporated into impact assessment frameworks.

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https://doi.org/10.1016/j.ijdrr.2024.104997
Received 14 August 2024; Received in revised form 19 November 2024; Accepted 19 November 2024

1. Introduction

Rapid urbanisation and globalisation are driving high levels of exposure and vulnerability to climatological and geological hazards [1]. Critical infrastructure networks are increasingly interdependent and downstream dependent sectors increasingly reliant on their continuity of supply [2]. Reducing disaster risk is a key international priority [3–6]. Growing urbanisation, coupled with increasing frequency and intensity of climate and hazard extremes [7,8], necessitates more effective disaster risk reduction (DRR) practices. Hazard impact assessments are used to inform disaster mitigation, response and recovery plans, and often used operationally by disaster risk management (DRM) groups or corresponding authorities [3,6,7]. During complex, multi-hazard events (e.g. prolonged volcanic activity or earthquake aftershock-liquefaction/landslide sequences), emergency managers and infrastructure managers must make challenging decisions regarding the allocation of resources and the management of critical infrastructure supply. The estimation of likely hazard impacts to distributed infrastructure networks can guide decision-makers to revise risk management strategies to reduce the impacts observed from a future hazard event.

Critical infrastructure systems are physically diverse, spatially extensive and vulnerable to the physical properties of hazards [9,10]. Quantification methodologies for physical vulnerability are generally well-established for single-hazard impacts [6,7,11]. Though essential, physical vulnerability cannot be the sole descriptor of the possible socio-economic impacts from hazards [11–16]. Vulnerability has long been considered multi-faceted, comprised of at least physical, systemic, social and economic factors (Turner et al., 2003; [3,14,17–20]), and substantial gaps remain in our understanding of systemic, social and economic vulnerability, and in particular, how these factors cascade and interact with physical vulnerability to drive impact (during a disaster) or to build resilience [11,12,19,21–25].

The systemic disruption of critical infrastructure during disasters can result in spatio-temporally extensive impacts, thus far not adequately captured by physical vulnerability metrics [11,16,20,26–28]. Systemic vulnerability is described as the susceptibility of a system or network to experience disruption or loss of service when subject to an external stress [11,12,22,23]. Improved methodologies for measuring and assessing systemic vulnerability, in addition to an improved understanding of the interface between physical and systemic vulnerability factors, will greatly enhance disaster response capabilities and resilience-building initiatives [6,11,29,30]. This research gap limits the usability and applicability of current vulnerability models in decision-making, planning and policy.

Critical infrastructure systems are recognised globally as being highly interdependent [9,31–35], meaning that the loss of function of a component within one infrastructure sector (e.g. the electricity sector) can greatly reduce the functionality of components in another sector which rely on its continued supply [31]. Due to the complexity of such networks systemic vulnerability is typically ascertained qualitatively or neglected in impact assessment frameworks [25,32]. Furthermore, current quantitative methods for systemic vulnerability calculation (such as criticality metrics) tend to be sector-specific, therefore not accounting for trans-sector interdependencies inherent in infrastructural networks [32,36–41]. Efforts to quantify systemic vulnerability in infrastructure networks have generally resulted in sector-specific applications, often for single-hazards [30,41–43], but recent post-event studies have developed methods for the exploration of multi-sector systemic vulnerability of infrastructure networks through time [16,35].

2. Systemic vulnerability of critical infrastructure: Quantification methodologies and their use in impact assessment frameworks

Complex network theory has become an important paradigm to interpret intricate, diverse systems and problems [44–47]. Complex network theory generally represents systems as interconnected graphs and has been the principal approach for systemic vulnerability analysis of critical infrastructure networks [36,39,48]. In these approaches, infrastructure networks are represented as graphs comprised of nodes and edges, where nodes are points or sites of interest (components), and the connecting edges represent the resource-carrying infrastructure lines (e.g., Ref. [44,46]). Representing infrastructure networks as graphs simplifies a complex system into a digestible format, suitable for iterative computational analysis. This allows for rapid simulation of infrastructure outage, and therefore facilitates the investigation of a broad range of possible outage scenarios within the infrastructure graph (e.g., Ref. [36]).

Complex network approaches have typically been used to assess the systemic vulnerability of electricity and transportation networks, generally from a national security perspective (e.g., Ref. [40,41,49–53]). Applications to other infrastructure sectors are less common, but are seeing increasing interest (e.g., Ref. [54]). Applications of complex network theory principles in infrastructure network systemic vulnerability assessments have generally been limited to one infrastructure sector, with little incorporation of interdependencies between sectors. Few studies quantify infrastructure system vulnerability for multiple sectors [34–36,48,54]. Some studies utilise graph theory to estimate reduction of service and restoration time [35,55–58], which requires complex information about node and edge capacity, failure thresholds and potential recovery operations. Other studies consider functional dependencies between components to be binary, assuming total loss of component functionality for dependent components in the network graph [36,48].

Systemic vulnerability is regarded as a necessary component of impact and risk assessment methodologies [2,6,11,59], yet still, a clear definition and method of inclusion in impact assessment frameworks remains elusive. Graphical representations of interdependent infrastructure are currently underutilised in disaster impact and risk assessments. More commonly, impact and risk assessments conduct criticality assessments of networks and assets.

Criticality has been defined as: ‘the degree of societal importance of each component within the critical infrastructure network’ [32]. A consequence-based approach is generally favoured when conceptualising criticality, namely, that the significance of an infrastructure component or element is measured by the systemic, socio-economic and environmental consequences of a disruption [25]. Theoharidou et al. [60] categorises criticality criteria into three groups: (1) the [spatial] extent of the affected population, (2) the severity of the effects on economic processes, infrastructural interdependencies, public trust, and security of the affected systems, and (3) the recovery time and the duration of long-term effects. Katina and Hester [61] instead define criticality through the degree of connections with other infrastructure components and systems. Though differing approaches exist, most are seemingly network-specific, meaning that the criticality of a component is only reflective of the importance of said component to the infrastructure system it sits within (e.g. the importance of an electricity sub-station to the electricity network) [62]. However, the nature of cascading impacts provoked by system interdependencies necessitates a more holistic, whole-of-network approach [55,56,63]. Further, criticality assessment approaches are yet to be tailored to specific hazard contexts and applied in impact and risk assessment frameworks.

3. PART I: Hazard-agnostic criticality of critical infrastructure networks

Using the principles of graph theory, in this study we represent infrastructure networks as directed graphs. Each infrastructure sector is represented as a directed sub-graph, where $G_{sub} = \{K, E\}$, where K is a set of n nodes $K = \{k_1, \ldots, k_n\}$ and E is a set of edges, or dependency links, where $\{k_i, k_j\} \in E$ represents a link from node k_i to k_j. Each edge (E) has an associated carrying capacity (c); for example, some electricity distribution lines are designed to carry 33 kV, and hence are limited to 33 kV in the network graph. Each sub-graph has at least one supply node and multiple demand nodes, and the possible paths between these supply and demand nodes are determined by the carrying capacity of edges and the topology of the network represented. Between supply and demand nodes often there are transition nodes (e.g. a water reservoir or pump in the water supply network) (Fig. 1). The path between supply and demand nodes can be written as a series of nodes and links (Fig. 1), and multiple paths can exist between the same pair of nodes.

Sub-graphs can then be related together by incorporating their interdependencies, which then generates a large directed graph comprised of multiple infrastructures sectors (Fig. 2). This large network graph is comprised of all nodes from all sectors, intra-sector edges and inter-sector edges, so that $G = \{\{k_{S1} + k_{S2} \ldots k_{Sn}\}, \{E_{sub} + E_{int}\}\}$, where Sn is the nth sector of interest, E_{sub} are intra-sector edges and E_{int} are inter-sector edges (Fig. 2). The edges are defined by their start node (k_i), end node (k_j), resource type carried (r) and carrying capacity (c), such that $E \subset \{k_i, k_j, r, c\}$. A directed graph assumes resources can only flow between nodes in one direction $(E \subset k_i \rightarrow k_j)$, but where two-way resource transmission occurs (e.g. electricity lines), the edge is duplicated, and the flow assigned in the other direction on this duplicated edge {e.g. $E \subset i \rightarrow j, j \rightarrow i$ }.

In this study, demand nodes can take two forms: resource catchments (such as water supply or electricity supply customer catchments) or critical sites (such as key industrial sites, hospitals, etc.). Where the demand node is a resource catchment, the number of private dwellings (PD) within that catchment is ascribed to the demand node. Where the demand node is a critical site, a critical site identifier is ascribed to the node (e.g. 'Critical Site 1', or 'CS1').

In order to quantify the relative importance of each node within the interdependent network graph, we simulated the failure of each node individually and calculated the resultant downstream disruption across all infrastructure sectors. We assume that, when node k_x fails, the failure would cause resource redistribution across paths from supply nodes to demand nodes that do not contain node k_x, if such paths exist. If no path exists between demand nodes and possible supply nodes after the failure of node k_x then the number of private dwellings and/or the critical site identifier (CS_x) associated with the disrupted demand node is recorded. Whilst several studies recognise the relative importance of some critical infrastructure sectors over others [31,35], we did not apply weightings to sectors, rather we simply summed the total private dwellings without service (PDWS) across all sectors following nodal failure. In future applications of this work weighting criteria can easily be applied but it was deemed inappropriate due to the sensitivities around restoration prioritisation and resource allocation during and after disaster events. The total disruption associated with the failure of each node is therefore

$$PDWS_{total} = \{PDWS_{S1} + PDWS_{S2} + \ldots + PDWS_{Sn}\}.$$

The resultant criticality of each node was then determined using the criteria in Fig. 3. Criticality tiers (CTs) are defined by $PDWS_{total}$

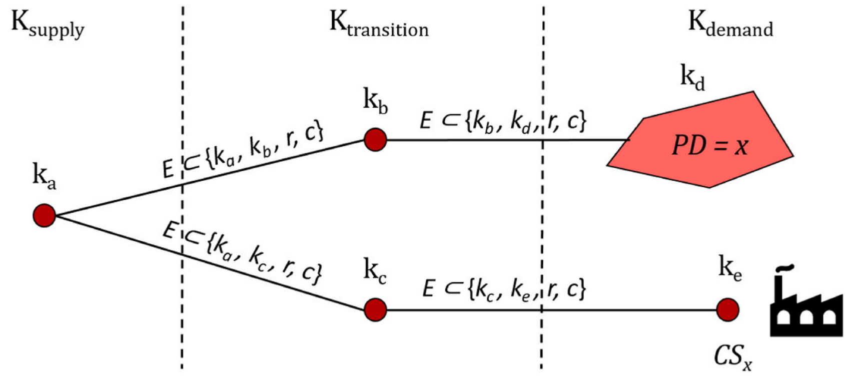

Fig. 1. Illustration of an infrastructure sector sub-graph, showing node and edge terminology, and the two different demand node types; private dwelling catchments and critical sites.

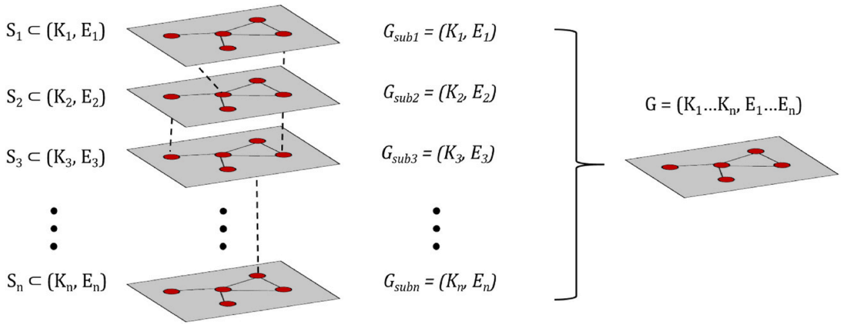

Fig. 2. Illustration of infrastructure sectors (S1…Sn), their sub-graphs (G¬sub1…Gsubn), and the interdependent resultant graph (G).

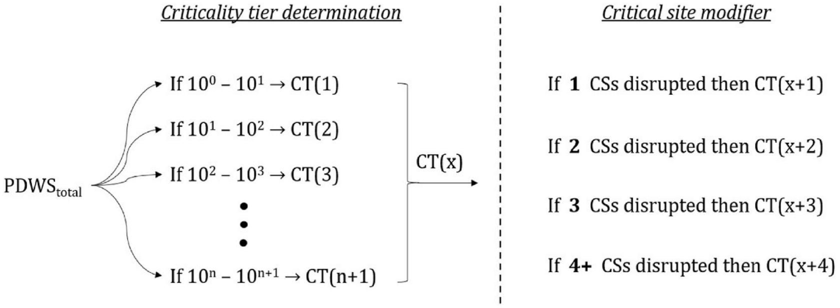

Fig. 3. Workflow for calculating criticality tiers (CTs) for infrastructure components (nodes), by assigning a CT based on the number of private dwellings without service across all infrastructure networks (PDWS_{total}) and modifying the CT if nodal failure also disrupts critical sites (CSs).

ranges, and increase in orders of magnitude, with CT1 defined as $10^{\circ} \le \mathrm{PDWS}_{total} < 10^1$, CT2 as $10^1 \le \mathrm{PDWS}_{total} < 10^2$, and so on. The use of criticality tiers is common in criticality assessment methodologies ([61,64], 2020), and due to its simplicity it was determined to be the most effective way to enhance the usability of the results of this study. Critical site information is incorporated by applying the critical site modifier (Fig. 3) which modifies the CT of a node if the failure of said node disrupts supply to at least one critical site.

4. PART II: Hazard-dependent systemic vulnerability of critical infrastructure networks

Part I of this study outlines a methodology for hazard-agnostic criticality determination for interdependent critical infrastructure networks. Part I assumes a single point failure within the network graph in order to estimate the downstream disruption of single-component failure and therefore determine the component's criticality. Infrastructure point-source failures may well occur, but in the context of disasters, it is much more likely that multiple components will be impacted in at approximately the same time or in sequence. Previous criticality assessment methodologies, and indeed Part I of this study, often incorporate a false sense of redundancy in infrastructure networks, particularly when two parallel infrastructure sites or lines are either in close proximity to one another, or spatially related by potential hazard footprints and are assumed to fail independently. The assumed redundancy through alternate resource paths in the network is not reasonable under certain conditions, for example, where a hazard travelling along a river channel is co-located with two river-crossing resource pipes, as illustrated in Fig. 4.

Components within the interdependent network graph can be grouped by their co-location within potential hazard extents. The potential grouping of components is determined by the hazard of interest; when considering tsunami hazard for example, components could be grouped by quantiles of potential tsunami run-up distance. Different hazards have different spatial behaviours, which can draw associations between components that had no prior dependency relationship. If two pipe bridges transmitting the same resource cross the same river channel many kilometres apart for example, they can still be subject to the same debris flow or volcanic lahar, thus drawing a relationship between the two components, and therefore not providing true redundancy. Depending on the hazard(s) of interest, there could be one or more groupings, and nodes could belong to many groups. Fig. 5 illustrates the concept of relating infrastructure components through hazard spatial behaviours, using the example of volcanic hazards.

Consideration must also be given to the intersection of hazard spatial patterns and graph edges, which represent resource-carrying lines, such as pipes, overhead lines and roads. The disruption of resource flow between nodes can be assumed to greatly reduce or entirely limit the functionality of nodes either end of the transmitting line that service the nodes. Therefore, in this methodology we account for the intersection of hazard patterns with resource-carrying lines by creating a group comprised of the servicing nodes at either end of disrupted lines as illustrated in Fig. 5. For ground-hugging hazards, such volcanic lahars, the intersection with subaerial or buried infrastructure lines is considered (e.g. buried pipes, roads) and for other hazards (e.g. volcanic ashfall) aerial components

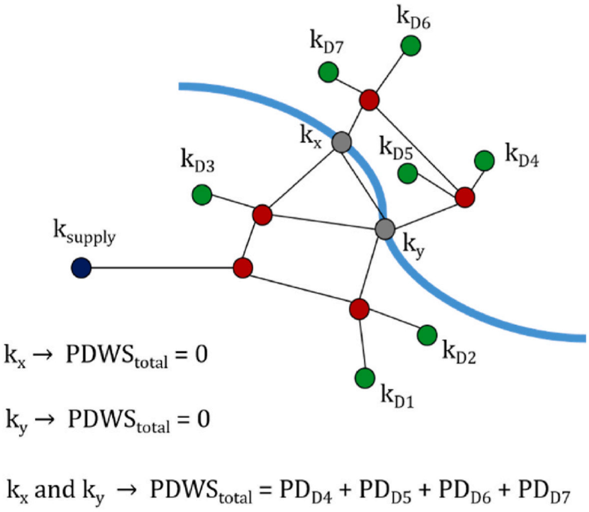

Fig. 4. An illustration demonstrating the necessity of nodal groupings when considering systemic vulnerability to a specific hazard. Green nodes represent demand nodes, blue nodes supply nodes, and grey nodes show nodes co-located along the same river channel (k_x and k_y). The failure of k_x or k_y results in no disruption to demand nodes, however, the failure of k_x and k_y results in disruption to k_{D4}, k_{D5}, k_{D6} and k_{D7}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

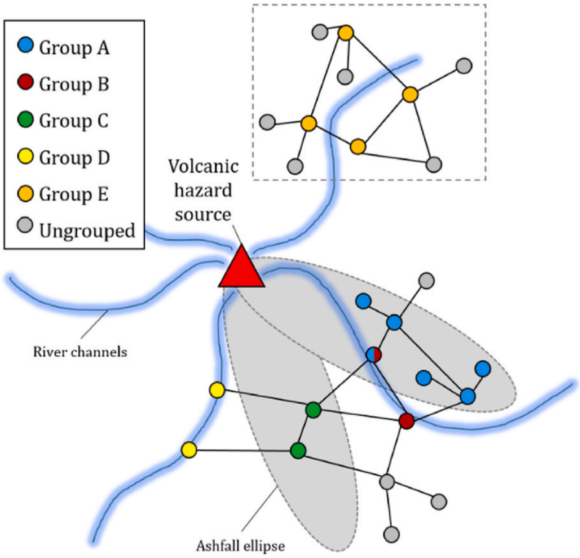

Fig. 5. An illustration of possible nodal groupings for multiple volcanic hazards. Nodes are grouped if they are co-located by a possible surface flow channel (i.e. river channels or topographic depressions) or ashfall dispersion axis. The hazard shapes used to group nodes will differ depending on the volcano of interest. Likely, or maximum, surface hazard volume will dictate the buffer distance from the surface flow channel, and likely, or maximum, ashfall volume and local meteorological controls will dictate the size and shape of the ashfall ellipse applied. The dashed box shows the possible nodal groupings for volcanic hazards when considering the intersection of volcanic hazard patterns and resource-transmitting lines. Nodes are grouped when either directly co-located with the hazard pattern, or either end of a resource-transmitting line that is crossed by the hazard pattern.

exposed to the hazard are considered (i.e. not buried pipes). The hazard spatial patterns used to group components depends on the local hazard context and purpose of the study, discussed further in Section 5.

In this study, we apply the systemic vulnerability quantification methodology to multiple volcanic hazards. For volcanic hazards, nodes can be related by various spatial mechanisms, but most commonly by surface flows in topographic depressions (e.g. pyroclastic density currents, lahars, lava flows) and through dispersal axes from a point source (e.g. ashfall) which are typically of ellipsoidal morphology [65]. For spatially extensive hazards, empirical studies or computational modelling can be used to select an appropriate extent for nodal groupings. In the following section, using the case study volcano of Taranaki Mounga[1] in Aotearoa New Zealand (hereafter referred to as Aotearoa), we group infrastructural components by proximity to topographic depressions that extend radially from the volcanic edifice, and by proximity to primary dispersal axes for ashfall. The hazard shapes used to group nodes will differ depending on the volcano or hazard of interest. For example, likely, or maximum, surface flow hazard volume could dictate the buffer distance from the surface flow channel, and likely, or maximum, ashfall volume and local meteorological controls could dictate the size, shape and directionality of the ashfall ellipse applied.

In order to calculate the systemic vulnerability of each node, the hazard-agnostic criticality tier calculation (Part I) must be integrated with the hazard-dependent nodal group information (Part II). Along directed edges, this is achieved by applying the rules: 1) all nodes upstream (in terms of source-sink resource flow) of the maximum criticality node within the group assume the maximum criticality of said node; 2) all nodes downstream (in terms of source-sink resource flow) retain the criticality calculated in the criticality assessment component of the analysis; 3) where resource flow is bi-directional, all nodes in the group assume the criticality of the maximum criticality node; and 4) where a node belongs to multiple groups it adopts the maximum criticality ranking assigned across all groups. This modified criticality ranking can thereafter be thought of as indicative of the systemic vulnerability. This is demonstrated in Fig. 6, where the initial criticality ranking (Part I) is modified as a result of a nodal grouping associated with a volcanic lahar channel (Part II).

5. Case study application: The systemic vulnerability of interdependent critical infrastructure networks to volcanic hazards in the Taranaki region of Aotearoa

5.1. Risk context

Taranaki Mounga volcano, in the Taranaki region of Aotearoa, is surrounded by infrastructure of national importance, including oil and gas and dairy farming production and processing sites. Taranaki Mounga has an estimated 33–42 % probability of producing an eruption within the next 50 years [66], which necessitates a robust understanding of volcanic risk. Taranaki Mounga has commonly produced ashfall, lahars, pyroclastic density currents (PDCs) and lava flows throughout its eruptive history [67](Fig. 7). Due to the high exposure of nationally important components to these hazards, it is highly relevant to quantify the systemic vulnerability of surrounding infrastructure networks to inform response and mitigation planning, and ultimately contribute to mitigating economic and societal disruption during future volcanic unrest and activity.

The Taranaki region is the only oil and gas producing region of Aotearoa. Buried pipelines carrying reticulated gas supply households and business on Te Ika-a-Māui the North Island, as well as supplying many key industrial sites, such as Huntley Power Station in the Waikato region, the largest thermal power station in Aotearoa. Te Waipounamu the South Island of Aotearoa relies on oil and gas production in the Taranaki region for bottled liquefied petroleum gas (LPG), used in homes, businesses and industry. Taranaki is the largest regional contributor to national milk solid production [69], and is a major site for dairy production and processing. Critical infrastructure servicing industries and settlements circumnavigate the volcanic cone; notably, state highways, water supply networks, electricity distribution and transmission networks, and telecommunications.

5.2. Engagement with data holders, data acquisition and curation

Recent developments in disaster risk science have emphasised the benefit of co-production processes in achieving disaster risk assessment and disaster risk management goals (e.g., Ref. [70]). Local stakeholders possess valuable knowledge about their assets and networks; this knowledge is rarely captured in static exposure inventories but can be elucidated through engagement with local experts. This work leveraged off the relationships and engagement processes established in Weir et al. [68] and Weir et al. [71]. Local stakeholders in the region, particularly the Taranaki Civil Defence and Emergency Management (CDEM) group, the Taranaki CDEM Lifelines Advisory Group (LAG), and their wider networks, facilitated data sharing and curation. Engagement with local agencies and stakeholders helped address some data gaps, but other gaps were supplemented by gathering information from publicly available asset management plans and validated using satellite imagery. Infrastructure interdependencies were generally deduced through stakeholder engagement and is also documented in several key reports ([64], 2020; [72]). The tools developed in this study were regularly validated through stakeholder engagement via the Taranaki CDEM LAG, and judgements made regarding the representation of infrastructure interdependencies in particular, were made with local stakeholder participation.

The critical infrastructure sectors of interest in this study are: electricity, water supply, waste water, road transportation, oil and gas (energy), and telecommunications. This follows the determination of critical infrastructure in the New Zealand Lifelines Council's National Vulnerability Assessment [73], with the exclusion of fuel supply, storm water, and facets of the broader 'transportation' and 'telecommunications' sectors (air, sea, rail; broadcasting, radio). Due to data availability and the granularity of this study, fuel supply to private and commercial users was excluded, however, oil and gas production and processing sites in the Taranaki region were still considered, as data was available [74] and this sector is of vital importance to the Taranaki region and Aotearoa. The storm water network was also excluded from this analysis due to data availability issues and inconsistencies in data quality across providers.

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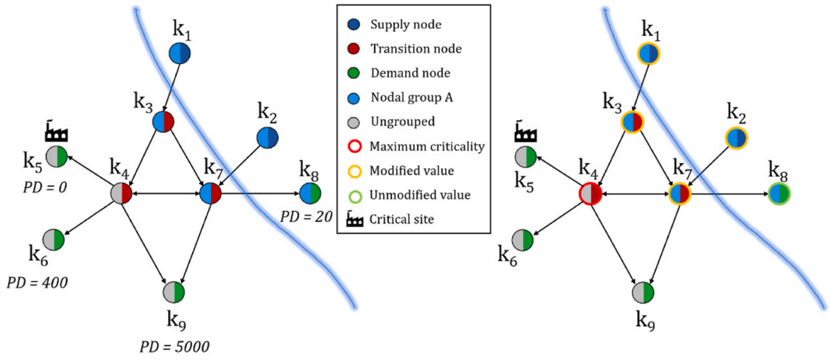
[1] The term *Mounga* is the te reo Māori language term for mountain, mount or peak and is a local variation of the more commonly used *Maunga*.



Part I: Hazard-independent criticality assessment		
Node	$PDWS_{total}$	Criticality Tier (CT)
k_1	0	1
k_2	0	1
k_3	0	1
k_4	400 + CS	4 (3 + 1 CS modifier)
k_5	0 + CS	2 (1 + 1 CS modifier)
k_6	400	3
k_7	20	2
k_8	20	2
k_9	5000	4

Part II: Hazard-dependent total systemic vulnerability		
Node	Group	Systemic vulnerability
k_1	A	4
k_2	A	4
k_3	A	4
k_4	A	4
k_5	-	2
k_6	-	3
k_7	A	4
k_8	A	2
k_9	-	4

Fig. 6. An illustration of a hypothetical quantification of hazard-agnostic criticality (Part I) and hazard-dependent systemic vulnerability (Part II).

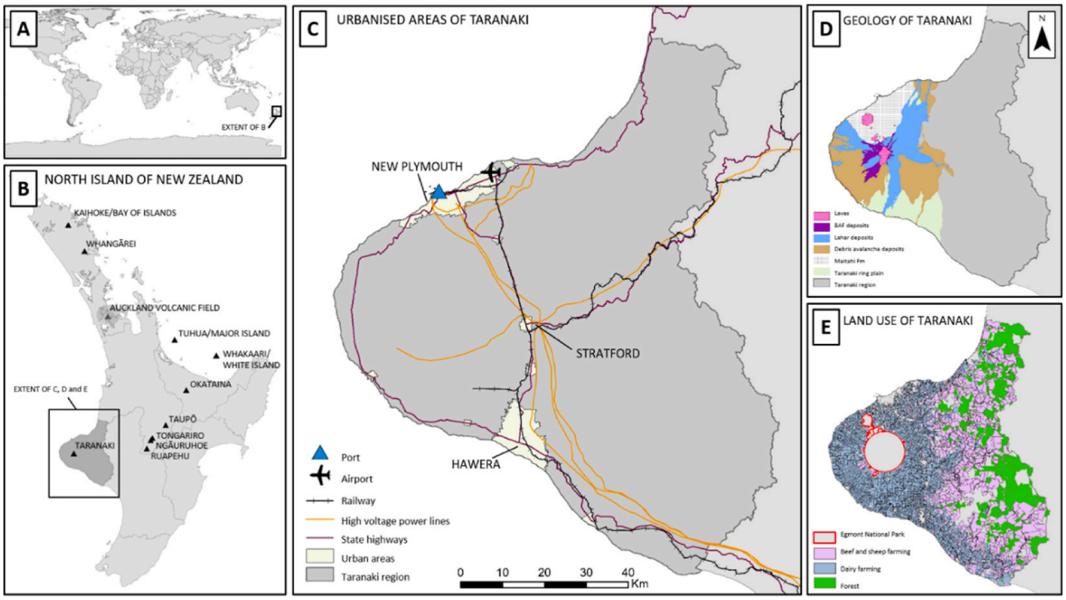


Fig. 7. A) The location of Aotearoa; B) the location of the Taranaki region and volcanic centres of Aotearoa; C) urban centres and selected critical infrastructure of the region; D) simplified geology of the Taranaki volcanic complex (modified from Zernack et al. (2009); E) land use of the Taranaki region. Figure from Weir et al. [68].

Telecommunications are only represented via cellular networks, and the inclusion of this data acts as a proxy for the response of the wider telecommunications network. Telecommunications data specific to agencies in the region were unavailable and determined to be sensitive in nature. Transportation sector exclusions (air, sea, rail) were made on the basis that, for regional-level systemic vulnerability analysis, the airport, port and railway loading stations are best acknowledged as 'critical sites' in this analysis, as their resource demand nodes are out-of-region. A similar approach was taken for the inclusion of 'northbound gas transmission' and 'southbound gas transmission' as critical sites.

With six critical infrastructure sectors of interest, data were acquired from a variety of sources, most notably from open-source data repositories (Land Information New Zealand (LINZ), Koordinates) and by acquiring the data directly from the owner/curator. In several instances, data were created or edited by the author by referring to official documentation and by using satellite imagery for validation (such as water supply inlets (supply nodes) inferred from the local council Water Asset Management Plans and validated using satellite imagery).

5.3. Determining critical infrastructure network configuration

Components for each sector were categorised as resource supply, transition and demand nodes (Table 1). The granularity of the catchment demand nodes was deduced by ascertaining the highest resolution at which the resource consumers could be attributed to a single demand node. For instance, for electricity distribution, when each private dwelling can be attributed to one distribution substation, ensuring no private dwellings are counted multiple times when calculating PDWS. Methods for quantifying the number of private dwellings per customer catchment vary across sectors and are detailed in Table 1. A schematic of the water supply network, including supply, transition and demand nodes is shown in Fig. 8. These schematics were co-created with the Taranaki LAG for each infrastructure sector to map the resource flow and directionality.

Critical sites are represented as demand nodes (Table 1) and represent high priority customers. There are many key industrial sites of supra-regional importance in the Taranaki region, mainly owing to the dairy industry and the on- and off-shore oil and gas reserves. These sites include gas treatment plants, electricity generation plants, dairy production and processing plants, methanol plants and fertiliser plants. These sites almost without exception rely on electricity supply, water supply and gas supply for their continued operations. These sites are designated ‘critical sites’ through at least one of the following mechanisms: 1) if they are deemed critical customers in exposure datasets shared by the data provider (e.g. the electricity distribution asset inventory shared with the lead author to conduct this research); 2) if they are deemed critical in regional assessments of critical infrastructure vulnerability [72]; and 3) if they are deemed critical in national critical infrastructure vulnerability assessments [73]. A total of 18 critical sites were identified, shown in Fig. 9.

5.4. Ascertaining inter-sector interdependencies

Interdependencies were deduced by 1) identifying key interdependencies from global literature (e.g. water supply pumps and treatment facilities require electricity) (e.g. Ref. [31,33]), 2) review of previous local qualitative interdependency analyses [72,73], and 3) consulting with local and national infrastructure managers and lifelines experts. The inter-sector critical interdependencies of relevance in this study are displayed in Table 2, and the component-to-component interdependencies in Fig. 10. Some identified interdependency relationships are recognised by not accounted for in this analysis due to difficulties with data access and verification; these exclusions are in italics in Table 2.

The Taranaki Lifelines Vulnerability Assessment [72] developed an interdependency matrix for local infrastructure sectors. The matrix has three levels: 1) minimal requirement for service to function, 2) important but can partially function and/or has full back up, and 3) required for service to function. The interdependency of all regional waste water treatment plants on water supply for example, is scored as 3, as water is required for the waste water treatment plant to function, and there is no capacity for sufficient water storage to maintain operations during water supply shortages. We included interdependency relationships that were scored ≥2, deeming those scored as 1 to be non-essential for this analysis. We also exclude the interdependences of all sectors on telecommunications, due to data availability and the acknowledgement that “*… most utilities services could continue core services at near full capacity without telecommunications in the short-term …*” [72].

5.5. Part I: Hazard-agnostic criticality

Infrastructure networks were digitised as graphs in MATLAB, and the PDWS calculations were automated. Edges were weighted for their capacity (e.g. the maximum voltage the electricity line can carry), thereby ensuring that when calculating downstream disruption from component failure, we are adequately accounting for the carrying capacity of the component. The graphs also account for directionality of flow between nodes. Each infrastructure sector was first represented as a sub-graph, and the downstream disruption (using the PDWS metric) caused by the failure of each individual component was computed. Following the calculation of intra-sector disruption, all sectors including interdependencies were digitised as a whole-network graph, and the inter-sector disruption caused by node failure was calculated. This was iterated 659 times, once for each node in the graph, and the PDWS associated with each node failure recorded (Fig. 11). We see a maximum criticality of CT10 for the Stratford electricity transmission Grid Exit Point (GXP), with no components falling in CT7 – CT9, indicating the extremely high reliance of the regional critical infrastructure networks on this particular component. 24 components fall within CT4 – CT6, generally these are water treatment plants, gas production facilities and electricity distribution substations. Many nodes fall in CT2 and CT3, indicating that between 100 and 10,000 private dwellings are without supply across at least one of the infrastructure sectors. 53 % of the nodes are calculated to be CT1, indicative of either low private dwelling reliance on these components, or reasonable redundancy in the network for point-source disruptors. The majority of nodes that fall within CT4 – CT10 belong to the electricity, oil and gas, and water supply sectors, in decreasing order of prevalence. For electricity and oil and gas, high criticality nodes are generally calculated to be as such due to the critical site modifier, whereas for the water supply sector, high criticality nodes are as such generally due to the high reliance of private dwellings on these components.

Clustering of high-criticality components is observed, predominantly in the urban centres of New Plymouth, Stratford and Hawera, which is to be expected, due to the co-location of critical infrastructure sites with population centres. No telecommunications

Table 1

Critical infrastructure sectors, node and edge counts, node classifications and methods for determining the number of private dwellings per customer catchment.

Sector	Abbreviation	Node count	Edge count	Dependent edge count	Supply nodes	Transition nodes	Demand nodes	Method for determining the number of private dwellings in customer catchments
Electricity	PS	84	212	567	Regional entry points	Substations	Customer catchments (25); CSs	Number of installation control points (ICPs) attributed to substations
Oil and gas	OG	76	77	11	Extraction sites	Production sites; storage tanks	Customer catchments (15); CSs; regional exit points	Number of residential properties downstream of connections to transmission pipes
Water supply	WS	143	209	77	Water supply inlets; bores	Water treatment plants; reservoirs	Customer catchments (47); CSs	Watershed analysis and spatial join with residential properties
Waste water	WW	148	148	0	Customer catchments (67); CSs	Pump stations	Waste water treatment plants	Watershed analysis and spatial join with residential properties
Road transportation	TR	112	176	351	Customer catchments; CSs	Road bridges	Customer catchments; CSs	Number of residential properties within 5 km of road spans between road bridges
Cell towers (telecommunication)	TC	96	82	34	Cell towers	–	Customer catchments (82); CSs	Voronoi tessellation [75]

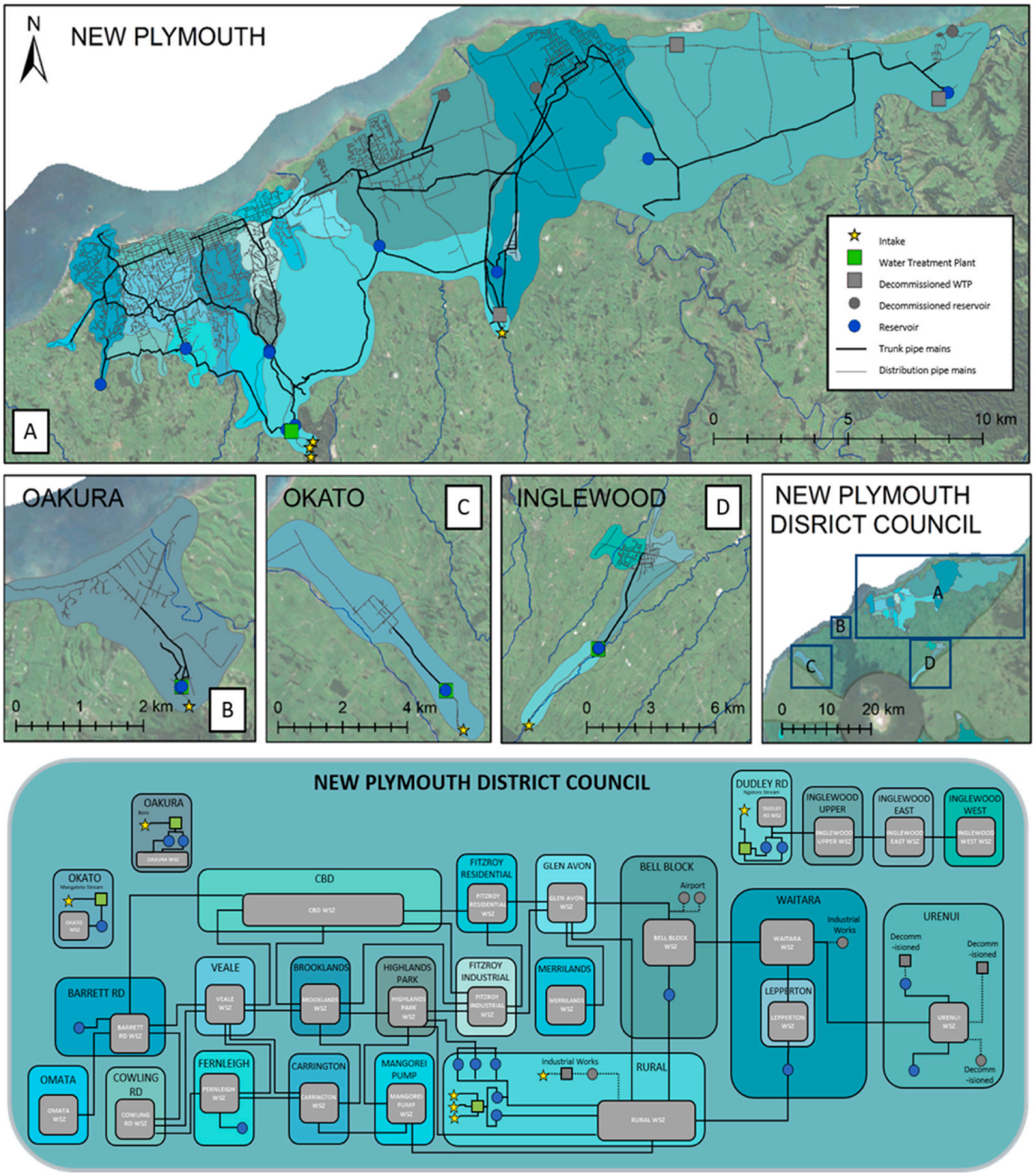


Fig. 8. Schematic for the simplified New Plymouth District Council water supply network. (A) shows the town of New Plymouth, (B) the town of Oakura, (C) the town of Okato and (D) the town of Inglewood. The simplified NPDC water supply network is also displayed as a non-spatial systems diagram (bottom pane).

component criticality exceeds CT2, presumably due to the low private dwelling count attributed to each cell tower, the intra-regional redundancy in the electricity network that the cell towers rely on, and the underrepresentation of telecommunications interdependencies in the model. Similarly, in the waste water network, only the waste water pumps and treatment plants are deemed high criticality (≥CT4), with no waste water catchment PDWS counts exceeding 103. Table 3 shows a summary of node count for each criticality tier in each infrastructure sector.

5.6. Part II: Hazard-dependent systemic vulnerability

Part II of the methodology requires spatial hazard information to create nodal groups. We used the hazard footprints for volcanic ashfall and lahars presented in Weir et al. [68]. Weir et al. [68] presents a suite of eruption scenarios for Taranaki Mounga, demonstrative of the credible range of volcanic behaviours expected for the next episode of volcanic activity, hence is appropriate for use in this case study application. The scenario suite is multi-phase and multi-hazard, with instances of ashfall and lahars of varying

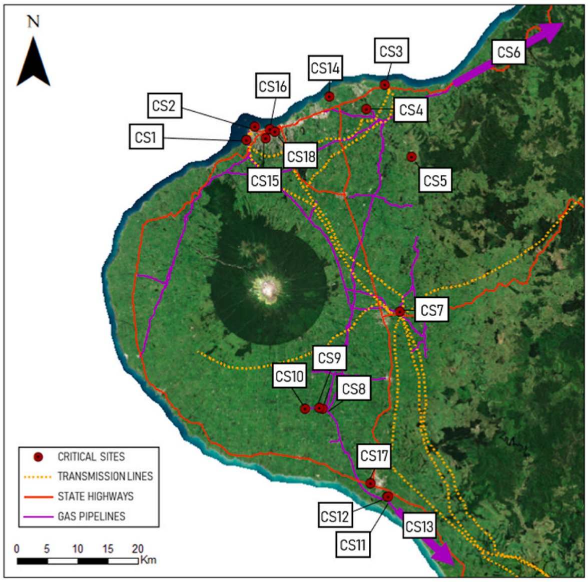


Fig. 9. Locations of critical sites (CSs) incorporated in this analysis (n = 18), overlain with key infrastructure sectors in the region.

Table 2
The interdependencies of infrastructure sectors in this study, as identified by global literature [31,33], regional critical infrastructure vulnerability studies [72], and in partnership with local infrastructure managers. Interdependencies excluded from this analysis are in italics. Sectors in bold (columns) are to be read as interdependent on sectors below (rows).

Sector	**Electricity**	**Water supply**	**Waste water**	**Oil and gas**	**Road transport**	**Telecommunications**
Electricity		Treatment	Pumping and treatment	Extraction, production and storage	*Traffic management*	Cell tower transmission
Water supply	*Cooling*		Treatment	*Cooling*	-	*Cooling*
Waste water	-	-		-	-	-
Oil and gas	*Generation*	-	Drying (Treatment)		-	-
Road transport	Site access	Site access	Site access	Site access		Site access
Telecommunications	*Coordination and operations*	*Coordination and operations*	*Coordination and operations*	*Coordination and operations*	*Coordination and operations*	

intensities at different times throughout the suite. For lahars, we group nodes using the spatial extent of the lahar with the furthest run-out distance in each of the hydrological catchments [68]. For ashfall, we applied a deposit thickness threshold to determine the area used to group nodes. There have been many reviews of ashfall impacts to infrastructure that determine that approximately 3 mm ashfall deposit thickness causes damage and disruption to the many infrastructure sectors ([10,76], 2017; [77]). We therefore apply this threshold to the spatial layer to determine our ashfall extent. There are a total of 20 ashfall footprints, and 40 lahar footprints considered for this analysis, displayed in Fig. 12, leading to a total of 60 nodal groupings.

5.7. Hazard-dependent systemic vulnerability

A total of 60 nodal groups were identified for the critical infrastructure network in the Taranaki region. 67 % of these groups are related to the lahar footprints, and 33 % related to ashfall footprints. 95 % of all grouped nodes belong to multiple groups, with 70 % of these belonging to 3 or more nodal groups. When adjusting the hazard-agnostic criticality rankings for systemic vulnerability, we find that 55 % of all nodes see a change in their CT value (see Fig. 13). The vast majority of these nodes belong to the electricity and oil and gas sectors, suggesting high systemic vulnerability of these sectors. The perceived redundancy in their networks (through parallel transmission infrastructure) may be made irrelevant in a volcanic context. Conversely, we see little to no change in the telecommunications and waste water sectors, suggesting low systemic vulnerability and high redundancy in their networks, or minimal co-location of these components with potential hazard footprints.

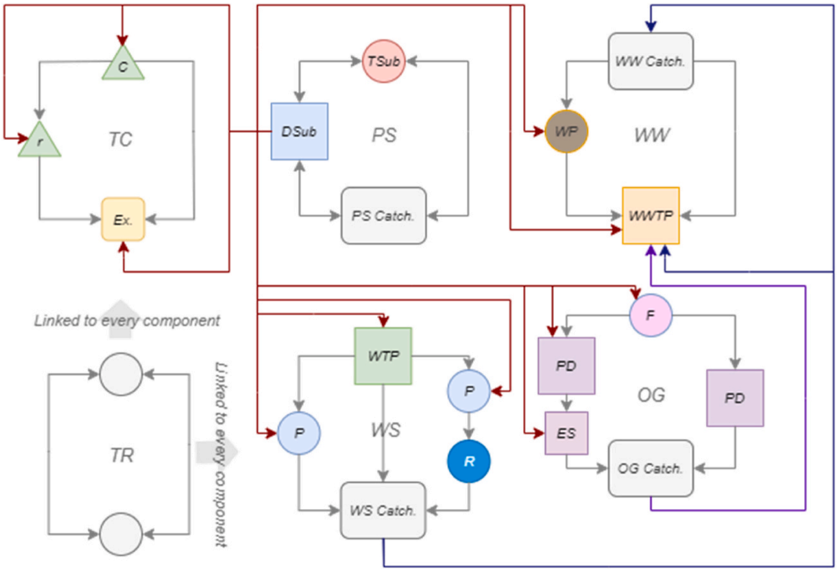


Fig. 10. Component-component interdependencies incorporated in this methodology for systemic vulnerability quantification. Within each sector, multiple pathways from source to sink are recognised. Components are labelled as per their abbreviations in the network model. In the electricity sector (PS): transmission substations (TSub); distribution substations (DSub); and catchments (PS Catch.). In the water supply sector (WS): water treatment plants (WTP); water pumps (P); water reservoirs (R) and catchments (WS Catch.). In the waste water sector (WW): waste water pumps (WP); waste water treatment plants (WWTP) and catchments (WW Catch.). In the energy sector (OG): oil and gas fields (F); oil and gas production stations (PD); oil and gas substations (ES); and catchments (OG Catch.). In telecommunications (TC): cell towers (C); cellular relays (r); and telecommunications exchanges (Ex). And the transportation sector (TR) is linked to every component in the network figure. Red lines represent electricity dependencies, blue lines water supply dependencies and purple lines energy (oil and gas) dependencies. Road transportation and cellular communications were identified by the Taranaki Lifelines Vulnerability Study [72] to be of medium priority for all components. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

We find a considerable increase in the criticality of electricity and oil and gas components after incorporating infrastructural interdependencies, and a further increase in the systemic vulnerability of critical components when overlaid with potential volcanic hazard spatial extent. We find the oil and gas sector to be highly systemically vulnerable to volcanic hazards due to several factors: the strong dependence on electricity supply, the exposure of resource-carrying pipes in known lahar channels, and the lack of redundancy in resource transport (from the west to north east of the volcanic edifice). Furthermore, the perceived redundancy of north-south resource transmission through the construction of parallel buried pipe infrastructure, is found to be false redundancy; parallel asset lines, unless one is located far from the volcanic edifice, are related by radial lahar channels, and are therefore not redundant in a volcanic context. The oil and gas sector is of great national significance ([64], 2020), and further exploration of the downstream impacts of oil and gas disruption is required.

The water supply sector is found to be most vulnerable in the South Taranaki District, where spatially extensive municipal supply schemes regularly traverse topographic depressions. In the eruption scenario suite [68], river catchments on the southern flanks of the volcanic edifice are commonly subject to lahars, as also observed in the geological record [67,78]. The propensity for municipal supply schemes in Taranaki to be fed by surface water inlets introduces high systemic vulnerability, which cascades through interdependent sectors, such as waste water and the oil and gas sector. The lack of water supply and treatment redundancy in New Plymouth District is apparent in both the hazard-agnostic (Part I) and hazard-inclusive (Part II) stages of the study, and though not commonly subject to ashfall or lahars in either the eruption scenario suite [68], or the geological record [67], the high societal dependence on these assets necessitates further analysis of the vulnerability of these assets to volcanic hazards. Interestingly, comparing the hazard-agnostic and hazard-inclusive results of the study shows that small, isolated municipal water supply schemes (principally located in South Taranaki) are not considered critical (Part I), due to low interdependency and low Private Dwellings Without Service (PDWS) following asset disruption, but are highly systemically vulnerable in the hazard-inclusive stage of the analysis (Part II).

6. Discussion

6.1. Potential benefits and applications

The increasing interconnected nature of globalised societies is increasingly the likelihood of small, short-lived hazard events inducing severe systemic impacts in space and time [59,79]. The multi-hazard and potentially long-lasting nature of volcanic eruptions creates a unique systemic vulnerability context, as volcanoes can frequently shock surrounding systems to varying degrees via diverse impact mechanisms [80]. The potential for frequent and recurring systemic shocks during prolonged volcanism impedes response and

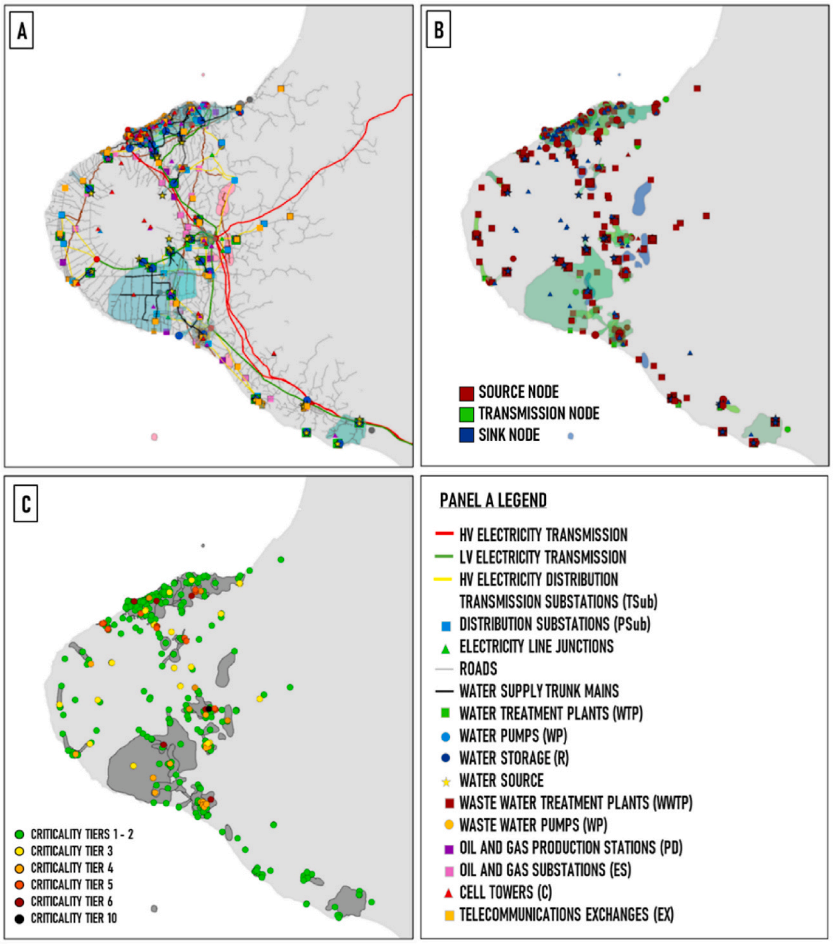


Fig. 11. The hazard-agnostic criticality rankings for an interdependent infrastructure network using a graphical, complex systemic approach. Panel A shows the exposure inventory of nodes, Panel B shows the source, transmission and sink nodes for each sector, and Panel C shows the criticality rankings of all nodes in the interdependent infrastructure model.

Table 3
The total number of infrastructure nodes in each criticality tier (CT), for each infrastructure sector.

	Electricity (71)	Water Supply (78)	Waste Water (53)	Oil and Gas (85)	Road Transportation (105)	Telecommunications (101)
CT10	1	0	0	0	0	0
CT9	0	0	0	0	0	0
CT8	0	0	0	0	0	0
CT7	0	0	0	0	0	0
CT6	4	3	2	4	3	0
CT5	13	0	0	10	11	0
CT4	20	12	1	2	7	0
CT3	21	4	9	19	24	0
CT2	11	37	18	33	6	45
CT1	1	22	23	17	54	56

recovery actions and can necessitate economic adaptations to new industries and sectors (e.g., Ref. [81]). Volcanic systemic vulnerabilities are particularly hard to quantify and qualify, and thus far have seen very limited development in risk assessment frameworks. This study presents a novel attempt to better conceptualise, analyse and quantify systemic vulnerability, whilst respecting the nuances of multi-hazard manifestation in space and time with respect to particular hazard contexts. There is the potential to adapt the methodology for applications to other disaster types, using hazard-specific spatial and temporal patterns (e.g. coastal hugging multi-pulse tsunami dynamics; dynamic or static triggered earthquakes and after-shock sequences).

Practitioners and governance bodies are calling for system-of-systems (SoS) approaches to disaster risk assessment and management, representing sector intra- and inter-dependencies using graph and network theory approaches [3,82]. The use of SoS approaches

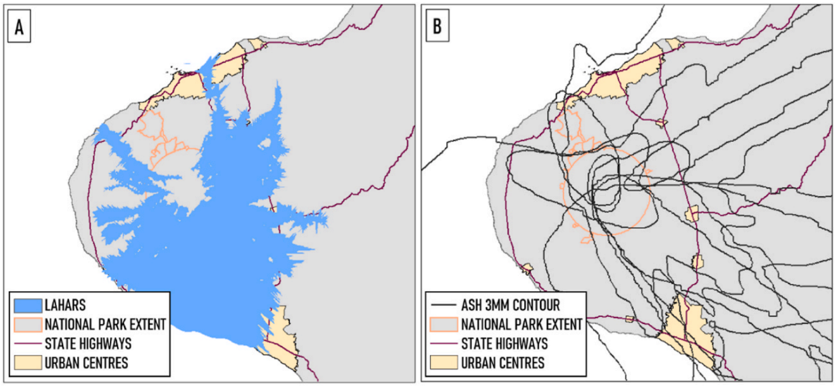


Fig. 12. The volcanic hazard footprints used for nodal groupings in this analysis. Panel A shows the volcanic lahar extent for each river catchment (n = 40), and Panel B shows the ashfall extent for exceedance of the 3 mm deposit thickness threshold.

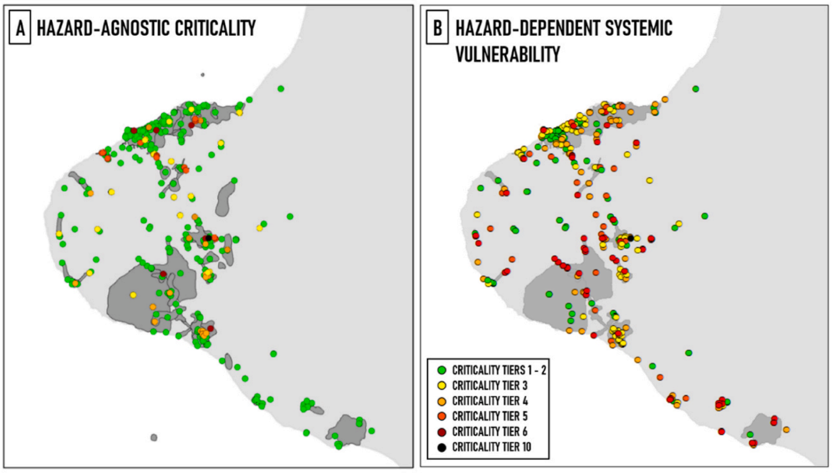


Fig. 13. The hazard-agnostic criticality (Panel A) and the hazard-dependent systemic vulnerability (Panel B) of interdependent infrastructure nodes for sectors in the Taranaki region of Aotearoa.

remain rare with limited applications to single-hazard and single-sector impact and risk studies (e.g., Ref. [54]). This is in part because capturing the dynamics of interactions between multiple complex systems (e.g., natural hazard and societal systems) suffers from the lack of metrics to quantify, disseminate and communicate the potential indirect and cascading impacts of disasters. In this study, we present a novel approach to quantify systemic vulnerability and impacts to better support decision-making.

Disaster risk creation is outstripping disaster risk management efforts, and despite global efforts to reduce disaster impacts, economic and social losses due to natural hazards are increasing [59]. This is in part due to the increased frequency of severe and compounding events but is in larger part due to increasingly high levels of systemic vulnerability to events [59]. Whilst it is recognised that proactive management of systemic risks is the key to future disruption reduction, we lack the tools to identify, assess and manage systemic risks [11]. A key knowledge gap is the characterisation of systemic vulnerability [83], where there is a distinct lack of models and tools to support the characterisation of potential systemic impacts under stress. This knowledge gap allows the proliferation of systemic risks, which undermines the sustainable development of nations and communities [79]. This study presents a novel methodology to characterise and quantify systemic vulnerability, thus enhance the capacity of disaster risk assessment to identify, assess and manage systemic risk, reducing the impacts of future disasters.

Given uncertainty concerning the future dynamics of an ongoing eruption, there is a need for rapid volcanic response tools that consider the current (or immediately previous) state of the volcano, in appreciation of the intra-eruption dependencies of volcanic activity [84–86]. Further, given the potential long-duration of volcanic activity and resultant impacts, there is a need for quick-to-implement testing tools for decision-making, response and mitigation planning. The tools developed in this study have the potential for rapid modification and re-design to suit different operational and research contexts and aim to support decision-makers in the dynamic highly charged emergency planning and response environment.

For decision-makers considering long-term infrastructure planning, this systemic vulnerability quantification can inform the identification of investment priorities for mitigation planning. The nature of the infrastructure network model allows iterative rapid testing of infrastructure failures and can be used to test the efficacy of resilience measures. A review of the co-production mechanisms utilised with stakeholders here, including an assessment of the uptake and success of the approach, is in preparation (Weir et al. in prep). The hazard-agnostic and hazard-dependent differentiation in the methodological stages broadens the range of potential applications of this study. This methodology should be applied in other risk contexts to quantify systemic vulnerability, including for different hazards (such as earthquake sequences or extreme weather events), to test its applicability.

6.2. Limitations and future research

An important limitation of the application of this study to Taranaki Mounga, is that the hazard footprints are from a suite of eruption scenarios that are demonstrative of the range of possible volcanic activity during the *next* eruptive phase. The scenarios are highly informed by the current state of the volcano and the current topographic landscape (current summit dome morphology, current hydrological channels etc.), and are not reflective of the volcanic and geographical context *after* the next period of eruptive activity. Similarly, the network model uses data for the current infrastructure network topology and must be updated for future infrastructure development. The flexibility of the tools presented here, including the eruption scenario suite, allow rapid and easy modification to suit changes in the volcanic or infrastructural context.

Information regarding redundancy measures at sites (e.g. back-up generation and water storage) was not widely available but should be considered in future work. It is however noted that such measures would see short-term reward, and these measures would inevitably be subject to the same factors interdependencies modelled for more permanent infrastructure (e.g. access to critical infrastructure sectors such as electricity, water supply and transportation). Workshops with local infrastructure managers could facilitate study validation and information gathering for future iterations.

The scope of infrastructure considered was limited to municipal critical infrastructure supply and infrastructure associated with major regional industries. Non-municipal supply (such as private water schemes) is common in rural Taranaki, and indeed in many volcanic areas, hence better methods and processes for their inclusion in analyses such as this must be considered in the future. Future iterations and applications of this analysis can modify the interdependency relationships as needed for the local context.

Assumptions were made regarding interdependencies of distributed infrastructure, using insights from published studies [31,54–56,58,87] and the local infrastructure context [72,73]. A key limitation of this study was the treatment of road transportation sector as part of the network graph for interdependent infrastructure. Due to the complexity of road network modelling (in particular), and the complexity of assigning the road network with a resource ‘source’ and resource ‘sink’, full inclusion of this sector in the interdependent network model was considered out-of-scope. Future work should investigate pairing this model with more sophisticated transportation models. We also acknowledge excluding fuel supply and storm water networks are a limitation. Other applications and future iterations of this work could work towards incorporating these additional sectors into the analysis.

7. Conclusions

A new methodology for quantifying systemic vulnerability in the face of spatio-temporally extensive hazards was developed and tested for volcanic multi-hazards. Most previously developed systemic vulnerability methods for distributed infrastructure are hazard-agnostic. While useful for other purposes, these methods are not appropriate in a volcanic risk context, where the spatio-temporal variability of volcanic hazards present a unique risk management challenge.

Applying this systemic vulnerability assessment method to distributed infrastructure in the Taranaki region revealed that the strongest inter-sector dependencies are to the electricity sector. The water supply, waste water, oil and gas and telecommunications sectors are all highly reliant on electricity for their functionality, and the lack of redundancy in electricity supply to the region introduces high systemic vulnerability. The current positioning of the Stratford Grid Exit Point (GXP), downwind of the likely volcanic ash transportation axis, necessitates the consideration of redundancy and mitigation measures before and during volcanic unrest and activity.

This study has developed a tool that allows the rapid assessment of the possible outcomes of hazard instances during hazard uncertainty and constitutes a decision-support tool of great value for long-term infrastructure resilience planning, and future infrastructure investment planning. The study also presents a novel contribution for the assessment of systemic impacts from volcanic eruptions, and a novel platform for the investigation of risk treatments and mitigation strategies before, during and after periods of volcanic activity. We envisage that the methodology of this study can be applied to other areas of interest in both its hazard-agnostic or hazard-dependent form, and that the systemic vulnerability quantification can be incorporated into volcanic multi-hazard impact assessment frameworks.

CRediT authorship contribution statement

Alana M. Weir: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Thomas M. Wilson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Mark S. Bebbington:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Craig Campbell-Smart:** Writing – review & editing, Methodology, Conceptualization. **James H. Williams:** Writing – review & editing, Methodology, Conceptualization. **Roger Fairclough:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization.

Funding

We gratefully acknowledge funding support from the Natural Hazard Research Platform (NHRP) (Grant 2015-MAU-01-NHRP), the He Mounga Puia Transitioning Taranaki to a Volcanic Future programme (Grant UOAX1913) and the Resilience to Natures Challenges (RNC) Volcano (Grant GNS-RNC047), Rural (Grant GNS-RNC045) and Multihazard Risk (Grant GNS-RNC043) programmes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank all those that contributed to the development of the methodology and the application to Taranaki Mounga: Todd Velvin and the wider Taranaki Civil Defence and Emergency Management Group, Teresa Gordon (Ministry for Primary Industries, formerly Taranaki Civil Defence and Emergency Management), the Taranaki Lifelines Advisory Group, New Plymouth District Council, Stratford District Council, South Taranaki District Council, Taranaki Regional Council, Powerco and Firstgas and Dr Natalia Deligne (United States Geological Survey, formerly GNS Science).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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