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ORIGINAL PAPER

Approaching the challenge of multi-phase, multi-hazard volcanic impact assessment through the lens of systemic risk: application to Taranaki Mounga

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Abstract

Effective volcanic impact and risk assessment underpins effective volcanic disaster risk management. Yet contemporary volcanic risk assessments face a number of challenges, including delineating hazard and impact sequences, and identifying and quantifying systemic risks. A more holistic approach to impact assessment is required, which incorporates the complex, multi-hazard nature of volcanic eruptions and the dynamic nature of vulnerability before, during and after a volcanic event. Addressing this need requires a multidisciplinary, integrated approach, involving scientists and stakeholders to co-develop decision-support tools that are scientifically credible and operationally relevant to provide a foundation for robust, evidence-based risk reduction decisions. This study presents a dynamic, longitudinal impact assessment framework for multi-phase, multi-hazard volcanic events and applies the framework to interdependent critical infrastructure networks in the Taranaki region of Aotearoa New Zealand, where Taranaki Mounga volcano has a high likelihood of producing a multi-phase explosive eruption within the next 50 years. In the framework, multi-phase scenarios temporally alternate multi-hazard footprints with risk reduction opportunities. Thus, direct and cascading impacts and any risk management actions carry through to the next phase of activity. The framework forms a testbed for more targeted mitigation and response planning and allows the investigation of optimal intervention timing for mitigation strategies during an evolving eruption. Using 'risk management' scenarios, we find the timing of mitigation intervention to be crucial in reducing disaster losses associated with volcanic activity. This is particularly apparent in indirect, systemic losses that cascade from direct damage to infrastructure assets. This novel, dynamic impact assessment approach addresses the increasing end-user need for impact-based decision-support tools that inform robust response and resilience planning.

Keywords Volcanic risk assessment · Disaster impact assessment · Co-creation · Dynamic risk · Disaster risk reduction · Aotearoa New Zealand

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1 Introduction

Effective volcanic impact and risk assessment underpins effective volcanic disaster risk management (DRM) (UNISDR 2015; Ministry of Civil Defence & Emergency Management (MCDEM) 2019; UNDRR 2019). The drivers of disaster risk can be influenced by practitioners, policy makers, society and individuals, but accurate assessment and reevaluation of risk is required to enable effective disaster risk management decisions (Spence 2004; Coppola 2011; World Bank 2014). Scientific advances in volcanic hazard assessment have increased the capacity for scientists and science agencies to provide more reliable advice to inform decision-making about future volcanic eruptions (Marzocchi et al. 2008, 2010; Lindsay et al. 2010; Sandri et al. 2014; Hayes et al. 2020; Wild et al. 2020). However, when developing appropriate risk management actions for those exposed to volcanic risk, evidence strongly suggests that impact and risk information is substantially more useful, useable and used than hazard information alone (Hicks et al. 2014; Hudson-Doyle et al. 2014b; Armijos et al. 2017; Thompson et al. 2017b; Hicks and Barclay 2018).

Impact assessment requires detailed information regarding hazard potential, exposure and the vulnerability characteristics of the exposed assets and communities (UNISDR 2015). Volcanic eruptions are recognised to be multi-phase events that have the potential to produce multiple hazards throughout an eruptive episode (Jenkins et al. 2007; Marzocchi and Bebbington 2012; Bebbington and Jenkins 2019, 2022). These hazards can have differing physical and chemical characteristics and are subject to different constraints in their spatial and temporal extent. Society is also dynamic, with various drivers influencing exposure and vulnerability in space and time, prior, during and following volcanic activity (Hicks and Few 2015; Few et al. 2017). Yet to date, impact and risk assessment frameworks are typically limited to producing static, single-phase estimations of impact and risk, despite global recognition of the systemic and dynamic nature of disaster risk (Jenkins et al. 2014b; World Bank 2014; Loughlin et al. 2015; UNDRR 2019).

Cascading hazards and vulnerabilities exacerbate the impacts observed from disasters and exhibit strong spatio-temporal dependencies (Zuccaro and De Gregorio 2013; Pescaroli and Alexander 2018; Zuccaro et al. 2018; Dunant et al. 2021a), particularly in a volcanic risk context (Biass et al. 2014, 2016; Hicks and Few 2015; Phillips et al. 2019). Indirect losses during and following disasters are well documented (Galderisi et al. 2011; Cherry et al. 2015; Armijos et al. 2017; Few et al. 2017; National 2017; Thacker et al. 2017a; Phillips et al. 2019; Schweizer and Renn 2019; UNDRR 2019) and are often witnessed far beyond the spatial and temporal extent of the hazard. Critical infrastructure networks are recognised to be essential for the well-being of communities and socio-economic activities and can be highly interdependent (Rinaldi et al. 2001). Despite global recognition of the contribution of indirect infrastructure loss of service to the total observed impact during disaster events (Zorn and Shamseldin 2015; Zorn 2017b; UNDRR 2019), there is little to no incorporation of this dimension in volcanic impact and risk assessment frameworks to date. Yet the inclusion of indirect impacts in volcanic impact assessment frameworks would likely enhance their quality and thus better inform resilience-building initiatives and inform critical infrastructure network management during volcanic crises.

Increasingly, these complex challenges are being addressed by multi-disciplinary teams of scientists and practitioners, that partner in the production of disaster risk reduction (DRR) knowledge and disaster risk management (DRM) strategies (Davies et al. 2015; Barton et al. 2020; Hayes et al. 2020; Weir et al. 2022). Effective disaster risk management (DRM) can be strengthened by partnerships between practitioners and scientists to

develop an understanding of what is legitimate, relevant and credible for the local risk context (Cash et al. 2003; Davies et al. 2015; Fearnley and Beaven 2018; Barton et al. 2020). It follows that collaboration with stakeholders with the relevant expertise and knowledge can greatly increase the effectiveness of impact assessments (Whybark 2015; Thompson et al. 2017b; Orchiston et al. 2018; Barton et al. 2020; Mach et al. 2020).

This study develops and presents a framework for impact assessment under multi-phase, multi-hazard volcanic events and tests the effectiveness of the framework for mitigation planning and risk management interventions. The framework incorporates direct and indirect impacts to interdependent infrastructure networks and was developed in partnership with local end-user agencies. The framework addresses the growing demand for impact-based decision-support tools to facilitate more targeted, considered response and mitigation planning, ultimately contributing to reducing losses associated with multi-hazard volcanic eruptions. We apply the framework to interdependent critical infrastructure sectors in the Taranaki region of Aotearoa New Zealand, where Taranaki Mounga[1] volcano is estimated to have a 33–42% likelihood of erupting within the next 50 years (Damaschke et al. 2018).

1.1 Multi-hazard impact and risk assessment: approaches

Multi-hazard impact and risk assessment has been identified as an important requirement for disaster risk assessment (AghaKouchak et al. 2018; Ordaz et al. 2019; UNDRR 2019), but is a research area in need of further development. Previous studies have generally been focused on hazard, particularly the quantification of cascading and interacting hazard relationships and their contribution to potential exposure and impacts (Zuccaro et al. 2008; Deligne et al. 2017a, b; Bathrellos et al. 2017; Yousefi et al. 2020; Dunant et al. 2021a, b; Skilodimou and Bathrellos 2021). There has been comparatively less attention given to integrating exposure, vulnerability and resilience elements of impact and risk within these frameworks (Ordaz et al. 2019; Phillips et al. 2019; Wang et al. 2020; Dominguez et al. 2021; Kc et al. 2021). Various studies have attempted and noted the difficulty in integrating the physical and spatio-temporal characteristics of different hazards to produce an appropriate common metric which can be used within multi-hazard impact and risk assessment frameworks (Kappes et al. 2012; Tilloy et al. 2019; Wang et al. 2020). Attempts to address this have led to contributions in quantifying multi-hazard potential, generally either qualitatively or semi-quantitatively as hazard classifications or indices, where multi-hazards are typically related by intensity, duration and/or recurrence interval to deduce the 'hazard level' at a given location (e.g. "high ashfall and high lahar hazard") (Tilloy et al. 2019; Wang et al. 2020). There has also been the strong appreciation that such frameworks and their resultant outputs can be highly technical, so a key consideration is also to ensure the resultant impact and risk metrics are suitable for end-user purposes (Wachinger et al. 2013; Hicks et al. 2014; Hudson-Doyle et al. 2014b, a; Davies and Davies 2018).

Few studies have considered the relative contribution from multi-hazards to observed or potential impact (e.g. damage and disruption) and how this manifests throughout a multi-hazard cascading initiation sequence. Notable exceptions include Zuccaro et al. (2008) and Zuccaro et al. (2018). Additionally, due to the uncertainty and complexity of probabilistic approaches, they have proven to be difficult for many DRM users to adopt, with the notable

[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.*

exception of insurance, building code regulation and construction, and some land use planning applications (Haynes et al. 2008; Global Facility for Disaster Reduction and Recovery 2014; Hudson-Doyle et al. 2014b; World Bank 2014; Davies and Davies 2018). Hybrid impact-led approaches that enhance the value of both deterministic (scenario) and probabilistic outputs are finding increasing favour (Thompson et al. 2017b; Ang et al. 2020; Hayes et al. 2020), especially in settings where scientists and users have attempted to collaboratively partner in DRR activities that distil the complexity of potential impacts in a credible, yet useable way (Haynes et al. 2008; Barclay et al. 2008; Hudson-Doyle et al. 2015; Ang et al. 2020; Hayes et al. 2020).

Volcanic multi-hazard impact and risk assessment is in the early developmental stages, with recent advances in multi-hazard assessment (Tierz et al. 2017; Hayes et al. 2020), single-phase multi-hazard impact assessment (Zuccaro et al. 2008; Jenkins et al. 2014a), and co-development of impact-based decision-support tools (Hicks et al. 2014; Wild et al. 2019, 2021) providing valuable insight into best-practice approaches and research development required.

2 Longitudinal multi-hazard volcanic impact assessment: design and requirements

2.1 Partnering with DRR knowledge end-users: needs and requirements

The collaborative development and management of impact assessment frameworks with information end-users can facilitate knowledge sharing and increase the relevance and uptake of scientific information (Davies 2015, Barton 2020). Well-managed collaborations between science, practice and policy have been found to result in enduring, partnerships that contribute to scientifically robust knowledge that meets the requirements of the decision-makers (Wyborn et al. 2017; Fearnley and Beaven 2018; Barton et al. 2020; Mach et al. 2020). This study was conducted alongside Weir et al. (2022) and shares the collaborative, co-production approach with stakeholders and research partners (refer to Weir et al. (2022) for more detail). As in Weir et al. (2022), 'co-production of [knowledge in] this study [was achieved via three main mechanisms]: embedding the lead science author of this study (Weir) in the most appropriate policy and practice agency (the local emergency management authority) for several weeks (1), regular semi-structured meetings between actors either side of the SPPI (2), and iterative ongoing validation of the outcomes with the emergency management agency's wider stakeholder networks (3). These mechanisms were used to establish the key objectives of this study (1), clearly identify the scope (1, 2), and ensure that the format and content of the study was relevant and applicable (1, 2, 3)' (p. 4, Weir et al. 2022).

During and after the embedding period, the lead author coordinated and facilitated monthly semi-structured meetings between volcanic hazard and risk scientists and emergency management practitioners involved in this study to identify and develop solutions for a series of key issues surrounding volcanic risk assessment and management for future Taranaki Mounga volcanism. This decision-making process had two main stages of methodological development: a knowledge stock take (Stage 1) and evaluation of the suitability of available volcanic impact assessment frameworks (Stage 2) (Table 1). Both the scientists and the practitioners were motivated to identify problems and develop solutions; however, some aspects were more strongly motivated by scientists (e.g. the development of

Table 1 The key scoping and problem identification stages in the co-production process

Relevant local context	Scoping stage	Problem	Solution
Taranaki Mounga has a high likelihood of producing an explosive eruption (Damaschke et al. 2018)	Stage 1: Knowledge stock-take and knowledge gap identification	Lack of understanding of the translation of potential hazards (Weir et al. 2022) into potential impact	Conduct a volcanic impact assessment for critical infrastructure sectors in the Taranaki region (this study)
The Taranaki region houses nationally and regionally significant critical infrastructure		Lack of impact assessment studies for critical infrastructure sectors in the Taranaki region (Weir et al. 2022)	
Taranaki Mounga has a high potential of producing a long-duration, multi-phase, multi-hazard eruption (Weir et al. 2022)	Stage 2: Evaluation of available volcanic impact assessment frameworks	Lack of available volcanic impact assessment frameworks for multi-phase, complex eruptions	Develop a multi-phase volcanic impact assessment framework (this study)
Critical infrastructure sectors in the Taranaki region are highly interdependent		Lack of volcanic impact assessment frameworks that incorporate indirect infrastructure impact	Develop a volcanic impact assessment framework for direct and indirect impacts (this study)
Local authorities are tasked with planning for and responding to volcanic activity (CDEM Act 2002)		Lack of volcanic impact assessment frameworks that test decision-making scenarios	Develop a volcanic impact assessment framework that allows testing of decision-making scenarios and optimal intervention time (this study)

The table shows the issues identified by Taranaki Civil Defence and Emergency Management (Taranaki CDEM, the local emergency management authority) and the authors co-creatively, and the resultant actions taken, documented in this study

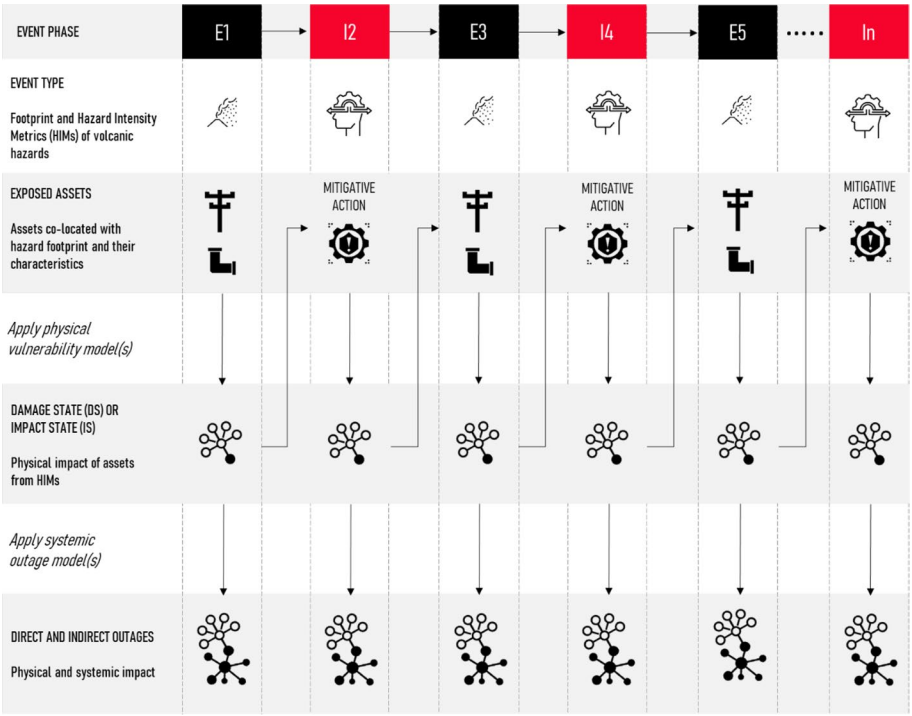

Fig. 1 The dynamic impact assessment framework comprised of five modules: (1) volcanic multi-hazard, multi-phase footprints (E_1, E_3, E_5…E_n), (2) risk management interventions (I_2, I_4 … I_n), (3) exposed assets and their characteristics, (4) direct impact to assets, and (5) indirect impact to assets

novel, sophisticated volcanic hazard and risk assessment tools), and some by practitioners (e.g. tools to support decision-making for volcanic risk management and volcanic crisis response). Balancing the scientific credibility and operational relevance of the resultant volcanic impact assessment framework enhanced the legitimacy of the research outcomes, as it well reflects the knowledge requirements of both scientists and practitioners.

2.2 Longitudinal multi-hazard volcanic impact assessment for interdependent infrastructure: framework design

This study presents a multi-phase, multi-hazard impact assessment framework that carries previously incurred component damage through to the next volcanic activity phase, assesses downstream, systemic outages associated with the physical damage of infrastructure assets, and allows the evaluation of mitigation or decision-making efficacy during an evolving multi-phase event sequence (Fig. 1). By alternating volcanic activity phases with decision-making opportunities, the framework allows testing of the timing of risk management actions and considers how different elements of systemic risk cascade to provoke losses in the event of a disaster. The study utilises pre-existing hazard, exposure and vulnerability tools and information as building blocks (or modules) in the framework, and applies the resultant framework to conduct a longitudinal impact assessment for distributed

interdependent infrastructure networks surrounding Taranaki Mounga volcano, in the Taranaki region of Aotearoa New Zealand.

2.2.1 Framework modules

The impact assessment framework is comprised of five key modules, detailed in the following sections. The modules are: (1) volcanic activity events (VAEs) (2) risk management interventions (RMIs), (3) exposed interdependent infrastructure assets, (4) volcanic multi-hazard direct impact and (5) indirect impact. The framework and its five constituent modules are illustrated in Fig. 1. The proposed dynamic volcanic impact assessment framework requires volcanic hazard footprints for a multi-phase eruption. The VAEs (E_1, E_3, E_5…E_n) are interspersed with potential opportunities for mitigation (RMIs; I_2, I_4, I_6…I_n) (Fig. 1). VAEs can consist of multiple volcanic hazards, such as ashfall concurrent with pyroclastic density currents (PDC) or lava flows. Spatial determination of hazard footprints is required in order to deduce the assets directly exposed to the volcanic hazards.

In this framework, accumulated direct impact to an infrastructure asset from volcanic hazards is carried through to the next event in the framework. For each VAE, relevant vulnerability models are applied to calculate the direct impact to exposed assets. As different volcanic hazards possess differing physical behaviours and properties, the best hazard intensity metric (HIM) to evaluate impact for one hazard may not be appropriate for use when assessing impact from a different hazard. An Impact State (IS) metric accounts for differing physical parameters and is used in this multi-hazard framework. Volcanic impacts can be expressed using different IS metrics, such as physical damage, service disruption or economic loss (Marzocchi and Woo 2009; Wilson 2015; Mcdonald et al. 2017).

Following the determination of direct impact, indirect impact through an interdependent network graph of critical infrastructure is then calculated. For the next VAE, the exposure inventory is comprised of the direct and indirect impact dataset from the previous VAE, thus carrying previously incurred damage and disruption throughout to the subsequent phases. RMIs exist between each VAE. If the RMI following a VAE is populated with a risk management action or decision, the exposure inventory is modified and carried through to the next event (e.g. if the RMI is roof cleaning before further ash deposition, the ashfall thickness at the start of the next VAE is 0 mm, rather than accumulating the thickness between phases).

2.3 Direct impact: accounting for multi-hazards

Volcanic ash physical vulnerability models have been derived from post-event observations, laboratory experimentation and expert elicitation (Spence et al. 2005; Stewart et al. 2006; Wilson et al. 2011, 2012, 2017; Jenkins et al. 2014b; Craig 2015; Thompson et al. 2017a), resulting in a suite of vulnerability models that typically assess vulnerability to ashfall using mathematical functions, e.g. fragility functions (Wilson et al. 2014, 2017; Blake et al. 2017). Vulnerability models regarding impacts from volcanic surface flows, such as lahars, are generally derived from post-event surveying (Baxter et al. 2005; Künzler et al. 2012; Jenkins et al. 2013, 2014a, 2015) and tend to determine threshold values that lead to gradational or absolute impact of the exposed asset, therefore generating a suite of binary or threshold vulnerability model types (Spence et al. 2004; Baxter et al. 2005; Wilson et al. 2014; Deligne et al. 2017b), though some fragility functions are available for building responses to flow hazards (Zuccaro and De Gregorio 2013; Jenkins et al. 2015).

Despite recognition that volcanic eruptions are inherently multi-phase events that often produce multiple hazards (Jenkins et al. 2007; Bebbington and Jenkins 2019; Lerner et al. 2019), there are few, if any, vulnerability models that account for the compounding and cascading nature of volcanic multi-hazard impacts (Zuccaro et al. 2008; Deligne et al. 2017b). In this framework, we applied a simplistic approach to account for multi-hazard interactions in volcanic contexts. As available vulnerability models for volcanic surface flows and critical infrastructure assets (excluding buildings) assume maximum impact upon contact (Wilson et al. 2014, 2017; Wilson 2015), we follow this approach in this framework. Surface flow vulnerability models can therefore be simply coupled with ashfall vulnerability models, by considering the accumulated impact, which is maximal if a lahar is involved. For multiple instances of ashfall, the HIM (in many cases, deposit thickness) is accumulated and the total HIM related to IS using an available physical vulnerability model. Remobilisation and cleaning of ashfall deposits can be applied in this framework, during the risk management intervention phases, and the resultant phases can be modified accordingly.

2.4 Indirect (cascading) impact to interdependent infrastructure networks

The proposed dynamic volcanic impact assessment framework requires an understanding of the critical infrastructure downstream dependencies and interdependencies between infrastructure sectors and asses in the exposed networks. Direct damage to assets reduces the functionality of dependent assets (Rinaldi et al. 2001; Setola et al. 2009; Zorn 2017a; Hempel et al. 2018). Recent advances in systems and network analysis quantify system dependencies for electricity, water supply and telecommunications in particular (Zorn and Shamseldin 2015, 2016, 2017; Thacker et al. 2017b; Zorn 2017b; He and Cha 2018) and allow the incorporation of these tools in impact assessment frameworks.

The cascading (indirect) infrastructural impacts following direct impacts to assets can be estimated, by propagating infrastructure disruption downstream in an interdependent network graph (Weir 2021). Here we apply that method to the multi-hazard multi-phase eruption suite developed by Weir et al. (2022) and use it to quantify the systemic vulnerability of the region to volcano events. Then, by introducing the opportunity for dynamic risk management intervention in the framework, we explore the degree to which this vulnerability can realistically be mitigated.

3 Case study risk context: Taranaki Mounga volcano, Aotearoa New Zealand

Taranaki Mounga (Mount Taranaki) is an active stratovolcano, located in the Taranaki region on the west coast of Te Ika-a-Māui the North Island of Aotearoa New Zealand (Fig. 2B). Volcanism at Taranaki Mounga is characterised by cycles of edifice growth and collapse (Zernack et al. 2011; Lerner et al. 2019; Cronin et al. 2021). The cone growth periods are characterised by effusive and lava dome-forming activity, interspersed with explosive sub-Plinian to Plinian eruptions (Platz et al. 2007; Turner et al. 2011; Lerner et al. 2019; Cronin et al. 2021). Typical far-reaching volcanic hazards include column-collapse and block-and-ash flow pyroclastic density currents (PDCs), ashfall, debris avalanches caused by edifice collapse, and frequent remobilisation of volcanic debris in the form of lahars (Fig. 2D). Proximal hazards, such as volcanic ballistic projectiles (VBPs) and lava

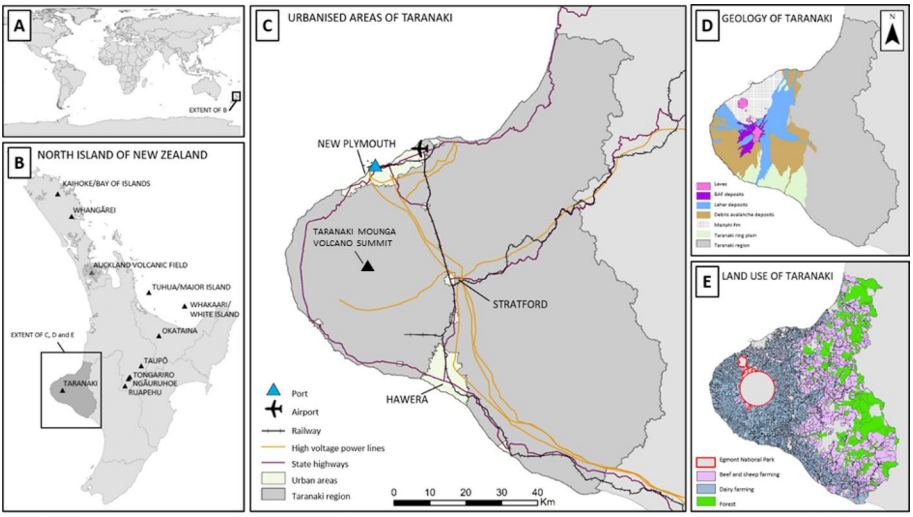

Fig. 2 **A** The location of Aotearoa-New Zealand; **B** the location of the Taranaki region and volcanic centres of Aotearoa New Zealand; **C** urban centres and selected critical infrastructure of the region; **D** simplified geology of the Taranaki volcanic complex; **E** land use of the Taranaki region. Modified from Weir et al. (2022). The geographic extent of **C**, **D** and **E** is −38.713711, 173.252031 (top left) to −39.929024, 175.071420 (bottom right)

flows, are relatively infrequent in Taranaki Mounga's eruptive history (Turner et al. 2011) and are typically constrained to the current extent of the Te Papakura o Taranaki National Park. Lerner et al. (2019) dated the most recent eruptive activity at Taranaki Mounga to 1780–1800 AD. This activity produced many small effusive and explosive eruptions, and a final dome-building event built the current summit topography (Neall 1972; Platz et al. 2012). Damaschke et al. (2018) estimates there to be a 33–42% probability of an eruption within the next 50 years.

The Taranaki region has the second highest Gross Domestic Product (GDP) per capita in Aotearoa New Zealand (NZD $68,427 in 2018; NZD $58,778 was the national average) (Stats NZ 2018). Dairy, together with oil and gas production and processing, are the two key economic activities in the Taranaki region (Venture Taranaki 2017). State highways circumnavigate Taranaki Mounga, providing vital transport links along the western part of the North Island (Fig. 2C). Other critical networks include freight-only railway lines, electricity transmission lines and oil and gas pipelines. The majority of local infrastructure is located in the three main population centres [New Plymouth (pop: 74,184), Stratford (pop: 9474) and Hawera (pop: 9810)] (Fig. 2C), with collection and transmission infrastructure ensuring continued supply to processing plants, and municipal supply of critical infrastructure to rural consumers.

The Taranaki region has 530 named rivers, most of which extend radially from Taranaki Mounga. Critical infrastructure such as telecommunications lines, water pipes, and oil and gas pipelines are often bound beneath road bridges or cross rivers as pipe bridges, meaning they are highly exposed to volcanic surface flows such as lahars and PDCs. Further, subaerial infrastructure such as electricity transmission and distribution lines are often co-located parallel to road transportation. Taranaki Mounga is within the Te Papakura o Taranaki National Park, which is managed by Te Papa Atawhai the Department of Conservation (DoC). The national park extends ~ 10km radially from the volcanic summit

(Fig. 2E), which limits urban development close to the volcanic edifice, thus ensuring minimal exposure of the built environment to volcanic hazards.

Regional Civil Defence and Emergency Management (CDEM) groups in Aotearoa New Zealand are entrusted with developing plans and strategies for the management of hazards relevant to their geographic region. Further, they are tasked with facilitating relationships, discussion and knowledge transfer between regional agencies, stakeholders and groups (MCDEM 2005, 2010, 2015). The Taranaki CDEM group is therefore responsible for volcanic risk reduction, response and resilience planning in the Taranaki region. The Taranaki CDEM group recognises that strong partnerships with researchers is a key element of producing actionable science for disaster risk assessment and management (New Zealand Government 2015).

Direct economic losses associated with a volcanic event at Taranaki only comprise a fraction of total expected loss: McDonald et al. (2017) calculates an 'initial shock' change in gross domestic product (GDP) of −66% (−$4106 million NZD) in the Taranaki region alone for a high-intensity volcanic eruption scenario. Indirect impacts, such as supply chain distribution, staffing shortage, air travel disruption, electricity/water outages, and business non-continuity, could cause substantial economic losses and are highly variable both spatially and temporally (Mcdonald et al. 2017).

4 Case study application: direct impact assessment data and models

Weir et al. (2022) developed a suite of multi-phase, multi-hazard volcanic eruption scenarios for Taranaki Mounga, using a modular scenario development framework. The scenario suite consists of nine hypothetical eruption scenarios (comprised of 'small' (S1, S2 and S3), 'medium' (M1, M2 and M3) and 'large' (L1, L2 and L3) sub-suites), each with six potential phases of volcanic activity [named phases 1d, 2p, 3d, 4p, 5d and 6p; where *d* is discrete (occurring over 1 day) and *p* is prolonged (occurring over weeks to months)] (Weir et al. 2022). The scenarios cover a credible range of volcanic magnitudes, styles, durations and hazards and were co-produced with end-users and decision-makers. Weir et al. 2022) includes many volcanic hazards as part of the scenario suite, but only provides spatial footprints for ashfall and lahar hazards. This is in part due to limited asset exposure within 10km of the summit (i.e. within Te Papakura o Taranaki National Park), which also constrains other hazards, such as pyroclastic density currents (PDCs) (Procter et al. 2010). We therefore consider direct impact from only ashfall and lahars in this initial impact assessment application.

Critical infrastructure exposure data were collected and compiled for six sectors: electricity, water supply, road transportation, wastewater, energy (oil and gas) and telecommunications. These six sectors are recognised to be of vital importance for national security and public welfare (Taranaki Civil Defence and Emergency Management Group 2018; Ministry of Civil Defence & Emergency Management (MCDEM) 2019; New Zealand Lifelines Council 2020; New Zealand Infrastructure Commission 2022). Membership of the Taranaki Civil Defence and Emergency Management (CDEM) Lifelines Advisory Group (LAG) is principally comprised of representatives from these six sectors, and the scope of critical infrastructure considered in this study was validated by end-users (Taranaki CDEM and the Taranaki CDEM LAG).

Spatial and asset characteristic data for these six sectors were acquired from a variety of sources, some from open-source data repositories (Land Information New Zealand (LINZ);

Table 2 Logic treatment of sequential ashfall and surface flow hazards in vulnerability model

Hazard 1	Hazard 2	
	Ashfall	Surface flow
Ashfall	Accumulate HIM (e.g. deposit thickness; ash loading) and apply in vulnerability model	Assume IS_{max}; no change with successive ashfall or lahars
Surface flow	Assume IS_{max}; no change with successive ashfall or lahars	Assume IS_{max}; no change with successive ashfall or lahars

Koordinates) and others were shared by the data owner(s). Data sharing by infrastructure providers was facilitated by Taranaki CDEM, the LAG, and their wider stakeholder network. Where appropriate, data sharing agreements were entered into, and where possible, any inconsistencies across data sources were addressed through consultation with data providers. This process of data collection, unification and quality checking was undertaken during the aforementioned embedding and engagement process with Taranaki CDEM. In several instances, asset data were created or edited by the first author by referring to official open-source documentation and validated using satellite imagery (such as water supply inlets, inferred from the district council Water Asset Management Plans) (Table 3). Asset classes are broadly distinguished as either nodes (e.g. electricity substations or water treatment plants) or lines (e.g. electricity lines and water supply pipes) (Table 3). Line-type infrastructure was broken into 100m spans for the purpose of analysis, consistent with hazard data resolution (Weir et al. 2022).

Several review studies compile global accounts and records of volcanic impacts to infrastructure and present an overview of the current global knowledge base (Wilson et al. 2014, 2017; Wilson 2015). Most vulnerability models used in the present application to Taranaki Mounga are to be found in these studies, supplemented by targeted studies on roads (Blake et al. 2017) and energy (Juniper 2018) sector vulnerability to volcanic hazards (Table 4). The vulnerability models used are either fragility functions (Blake et al. 2017; Wilson et al. 2017) or damage matrices (Juniper 2018; Wilson et al. 2014). When applying fragility functions, a randomly generated number was used to generate one impact outcome, consistent with other recent fragility function application approaches (Williams et al. 2020, 2022).

In Weir et al. (2022), the hazard intensity metrics (HIMs) presented in the eruptions scenarios are deposit thickness (mm) for ashfall, and presence/absence for lahars, consistent with lahar vulnerability models for critical infrastructure assets in Wilson et al. (2014). Lahar vulnerability models available in Juniper (2018) use dynamic pressure (kPa) as the HIM, which is absent from the Weir et al. (2022) scenario suite. Therefore, in this study we assume energy assets exposed to lahars incur total damage, consistent with Wilson et al. (2014), where across all critical infrastructure sectors studied, lahar flow velocities > 0 m/s and lahar flow depth > 0 m result in the asset reaching the maximum impact state (in Wilson et al. (2014), Damage Level 3: Replacement or financially expensive repair).

When assets are exposed to multiple hazards, we apply the coupled physical vulnerability approach for ashfall and lahars (Table 2). Typically, when an asset is exposed to a

Table 3 The critical infrastructure sectors, providers, asset classes, and (geospatial and asset characteristic) data sources in this study, where 'DSA' is *data sharing agreement with provider*, 'OS' is *open-source data* and 'FAS' is *first-author-supplemented data*. Also shown are the vulnerability models applied for each asset class, for ashfall and lahars

Sector	Sub sector	Provider	Asset Class	Type (node or line)	Data source	Ashfall Vulnerability Model	Lahar Vulnerability Model
Electricity	Transmission	Transpower New Zealand Ltd	Electricity Lines	Line	OS	Wilson et al. (2017)	n/a
			Substations	Node	OS	Wilson et al. (2017)	Wilson et al. (2014)
			Poles	Node	OS	n/a	Wilson et al. (2014)
	Distribution	Powerco Ltd	Electricity lines	Line	DSA	Wilson et al. (2017)	n/a
			Substations	Node	DSA	Wilson et al. (2017)	Wilson et al. (2014)
			Poles	Node	DSA	n/a	Wilson et al. (2014)
Water supply	Collection	District councils (NPDC; SDC; STDC)	Surface water intakes; groundwater intakes (bores)	Node	OS; FAS[1]	Wilson et al. (2014)	Wilson et al. (2014)
	Treatment	District councils (NPDC; SDC; STDC)	Water treatment plants	Node	OS; FAS[1]	Wilson et al. (2017)	Wilson et al. (2014)
	Distribution	District councils (NPDC; SDC; STDC)	Water pipes (including aerial crossings)	Line	OS; FAS[1]	n/a	Wilson et al. (2014)
	Storage	District councils (NPDC; SDC; STDC)	Reservoirs	Node	OS; FAS[1]	Wilson et al. (2014)	Wilson et al. (2014)
Road transportation	State Highways	Waka Kotahi NZ Transport	Roads	Line	OS	Blake et al. (2017)	Wilson et al. (2014)
			Bridges	Node	OS; FAS[2]	*Assumed as roads;* Blake et al. (2017)	Wilson et al. (2014)
	Other	District Councils (NPDC; SDC; STDC)	Roads	Line	OS	Blake et al. (2017)	Wilson et al. (2014)
			Bridges	Node	OS; FAS[2]	*Assumed as roads;* Blake et al. (2017)	Wilson et al. (2014)

Table 3 (continued)

Sector	Sub sector	Provider	Asset Class	Type (node or line)	Data source	Ashfall Vulnerability Model	Lahar Vulnerability Model
Wastewater	Treatment	District councils (NPDC; SDC; STDC)	Wastewater treatment plants	Node	OS	Wilson et al. (2017)	Wilson et al. (2014)
	Transmission	District councils (NPDC; SDC; STDC)	Wastewater pipes (including aerial crossings)	Line	OS	n/a	Wilson et al. (2014)
			Wastewater pumping stations	Node	OS	Wilson et al. (2014)	Wilson et al. (2014)
Energy	Upstream	Various exploration and production companies (~20)	Well Heads	Node	DSA	n/a	Juniper (2018)
			Production facilities	Node	DSA	Juniper (2018)	Juniper (2018)
	Transmission (mid-stream)	First Gas Ltd (and partners)	Pipelines (including aerial crossings)	Line	DSA	n/a	Juniper (2018)
			Pipeline substation	Node	DSA	n/a	Juniper (2018)
	Storage	Various transport, storage and processing companies (~6)	Tanks	Node	DSA	Juniper (2018)	Juniper (2018)
	Distribution	Powerco Ltd	Pipelines	Line	DSA	n/a	Juniper (2018)
Telecommunications	Collection	Vodafone NZ Ltd, Spark NZ Ltd, 2 Degrees Mobile Ltd	Cellular towers	Node	OS; FAS[1]	Wilson et al. (2014)	Wilson et al. (2014)
	Transmission	Chorus NZ Ltd	Exchanges	Node	OS; FAS[1]	Wilson et al. (2014)	Wilson et al. (2014)

[1]Data inconsistencies between district councils were supplemented using publically available asset management plans and satellite imagery

[2]Data supplemented by inferring bridge localities at the intersection of roads and rivers (publically available datasets)

Table 4 Impact metrics and hazard intensity metric (HIM) requirements for the vulnerability models used in this impact assessment application, and details of conversions made from available HIMs in Weir et al. (2022). Also shown are conversions made between impact metrics in available studies, and the impact metric used in this study (Wilson et al. 2017)

Study	Data type	Impact metric description	HIM requirements (ashfall)	HIM requirements (lahar)	Impact metric tiers and classifications		HIM conversion for this application (ashfall)	HIM conversion for this application (lahar)	IS conversion for this application	
Juniper (2018)	Expert judgement	Impact State (IS); 4-tier	Ashfall load (kPa)	Dynamic pressure (MPa)	D0	No physical damage	Convert thickness (mm) to load (kPa), assuming a deposit density of 1000 kg m^{-3}	Assume presence of lahar (> 0 MPa) results in D3	D0	IS_0 (Wilson et al. 2017)
					D1	Minor (no structural) damage			D1	IS_1 (Wilson et al. 2017)
					D2	Major (structural) damage			D2	IS_2 (Wilson et al. 2017)
					D3	Total physical asset destruction			D3	IS_3 (Wilson et al. 2017)
Blake et al. (2017)	Empirical (impact data); expert judgement; laboratory experimentation	Impact State (IS); 4-tier; disruption	Deposit thickness (mm)	n/a	IS_0	No disruption	n/a	n/a	IS_0	IS_0 (Wilson et al. 2017)
					IS_1	Skid resistance reduction			IS_1	IS_1 (Wilson et al. 2017)
					IS_2	Impassable for some vehicles			IS_2	IS_2 (Wilson et al. 2017)
					IS_3	Impassable if tephra unconsolidated			IS_3	IS_3 (Wilson et al. 2017)

Table 4 (continued)

Study	Data type	Impact metric description	HIM requirements (ashfall)	HIM requirements (lahar)	Impact metric tiers and classifications	HIM conversion for this application (ashfall)	HIM conversion for this application (lahar)	IS conversion for this application
Wilson et al. (2017)	Empirical (impact data); expert judgement	Impact State (IS); 4-tier; aggregate of physical damage and disruption	Deposit thickness (mm)	n/a	IS_0 No damage IS_1 Cleaning required IS_2 Repair required IS_3 Replacement or financially expensive repair	n/a	n/a	n/a
Wilson et al. (2014)	Empirical (impact data); expert judgement	Impact/Damage Level (DL); 4-tier; aggregate of physical damage and disruption	Deposit thickness (mm)	Flow depth (m) or flow velocity (m/s)	DL0 No damage DL1 Cleaning required DL2 Repair required DL3 Replacement or financially expensive repair	n/a	Assume presence of lahar results in flow depth > 0 m	n/a

lahar, total asset damage is incurred (Wilson et al. 2014), and thus in this study, we assume the maximum impact state until the end of the scenario, regardless of further exposure to ashfall and lahar hazards. For multiple instances of ashfall, the thickness is accumulated and the total thickness is related to an impact state using the vulnerability models listed in Table 3. The impact metrics used in the physical vulnerability models applied in this study are shown in Table 4. For this application, we adopt the four-tiered 'Impact State' (IS) metric used by (Wilson et al. 2017) and Wilson et al. (2014) and make necessary conversions from Blake et al. (2017) and Juniper (2018) (Table 4).

To quantify indirect impact on infrastructure sectors, we use the graphical approach and tools developed for the Taranaki region in Weir (2021). The graphical approach for interdependent infrastructure determines the reach of source to sink resource flow following direct impact to assets. In this application, we assume assets are functional under IS0 and IS1 (no damage and cleaning required, respectively) and complete loss of functionality under IS2 and IS3 (repair required and replacement required (or financially expensive repair), respectively). Assets determined to be at IS2 or IS3 following direct impact from volcanic hazards are therefore absent in the resultant network graph configuration, and the source to sink disruption is recorded and carried through to the next event in the framework. Indirect impact (i.e. loss of service due to physical damage upstream of resource flow) is assumed to be binary, and assets indirectly impacted are recorded as being 'indirectly disrupted' (ID).

5 Longitudinal volcanic multi-hazard impact assessment results

5.1 Direct impact assessment: results across sectors

The direct, physical impact to assets for six infrastructure sectors (electricity, water supply, waste water, oil and gas, transportation and telecommunications) were calculated for all nine eruption scenarios in the scenario suite. An IS is given for each asset in the inventory for each phase of volcanic activity (1d, 2p, 3d, 4p, 5d and 6p; where *d* is 'discrete' (phase duration 1 day), and *p* is 'prolonged' [phase duration is user specified) (Weir et al. 2022)], providing a longitudinal direct impact analysis under variable, credible volcanic regimes. Direct impact data is available for each sector ($n=6$), at each phase ($n=6$) of each scenario ($n=9$), resulting in 324 data frames (though 30 of these data frames show no change in direct impact due to volcanic inactivity). The direct impact to the electricity sector (transmission and distribution) is shown in Fig. 3, and the direct impact to water supply in Fig. 4. Figure 5 shows the direct impact to electricity infrastructure at each volcanic activity phase during the scenario (phases 1d, 2p, 3d and 4p), using scenario M2 as a representative mid-range scenario.

Across all sectors, 58% of nodes achieve IS3 in at least one scenario (Table 5), with 40% of nodes at IS3 for at least two of the eruption scenarios. One water supply inlet in South Taranaki district, upstream of a large municipal supply catchment, reaches IS3 in 8 of the 9 eruption scenarios. Of the 21 nodes that reach IS3 for 5 or more scenarios, 11 of these nodes are water supply nodes (9 surface water inlets, 1 water treatment plant and 1 reservoir), 5 are oil and gas production or transmission sites, 2 are electricity distribution substations, 2 are cell towers and 1 is a waste water treatment plant.

There are 563 occurrences of a node asset reaching IS3 across all sectors, for all scenarios. Of these, 63% are due to exposure to lahars (Table 6). There are 167 node assets that reach

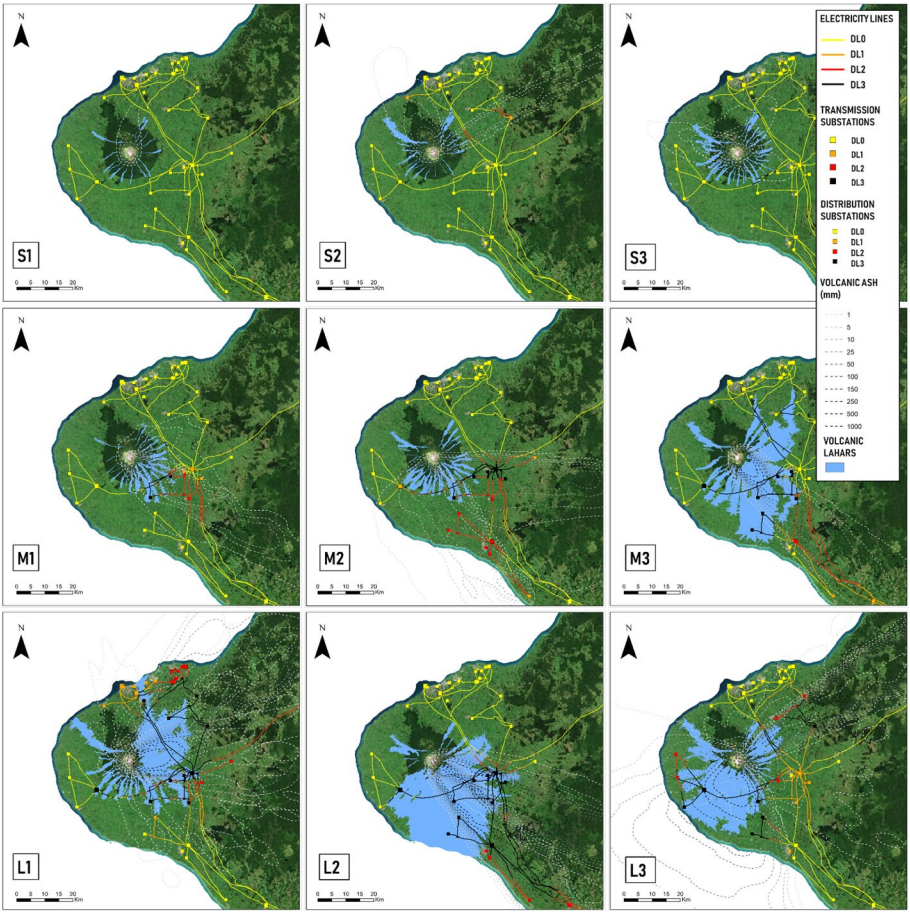

Fig. 3 The direct impact to electricity transmission and distribution infrastructure in the Taranaki region of Aotearoa New Zealand. The impact is shown at volcanic activity phase 6p (i.e. at the end of the eruption sequence) for each of the nine scenarios (S1–L3)

IS2, corresponding to 'requires repair', at least once throughout the scenario suite from exposure to ashfall. Of these nodes 28% are water supply nodes, 19% are waste water, 19% are telecommunications, 17% are electricity, and 17% are oil and gas. For infrastructure lines, the total length in different ISs was determined for the subaerial electricity and transportation sectors. For other sectors with buried line infrastructure (water supply, waste water and oil and gas), the total number of breakage points were summed, as impact was assumed only in topographic depressions upon contact with a lahar, where buried infrastructure is generally carried by road or pipe bridges. The total length and number of breakage points for each scenario are shown in Table 7.

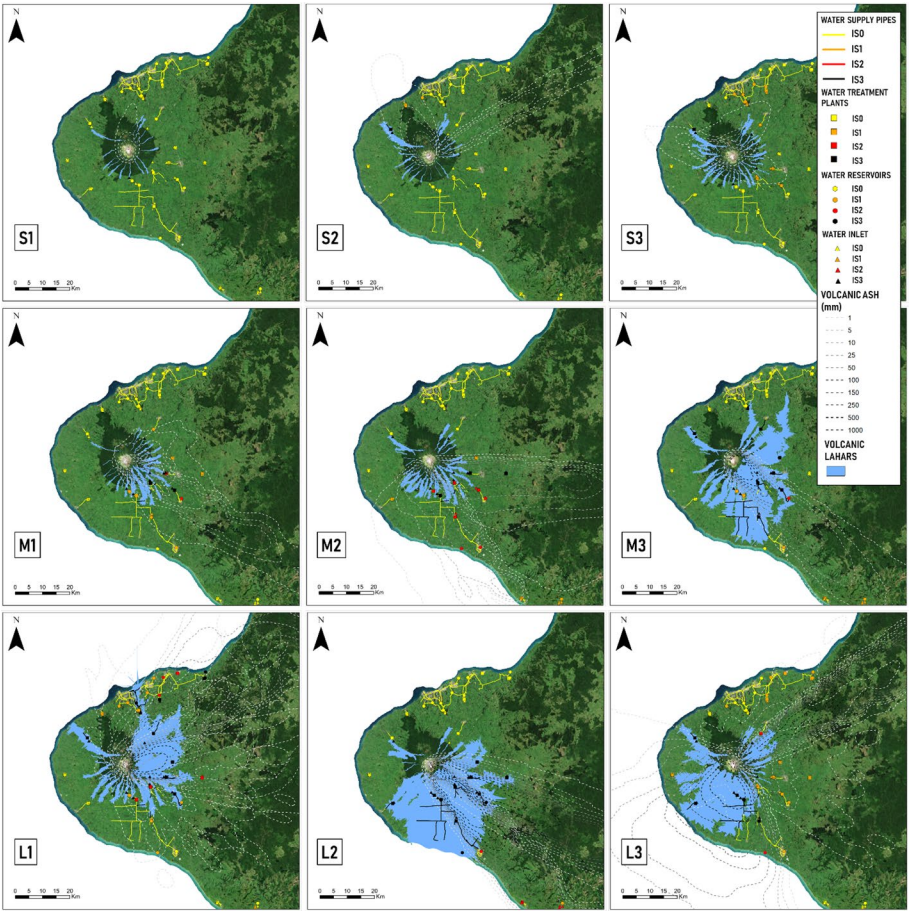

Fig. 4 The direct impact to water supply infrastructure in the Taranaki region of Aotearoa New Zealand. The impact is shown at volcanic activity phase 6p (i.e. at the end of the eruption sequence) for each of the nine scenarios (S1–L3)

5.2 Indirect impact assessment for interdependent infrastructure

The indirect impact is quantified in terms of number of assets (nodes) indirectly disrupted (ID) and the number of private dwellings without service (PDWS), as in Weir (2021). The indirect impact was calculated for each phase ($n=6$) of each scenario ($n=9$), across all sectors, resulting in 54 data frames. Figure 6 shows the direct impact to all infrastructure sectors across the phases of volcanic activity, and Fig. 7 shows the direct and indirect impact for the same phases. Inter-sector indirect impact occurs to all infrastructure sectors during Scenario M2, with the exception of the transportation sector, as transportation is not dependent on any other sectors included in the infrastructure systems tool. During Scenario M2 the greatest indirect impact is to the oil and gas sector. Due to the sector's strong dependence on electricity, and the pinchpoints present in the network, supply is disrupted from the first phase of volcanic activity (M2_1d) (Fig. 7). Electricity supply across west and south Taranaki is disrupted due to structural damage of high voltage transmission

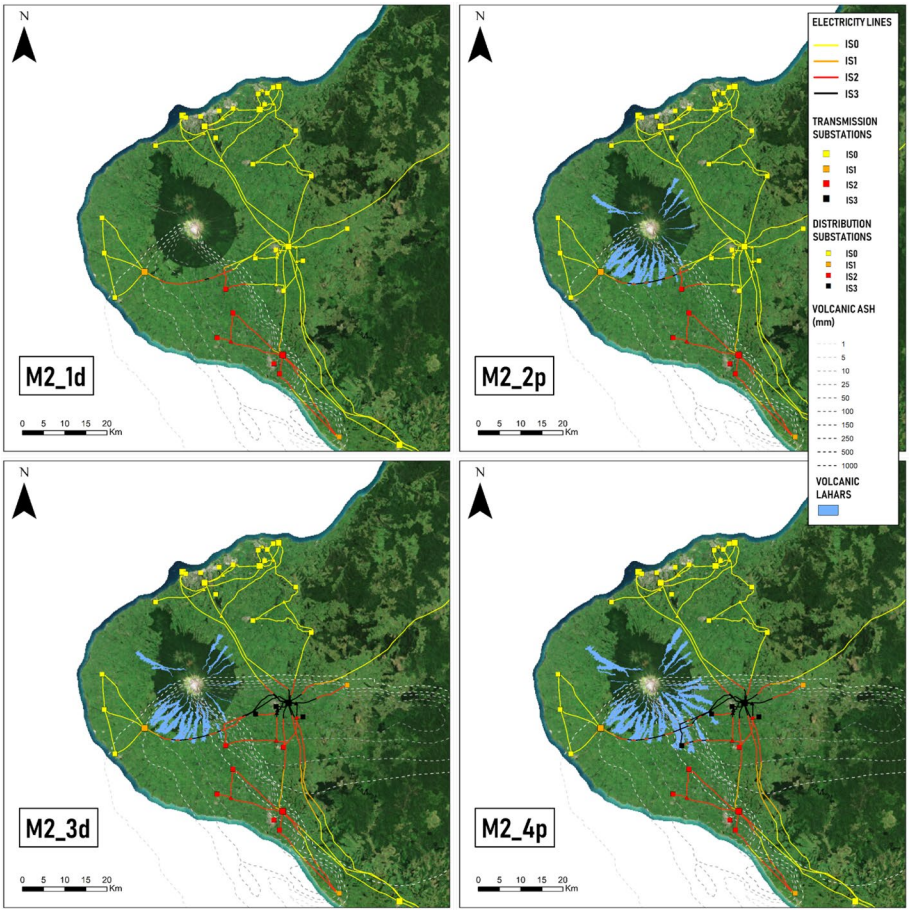

Fig. 5 The direct impact to electricity transmission and distribution infrastructure for phases 1d, 2p, 3d and 4p of eruption scenario M2. Scenario M2 has no volcanic activity (including post-eruptive lahars) during phases 5d and 6p, therefore map M2_4p is the final phase for direct impact in scenario M2

Table 5 The number of node assets per sector in IS2 (requires repair) or IS3 (requires replacement) at end of each eruption scenario

	Taranaki Mounga volcanic eruption scenario (Weir et al. 2022)								
Critical infrastructure sector	S1	S2	S3	M1	M2	M3	L1	L2	L3
Electricity ($n=50$)	0	0	0	7	18	14	28	21	14
Water supply ($n=96$)	1	3	6	18	33	33	49	57	24
Waste water ($n=80$)	0	0	0	7	31	9	32	37	5
Oil and gas ($n=61$)	0	7	4	4	20	21	26	26	23
Transportation ($n=16$)	0	0	1	2	5	3	12	10	10
Telecommunications ($n=111$)	0	1	4	6	19	19	41	36	20
Total	1	11	14	42	121	96	176	177	85

Table 6 The number of node assets per sector that achieve IS3 (requires replacement) as a result of lahars for each eruption scenario

	Taranaki Mounga volcanic eruption scenario (Weir et al. 2022)								
Critical infrastructure sector	S1	S2	S3	M1	M2	M3	L1	L2	L3
Electricity ($n=50$)	0	0	0	2	2	13	13	15	3
Water supply ($n=96$)	1	2	6	7	8	32	29	37	16
Waste water ($n=80$)	0	0	0	1	1	8	19	4	2
Oil and gas ($n=61$)	0	4	4	1	4	20	16	19	8
Transportation ($n=16$)	0	0	1	2	5	3	12	10	10
Telecommunications ($n=111$)	0	1	0	0	0	14	20	20	7
Total	1	7	10	9	15	87	97	95	36

Table 7 Infrastructure lines for each sector in IS2 (requires repair) or IS3 (requires replacement) at the end of each scenario. For electricity lines and transportation, the length in IS2 or IS3 is given. For water supply, wastewater and oil and gas, the total number of breakage points is given, as impact by lahar to buried infrastructure was assumed in topographic depressions (where the lines are generally carried by road or pipe bridges)

	Taranaki Mounga volcanic eruption scenario (Weir et al. 2022)								
Critical infrastructure sector	S1	S2	S3	M1	M2	M3	L1	L2	L3
Length (km)									
Electricity (915 km)	0 km	18 km	0 km	98 km	277 km	176 km	406 km	450 km	214 km
Road (390 km)	0 km	0 km	4 km	12 km	23 km	19 km	58 km	47 km	56 km
Breakage point count									
Water supply (176 km)	1	6	9	8	13	19	28	35	15
Waste water (154 km)	0	2	5	8	10	17	23	27	11
Oil and gas (531 km)	0	4	7	3	6	12	12	15	8
Telecommunications (n/a)	–	–	–	–	–	–	–	–	–

infrastructure on the southern side of Taranaki Mounga, coupled with disruption of a transmission substation in Hawera. Dependent assets across all sectors in south and west Taranaki are therefore indirectly impacted.

Inter-sector indirect impact is observed for all sectors besides transportation (Fig. 7), due to lack of transportation interdependence with other sectors. Intra-sector indirect impact is observed across all sectors, but particularly in electricity, water supply, waste water, and oil and gas, due to their heavy reliance on resource flow from a limited number of nodes. Physical impact to the electricity sector is the most common cause of inter-sector indirect impact, due to the strong interdependencies within the network.

Generally, low-intensity scenarios (S1–S3) result in minimal indirect impact and are largely restricted to the water supply and oil and gas sectors. Scenario S2, however, causes IS2 physical impact to transmission and distribution lines supplying New Plymouth and hence encompasses high indirect impact relative to the other scenarios in the 'S' (small) suite. For the larger scenarios (M1 – L3), total network disruption is often observed, with near-complete disruption of the electricity and oil and gas sector observed for Scenarios

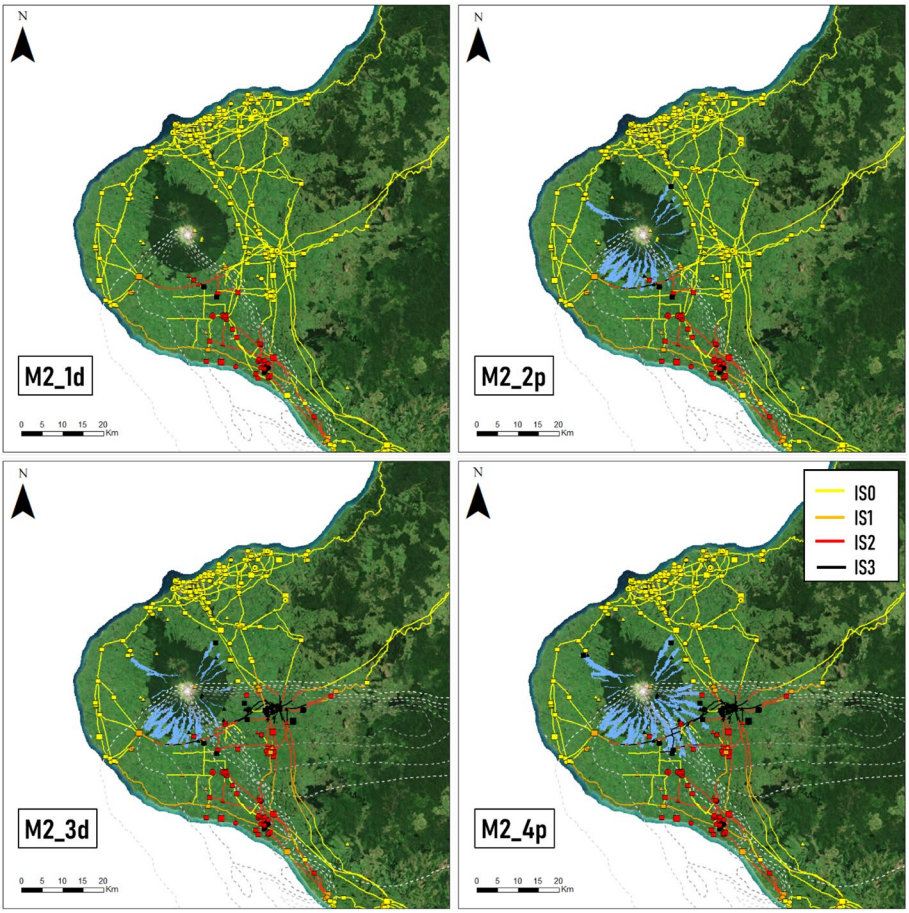

Fig. 6 The direct impact to all six infrastructure sectors for phases 1d, 2p, 3d and 4p of scenario M2. Scenario M2 has no volcanic activity (including post-eruptive lahars) during phases 5d and 6p, therefore map M2_4p is the final phase for direct impact in scenario M2

M2, M3, L1 and L2, with near-complete disruption of oil and gas (but not electricity) observed in Scenario L3. Physical impact to Stratford grid exit point (GXP), a transmission substation located in Stratford, which services nearly the entire region with electricity, is the cause of the most substantial indirect impact and is observed in scenarios M2, M3, L1 and L2.

A summary of the total nodes directly or indirectly impacted by each scenario is shown in Table 8. The highest count of nodes directly or indirectly impacted occurs in scenario L2, where both Stratford GXP and Hawera electricity transmission substation are both at IS3. This is also the case for scenario M2, the scenario with the second highest count of disrupted and damaged nodes. Generally, the most extensive indirect impact is seen during volcanic activity phases 1d and 2p across the entire scenario suite, with ashfall provoking direct and indirect impact during phase 1d and lahars provoking direct and indirect impact in phase 2p. Across all scenarios, the indirect impact in phases 3d, 4p, 5d and 6p is minimal relative to phases 1d and 2p. Of all nodes that reach IS2 or IS3 during the analysis, the

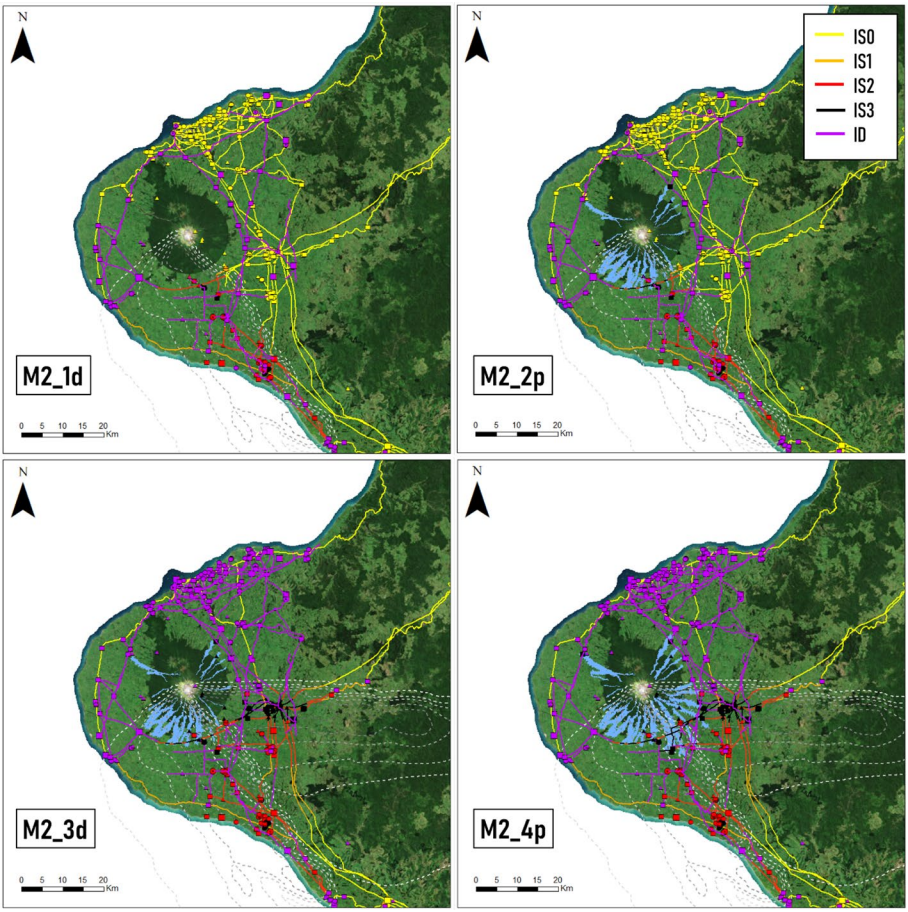

Fig. 7 The direct and indirect impact to all six infrastructure sectors for phases 1d, 2p, 3d and 4p of scenario M2. Scenario M2 has no volcanic activity (including post-eruptive lahars) during phases 5d and 6p, therefore map M2_4p is the final phase for direct and indirect impact in scenario M2

Table 8 The number of nodes in Impact State 2 (IS2; requires repair), Impact State 3 (IS3; requires replacement) or indirectly disrupted (ID) in the last phase of volcanic activity (6p) for each scenario

	Taranaki Mounga volcanic eruption scenario (Weir et al. 2022)								
Critical infrastructure sector	S1	S2	S3	M1	M2	M3	L1	L2	L3
Electricity ($n=50$)	0	19	4	23	48	33	48	50	40
Water supply ($n=96$)	1	27	11	19	93	55	86	95	71
Waste water ($n=80$)	0	22	7	24	70	53	71	73	69
Oil and gas ($n=61$)	0	34	56	56	56	49	55	58	37
Transportation ($n=16$)	0	0	1	2	5	3	12	10	10
Telecommunications ($n=111$)	0	31	5	7	101	46	89	109	68
Total	1	133	85	129	368	236	349	385	285

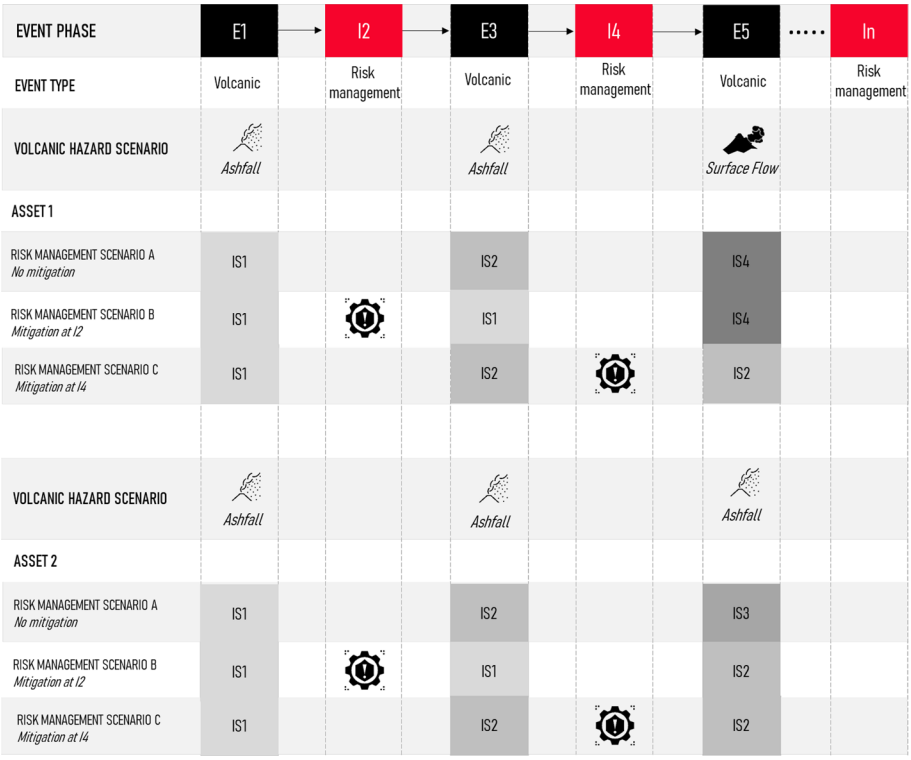

Fig. 8 An illustration of the testing of mitigation strategies. For Assets 1 and 2 (both subject to multi-hazards), the timing of the 'mitigation strategy' (black exclamation icon) affects the resultant impact state of the asset

five single nodes which result in the most considerable indirect impact are Stratford transmission GXP, Hawera electricity transmission substation, Ōpunake electricity transmission substation, the gas transmission pipe bridge in Hangatahua (Stony) river catchment (SW of volcanic edifice), and Kapuni water treatment plant (WTP). Infrastructure lines servicing these nodes are also frequently reaching IS2 and IS3, resulting in extensive indirect impact.

5.3 Risk management scenarios: testing efficacy

The timing and nature of risk management action(s) is/are crucial in reducing the adverse impact of hazardous events. The decision-making phases of the framework (I2, I4 … I_n) allow the testing of mitigation strategies. Figure 8 uses a hypothetical volcanic eruption scenario to illustrate the potential reduction in the impact state of assets given different timing of intervention strategies. We include risk management interventions in Scenario M2 to demonstrate the full extent of the dynamic impact assessment framework. These risk management interventions were identified through end-user consultation and were determined to be feasible measures to implement during an ongoing volcanic sequence at Taranaki Mounga. Here, we test two hypothetical risk management decisions: cleaning of electricity substations and lines in IS1 ('cleaning required') and IS0 ('no damage') during I2, and the physical covering of Stratford grid exit point (GXP) transmission substation, therefore

Table 9 Framework nomenclature for the application of risk management interventions to volcanic eruption scenario M2. Volcanic activity phases are renamed and two risk management interventions are included in the framework (I2 and I4). No risk management intervention occurs during I6

	E1	I2	E3	I4	E5	I6	E7
Volcanic activity events in scenario M2							
Phase name (Weir et al. 2022)	M2_1d	–	M2_2p	–	M2_3d	–	M2_4p
Risk management interventions in scenario M2							
Description	–	Cleaning of electricity infrastructure in IS0 and IS1	–	Mitigation of ash-fall at Stratford GXP	–	–	–

mitigating ashfall impacts to this site, during I4 (Table 9). The volcanic activity phases are renamed in Table 9 to suit the inclusion of risk management interventions.

Figure 9 shows the direct and indirect impact of volcanic eruption scenario M2 with the addition of risk management phases outlines in Table 9. When comparing Fig. 7 with Fig. 9, we see that the cleaning of electricity lines and substations (during I2) and the physical mitigation of Stratford GXP (during I4) results in a large reduction in the potential direct and indirect impact. This is particularly apparent in the difference between the indirect impact for both figures, due to the high system dependency on Stratford GXP.

6 Discussion

This study integrates the growing knowledge base surrounding the co-production of disaster knowledge (Hicks et al. 2014; Davies et al. 2015; Whybark 2015; Fearnley and Beaven 2018; Hayes et al. 2020; Mach et al. 2020), spatio-temporal dependencies in volcanic systems (Jenkins et al. 2007; Zuccaro and De Gregorio 2013; Elissondo et al. 2016; Tierz et al. 2017; Bebbington and Jenkins 2019; Ang et al. 2020), and infrastructure vulnerability to volcanic hazards (Wilson et al. 2012, 2014; Dominguez et al. 2021), to conduct a longitudinal volcanic multi-hazard impact assessment for distributed infrastructure sectors surrounding Taranaki Mounga. This approach for volcanic impact assessment allows the investigation of multi-phase, multi-hazard volcanic activity, and the relative contribution of these components to impact or risk. The framework presented in this study meets the growing end-user need for impact-based decision-support tools and allows the testing of mitigation strategies under different volcanic regimes and can be customised for applications to other volcanic risk contexts.

6.1 Longitudinal modular impact assessment

Designing flexibility and modularity into impact assessment frameworks enhances the relevance of the outputs in practice and policy, but also in science, where the ever-changing state of knowledge necessitates the continual refinement and modification of previous work. Given volcanic uncertainty, there is a need for rapid volcanic response tools that are dependent on the current (or immediate previous) state of the volcano, in appreciation of the temporal dependencies of activity (Bebbington and Jenkins 2019; Jenkins et al. 2007).

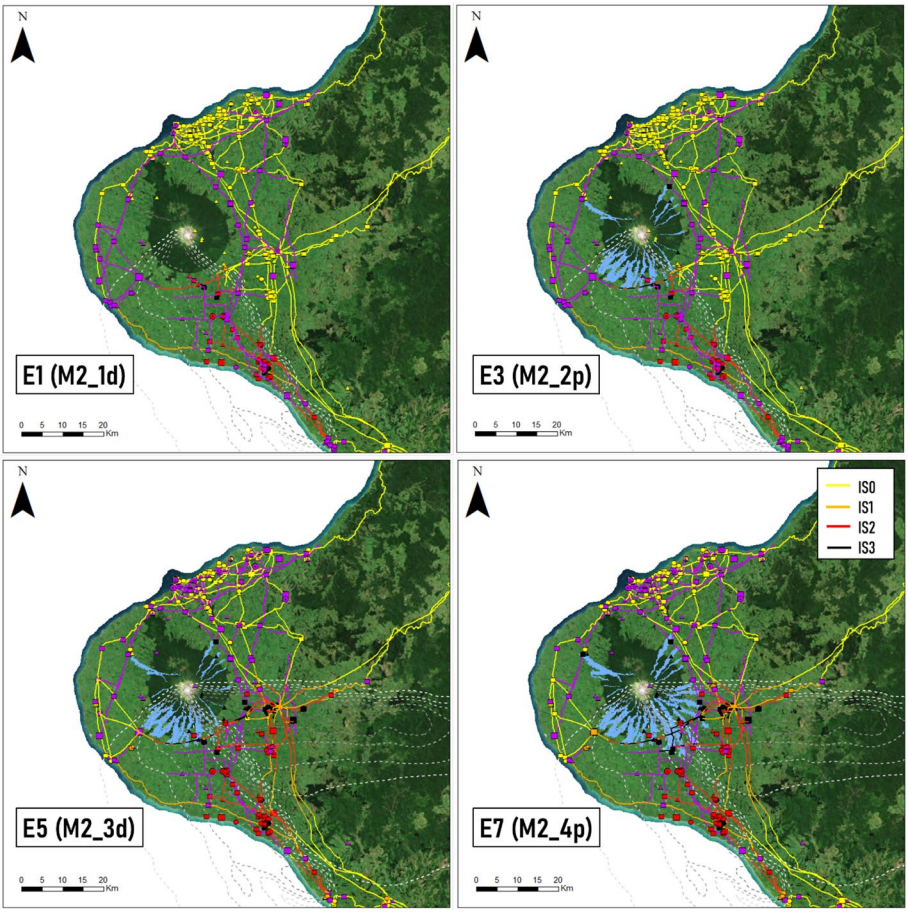

Fig. 9 The direct and indirect impact to all six infrastructure sectors for scenario M2 with the implementation of mitigation measures. Phase E1 shows volcanic activity phase M2_1d, phase I2 involves the cleaning of electricity lines and substations in IS0 and IS1, phase E3 shows volcanic activity phase M2_2p, phase I4 involves the physical mitigation of Stratford GXP to volcanic ashfall, phase E5 show volcanic activity phase M2_3d, phase I6 involves no risk management decisions, and phase E7 shows volcanic activity phase M2_4p. Scenario M2 has no volcanic activity (including post-eruptive lahars) during phases M2_5d and M2_6p, therefore map M2_4p is the final phase for direct and indirect impact in scenario M2

Furthermore, 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 frameworks presented here have the potential for rapid modification and re-design to suit different operational and research contexts, and support decision-makers in the dynamic highly charged emergency planning and response environment.

The inclusion of risk management interventions in this framework was spurred from recent advances in the science field, which recognise the utility of iterative mitigation testing and planning (Dominguez et al. 2021; UNDRR 2019; UNISDR 2015; Zuccaro et al. 2018). Disruption of critical infrastructure service has implications for emergency management, particularly for welfare and building habitability, and implications for national-scale disruption of resource supply. Direct damage of assets introduces higher repair costs and

requires labour, access and time to restore operations, which may not be possible during periods of volcanic uncertainty. This framework provides a platform for this exploration and enables and empowers risk managers to take a more active role in science production.

The modularity of the framework facilitates application in other volcanic risk contexts. Volcanic hazard footprints, risk management interventions, exposure inventories, direct impact and indirect impact modules can be substituted in the impact assessment framework. These modifications can be made at various times during the disaster planning, response and recovery life cycle (i.e. pre-event, syn-event and post-event).

6.2 Implications for risk management at Taranaki Mounga

The results of this study illustrate that the indirect impact to infrastructure networks from volcanic hazards is potentially far more extensive and pervasive than direct impact to infrastructure assets during the majority of modelled scenarios. Generally, the majority of nodes in the interdependent network graph without supply are due to indirect supply outages, rather than due to physical impact of infrastructure, and the number of nodes systemically disrupted, and the spatial reach of the disruption, remains fairly consistent across many of the volcanic eruption scenarios. The commonalities in provoking widespread indirect impact seem to be direct damage (IS2 or IS3) to Stratford GXP, coupled with direct damage to Hawera electricity transmission substation, or a combination of neighbouring electricity distribution substations. This highlights the strong dependency of the distributed infrastructure network on the electricity sector in particular.

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. The oil and gas sector is of great national significance (New Zealand Lifelines Council 2020; New Zealand Lifelines Council 2017), 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. 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.

In consideration of these issues, the merit of the risk management modules of the scenario framework becomes apparent. The study shows that for potential eruptive activity at Taranaki Mounga, mitigation measures see the most potential benefit after the initial phases of volcanic activity (before phase 3d); however, the study also shows that this is a sensitive, uncertain environment that requires further investigation and thorough exploration of possible risk treatment strategies, and optimal intervention opportunities.

6.3 Recommendations for future volcanic multi-hazard impact assessment

There is considerable scope for the framework to be adopted and tested in other volcanic risk contexts, nationally and globally. Future studies could pair the impact assessment framework with information regarding periods of volcanic unrest (and associated decisions regarding emergency management and infrastructure management), and response and recovery decisions. However, applications and iterations of this work will need to take

similar care to mitigate the risks associated with engaging practitioners, carefully managing response capacity due to limited access, staffing and resources.

In future work, it must be acknowledged that periods of quiescence can vary hugely, and this should be incorporated in future iterations of this work, through the mechanisms employed in Weir et al. (2022) to develop the eruption scenario suite. In tandem, the duration and timing of risk management interventions and of mitigation measure implementation should be carefully considered in partnership with stakeholders and users. Further facets of vulnerability could be included in the framework. Here, physical and systemic vulnerability were considered with regards to distributed infrastructure, but in the future, social and economic vulnerability could be incorporated. We also encourage the investigation of habitability following lifeline disruption due to volcanic activity, and how life-safety and wellbeing concerns (due to volcanic hazard and critical infrastructure disruption, respectively) will inform evacuations and emergency supply distribution.

Further interdependencies could be considered as part of this work, such as fuel supply, supply chains, landline telecommunications, storm water and rail, port and airports. In particular, we suggest the more granular analysis of road network disruption, as road functionality is such as crucial component of emergency response.

7 Conclusions

The framework presented and applied in this study shows the benefit of longitudinal volcanic multi-hazard impact assessment. Volcanic eruptions can be, and often are, multi-phase, multi-hazard, complex events that necessitate a similarly multi-phase societal response. Allowing for risk management interventions between periods of volcanic activity allows more targeted, informed mitigation planning and meets the identified end-user need for impact-based metrics and tools when planning for disasters.

This study utilised the growing knowledge base surrounding co-production of disaster knowledge, spatio-temporal dependencies in volcanic systems, and infrastructure vulnerability to volcanic hazards to conduct a dynamic impact assessment for distributed infrastructure surrounding Taranaki Mounga. This study applied a suite of multi-phase volcanic multi-hazard eruption scenarios to estimate the direct and indirect impact of these scenarios for infrastructure. The dynamic, modular, flexible nature of these impact scenarios allows for investigation of the spatio-temporal linkages inherent in volcanic systems, and how they manifest in impacts to the built environment and surrounding communities.

The volcanic impact assessment outputs in this study could be paired with other tools to investigate the national-level disruption from Taranaki volcanism, which aligns well with Aotearoa New Zealand's risk profile (Willis 2014). Of particular note is the independence and recovery model developed for national-scale critical infrastructure network disruption (Zorn 2017a, 2017b). The frameworks could feasibly include other dimensions of systemic risk besides cascading infrastructure failure. The could align well with the identified need for more targeted analysis of social, economic and environment aspects of vulnerability (Few et al. 2017; Hicks and Few 2015; Kappes et al. 2012). The feasibility of application of these frameworks to other geological hazards is unknown, but has the potential to offer great reward to practitioners that manage large risk profiles in an evolving hazard landscape.

For the Taranaki region, these tools provide a test bed for mitigation strategies. These hazard and impact scenarios should be viewed as demonstrative of the diversity of impacts

expected from future activity at Taranaki Maunga, and as such, should be used to test and plan for the best response and resilience-building strategies. Costing of different risk management actions can and should be considered in order to make an evidence-based case for infrastructure investment.

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Declarations

Conflict of 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.

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