VOLCANICA Article in Press

This is an uncorrected proof, meaning that this manuscript has not been copyedited or formatted according to Volcanica's styles and standards. In turn, this means that article content, including text, may still change prior to final publication. Although articles in press do not have all bibliographic details available yet, they can be cited using the year of online publication and the DOI, as follows: author(s)(year), article title, Volcanica, DOI.

Juniper, Z., Weir, A., Wilson, T., Stewart, C., Deligne, N., Craig, H., Campbell-Smart, C., Fairclough, R., Procter, J., Williams, J. and Coultas, E. (2026) "Vulnerability of the petroleum sector to volcanic hazards: application to multi-hazards at Taranaki Mounga volcano, Aotearoa New Zealand", Volcanica, 9(1). doi: 10.30909/vol/kcor7174.

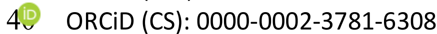
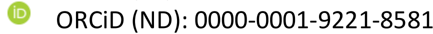
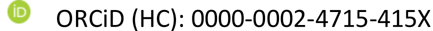
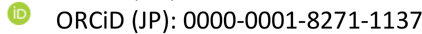
Article in Press

Vulnerability of the petroleum sector to volcanic hazards: application to multi-hazards at Taranaki Mounga volcano, Aotearoa New Zealand

Zoë Juniper[1,2], Alana M. Weir[1,3], Thomas M. Wilson[1], Heather Craig[*1], Carol Stewart[4], Natalia I. Deligne[5,6], Craig Campbell-Smart[7], Roger Fairclough[8], Jon Procter[9], James H. Williams[1], and Emma Coultas[1]

[1] School of Earth and Environment, University of Canterbury | Te Whare Wānanga o Waitaha, Ōtautahi Christchurch, Aotearoa New Zealand
[2] Ministry for Primary Industries, Aotearoa New Zealand
[3] Department of Earth Sciences, University of Geneva | Te Whare Wānanga o Waitaha, Ōtautahi Christchurch, Aotearoa New Zealand
[4] School of Health Sciences, College of Health | Te Kura Hauora Tangata, Massey University | Te Kunenga Ki Pūrehuroa, Te Whanganui-a-Tara | Wellington, Aotearoa New Zealand
[5] U.S. Geological Survey, Hawaiian Volcano Observatory, USA
[6] GNS Science, Lower Hutt, Aotearoa New Zealand
[7] Taranaki Civil Defence and Emergency Management, 45 Robe Street, New Plymouth 4310, Aotearoa New Zealand
[8] Neo Leaf Global Ltd, 120 Cheviot Road, Lower Hutt, 5013, Aotearoa New Zealand
[9] Earth Sciences Department, School of Agriculture and Environment, Massey University, Palmerston North, 4442, Aotearoa New Zealand

[*] heather.craig@canterbury.ac.nz

ORCiD (AW): 0000-0001-7449-016X
ORCiD (TW): 0000-0002-8816-0708
 ORCiD (CS): 0000-0002-3781-6308
 ORCiD (ND): 0000-0001-9221-8581
 ORCiD (HC): 0000-0002-4715-415X
 ORCiD (JP): 0000-0001-8271-1137
ORCiD (JW): 0000-0002-7564-0032

Keywords: impact assessment; volcanic risk assessment; energy sector; expert workshop; Mt Taranaki; critical infrastructure

Abstract

Volcanic eruptions can cause substantial damage and disruption to infrastructure and communities. Contemporary societies typically depend on petroleum infrastructure. Volcanic unrest and eruptions can cause considerable operational and structural challenges for the petroleum sector. The vulnerability of this sector to volcanic hazards is understudied when compared to other potentially dangerous phenomena (e.g., earthquakes). In this paper, we present new volcanic physical vulnerability models for the four key asset classes of the petroleum sector: wells, pipelines, production facilities, and storage tanks. The vulnerability models are developed based on a literature review and facilitated expert judgement in the form of workshops with petroleum engineers and volcanic risk experts. These models consider four hazard intensity metrics (burial thickness, static load, dynamic pressure and airborne ash concentration) and are thus applicable to multiple volcanic hazards. We apply these models to pre-existing multi-hazard eruption scenarios for Taranaki Mounga volcano in Aotearoa New Zealand, using an available impact assessment framework to demonstrate their usability in impact and risk modelling. Our impact assessment indicates that a future eruption of Taranaki Mounga volcano could cause widespread impacts

Article in Press

to the petroleum sector, which would in turn create a prolonged national emergency due to energy supply shortages for major industries and consumers. These vulnerability models may be applied in other volcanic regions worldwide to inform risk reduction and readiness actions.

65

1 Introduction

Critical infrastructure systems are essential to the functioning of modern society. Disasters damage and disrupt critical infrastructure networks, which can result in extensive loss of service to communities and industries (UNDRR 2019). Volcanic eruptions can generate hazards such as ashfall, pyroclastic density currents (PDCs), and
70 lahars that damage infrastructure, interrupt transport and essential services, and trigger cascading socio-economic impacts that potentially extend beyond the immediate hazard footprint (Wilson et al., 2017). Provision of infrastructure supply is a key priority for disaster risk management and emergency planning, and an improved understanding of component and system vulnerability will enhance disaster risk reduction (Global Facility for Disaster Reduction and Recovery 2014; World Bank 2014; UNDRR 2019).

75

Energy is an essential part of modern society. Fossil fuels (petroleum, coal, natural gas and their by-products) are fundamental for modern energy needs, contributing to electricity generation (coal, oil, and gas), transport fuels (oil and gas), food production (gas), and cooking and heating energy sources (coal, oil, and, gas) (International Energy Agency 2017). The world currently consumes approximately 169.0 exajoules (EJ; equal to 10^{18} joules) of
80 oil and 68.4 EJ of gas per year, comprising over half of global energy supply requirements (International Energy Agency, 2021). Most nations formally recognise the need to move away from burning high carbon-emitting fuels such as coal and oil to pursue near-zero-emission energy systems, reduce indoor and outdoor air pollution, and slow anthropogenic climate change. Goal 7 of the United Nations' Sustainable Development Goals (UN, 2015) refers to the need to 'ensure access to affordable, reliable, sustainable and modern energy' for all. However, at
85 present, petroleum is woven into the fabric of society and global economies and will likely remain a lifeline service in the global energy mix in the medium- to long-term. This is particularly the case for natural gas, which is considered to have an important role in transitioning to decarbonised energy system futures due to its lower carbon content (15.3 kg/GJ compared to 25.8 kg/GJ for coking coal, 26.2 kg/GJ for non-coking coal and 20 kg/GJ for crude oil) (Safari et al., 2019). Though energy transition planning is under development, there will be a reliance
90 on fossil fuel sources for the years to come. Further, in some contexts existing petroleum assets and networks are being considered for utilisation under future energy transition scenarios (International Energy Agency 2021).

Early development and exploration of the petroleum sector was characterised by a lack of concern for health and safety and natural hazard risk that does not align with modern standards. However, the sector has since
95 developed comprehensive risk management systems for its operations, especially after industrial disasters such as Deepwater Horizon (2010), Gulf War (1991), Piper Alpha (1988), and exposure to natural hazards such as Hurricane Katrina (2004) that disrupted the sector and caused damage (American Society of Civil & Wind-Induced Forces Task, 2011; Bratspies, 2011; Brinkley, 2007; Hull, 1996; Reader & O'Connor, 2014; Skogdalen & Vinnem,

Article in Press

2012). These disasters also brought about closer public scrutiny and expectations of higher standards, enforced through legislation and regulatory oversight (Bratspies, 2011).

The risk of natural hazards impacting industrial facilities such as oil and gas storage tanks, refineries and pipelines is increasingly recognised (Krausmann et al., 2011a), and efforts are continuing to develop risk assessment frameworks for Natural Hazards Triggering Technological Accidents (Natech) events (Krausmann et al., 2019). For some hazards such as earthquakes, flooding, and lightning strikes, analysis of Natech incident databases has allowed for identification of vulnerable system components and failure modes (Krausmann et al., 2011b), and progress has been made towards quantitative risk assessment (Kraussman et al., 2019). Cruz and Suarez-Paba (2019) note that while earthquake-triggered Natech accidents have been studied since the 1970s, other geological hazards, have received far less attention.

Volcanic unrest and eruptions can cause considerable operational and structural challenges for the petroleum sector; despite this the impacts of volcanism on petroleum systems remains understudied. Eruptions are one of the most damaging natural hazards that impact human societies and associated critical infrastructure (Loughlin et al. 2015; Deligne et al. 2022). Globally, over one billion people are estimated to live within 100 km of an active volcano (Freire et al. 2019). While areas of active volcanism and known petroleum reserves generally do not coexist globally, important areas of overlap include southern Alaska, the west coast of the USA, Kamchatka (Russia), southern Chile and Argentina, Italy, Indonesia and Aotearoa New Zealand (Figure 1).

Article in Press

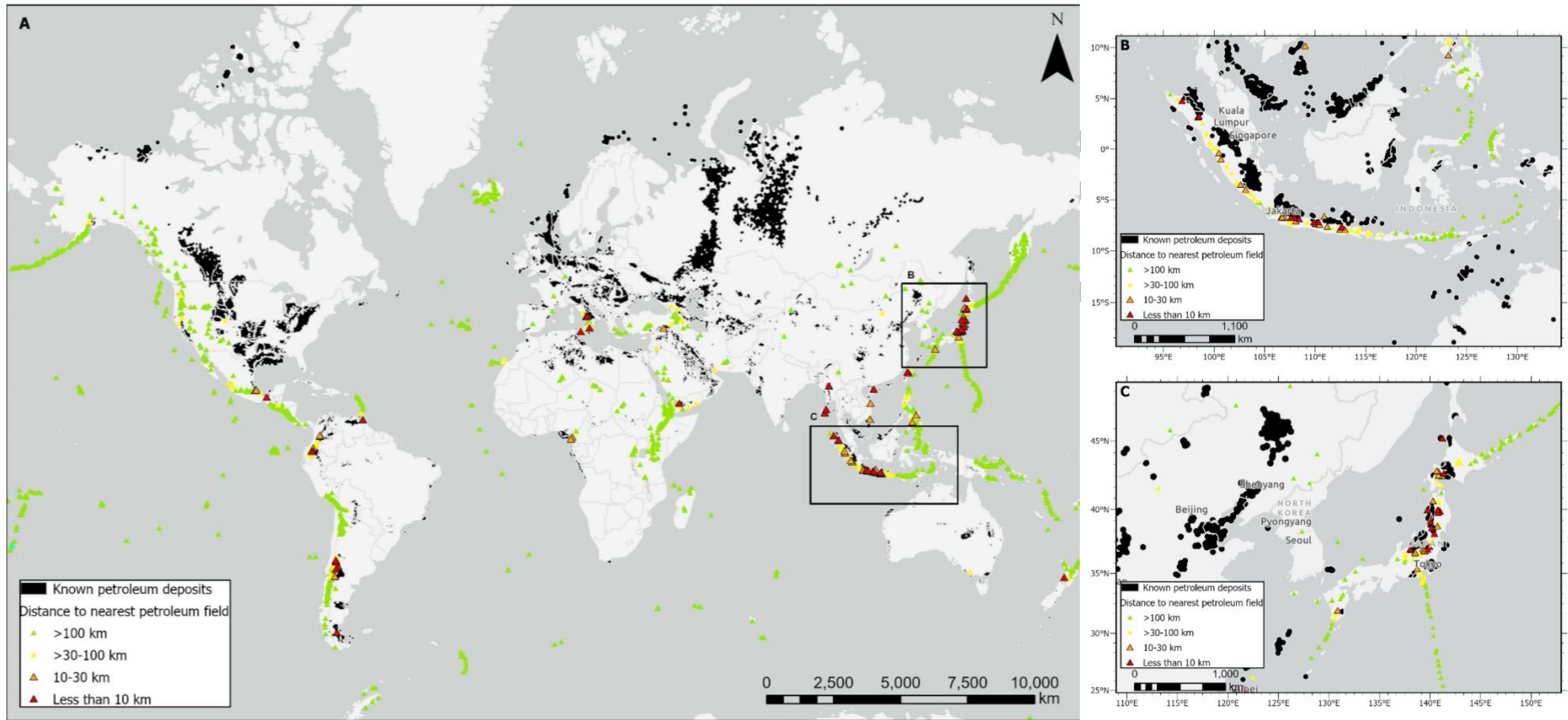


Figure 1: A) Global distribution of Holocene volcanoes (triangles) (Global Volcanism Program, 2023, version 5.1.0) and known oil and gas deposits (black) (Lujala, Rod, & Thieme, 2007, version 1.2). Volcanoes within 10 km of any part of an oil and/or gas field are indicated with red triangles; those within 10 km are indicated with red triangles; those within 10-30 km are indicated with orange triangles; those within 30-100 km are indicated with yellow triangles; and volcanoes more than 100 km from any part of an oil and/or gas field are indicated with green triangles. Inset maps B) and C) show the volcanically active areas near oil and/or gas fields around Indonesia and Japan respectively.

Despite the relatively large amount of geographic intersection between volcanic centres and petroleum fields, there has been few recorded historical examples of volcanic impacts to petroleum sites and assets. This is likely due to a combination of factors including: some underreporting due to commercial sensitivities; the locating of production facilities away from areas that have been previously exposed to volcanic hazards; underdevelopment of petroleum fields proximal to volcanoes due to lack of investment and/or awareness of volcanic risk; and strengthening of some exposed petroleum assets to reduce volcanic impacts (Juniper 2018).

In this article we present new volcanic physical vulnerability models for the petroleum sector, for the four key asset classes of the petroleum sector (wells, pipelines, production facilities and storage tanks). The vulnerability models are developed for four hazard intensity metrics (burial thickness, static load, dynamic pressure and airborne ash concentration) and are thus applicable to multiple volcanic hazards, including volcanic flow hazards and tephra/ash. We apply these models to pre-existing multi-hazard eruption scenarios for Taranaki Mounga[1] volcano (Aotearoa New Zealand) using an available volcanic impact assessment framework.

1.1 Volcanic hazard impacts to the petroleum sector

The only known documented instances of volcanic eruption hazards causing impacts to petroleum infrastructure are due to flow hazards (lahars and lava flows). The 1989/1990 eruptions of Redoubt volcano, Alaska, generated lahars that inundated the tank farm at the Drift River Oil Terminal. While the terminal is a storage facility rather than an active production or exploration facility, it was temporarily shut down, and offshore production supplying the terminal was suspended (Brantley, 1990; Dorava & Meyer, 1994). As a mitigation response to this event, a six-metre high bund was built around the facility to reduce lahar and flooding impacts (Waythomas et al., 1997). Critical equipment was also raised at least a metre above ground level (Krausmann and Salzano, 2017). Another eruption of Redoubt volcano in 2009 generated lahars, but the bunds prevented inundation with only minor overtopping such that the lahars did not affect the tank farm. However, the lahars inundated the facility's runway, preventing any emergency response to an oil spill. This raised concern among communities and led to the removal of 6 million gallons of stored oil (Bull and Buurman, 2013; Cook Inletkeeper, 2009).

Fuel storage tanks have also been destroyed by lava flows, sometimes causing loss of life. The January 2002 eruption of Nyiragongo volcano in the Democratic Republic of Congo generated lava flows through the city of Goma, which had a population of approximately 400,000 in 2002 (Global Volcanism Program, 2001). Tedesco et al. (2007) report that between 60 and 100 people were killed by an explosion at a petrol station, with a further 470 injured. There were further explosions at fuel depots across the city. On a smaller scale, a fuel tank in the path of a lava flow from Mount Etna, Sicily, exploded in 2002, injuring 32 people (Ancione et al., 2015). Jenkins et al. (2017) reported a single explosion from lava flow contact with a cooking gas canister during the eruption of

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

Article in Press

Fogo, Cape Verde, and notes that fuel sources (e.g. gas canisters, diesel generators) in the forecasted path of the lava flow were removed to reduce fire and explosion risk.

160 Similarly, only a limited number of studies have assessed the vulnerability of petroleum infrastructure components to volcanic hazards. All these studies relate to Mount Etna, Sicily, which has erupted both explosively and effusively in recent years. Over a million people live within 30 km of Mount Etna, and there are substantial industrial installations nearby. Ancione et al. (2015) overlaid a projected lava flow path from Mount Etna with existing fuel storage tanks to create damage zones, intended to be useful for local emergency planning. Ashfall
165 hazards have also been considered. Milazzo et al. (2012, 2013a, 2014) considered the vulnerability of both fixed and floating roof fuel storage tanks to ash loading (via mechanisms of collapse, sinking or capsizing), and concluded that tanks would only suffer damage to their roofs in the event of extremely large explosive eruptions. These authors then combined probabilistic ashfall hazard modelling with tank locations to create a vulnerability map for the region (Milazzo et al., 2013b).

170

2 Development of physical vulnerability models for the petroleum sector

2.1 Overview of methods

There are many methods for volcanic vulnerability model development, including empirical studies, expert workshops, physical (e.g. laboratory) studies, and mixed methods approaches (Fitzgerald et al. 2023; Wilson et
175 al., 2017; Hayes et al., 2023). For this study we use a hybrid approach combining expert judgement (via expert workshops with petroleum industry professionals) and findings from the literature on vulnerability thresholds for analogous hazards (Wilson et al., 2014). This was necessary due to the lack of empirical data and numerical modelling data for volcanic hazard impacts to the petroleum sector. We used a holistic systems approach based on a critical infrastructure tier scheme, summarised in Figure 2 and using the upstream petroleum sector as an
180 example.

Article in Press

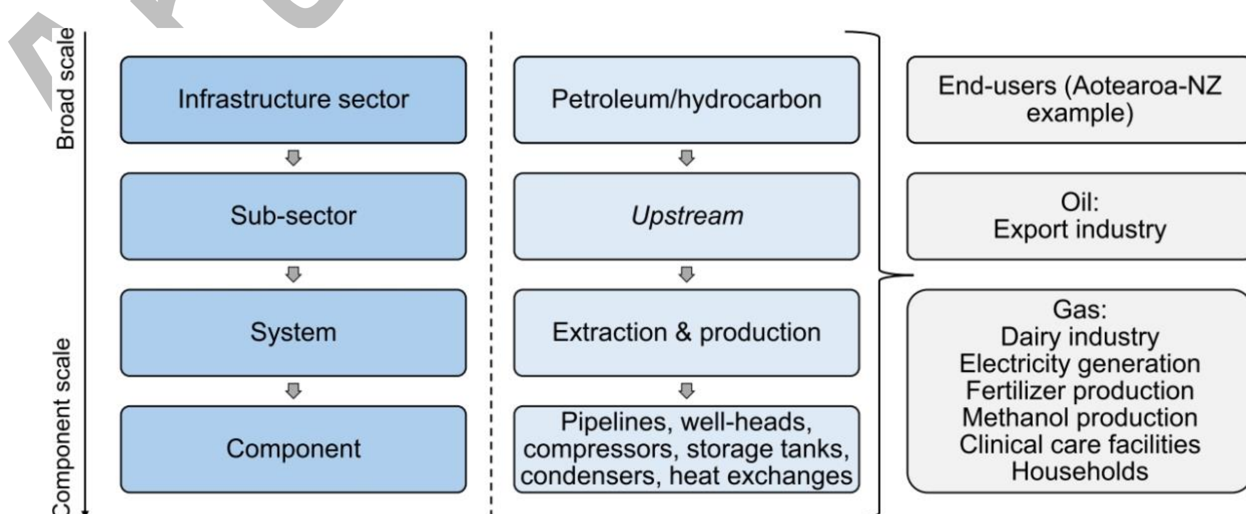


Figure 2: Conceptual critical infrastructure tier scheme, adapted from Wilson (2015) applied to the petroleum sector. The left column illustrates the generic hierarchy from broad infrastructure sector to sub-sector, system, and

component scales. The central column applies this structure to the petroleum/hydrocarbon sector, showing the upstream sub-sector, extraction and production system, and representative physical components (e.g., pipelines, well-heads, compressors, storage tanks, condensers and heat exchangers). The right column provides examples of end-users in Aotearoa New Zealand (NZ) that depend on petroleum products, highlighting key downstream dependencies and systemic interconnections.

Expert judgement is commonly necessary for sectors with little to no prior exposure to volcanic hazards. The expert workshop process is considered the most efficient and robust method to engage with sector experts (Evans, 2013). Expert workshops require careful planning. Aims need to be clearly defined, and appropriate attendees invited (Pattillo, 2017). Typical rational aims could include deriving the generic categorisation of the petroleum assets in the region of interest. Such workshops can also have further benefits, such as strengthening relationships between researchers, industry experts and emergency managers, and raising awareness of volcanic hazard risk mitigation within the industry.

Developing physical vulnerability models for the petroleum sector's assets requires building relationships between the impacts (such as damage or loss of service) from different volcanic hazards and the variable hazard intensities (such as static load for ashfall or dynamic pressure for pyroclastic density currents). Such information is typically derived primarily from post-event impact assessments and supplemented by laboratory testing of specific components (Wilson et al., 2014; 2017). However, for the petroleum sector, the lack of documented volcanic impacts or applicable empirical data has led us to focus instead on reviewing literature to identify analogous events, hazard impacts and/or asset types. We supplemented this with expert workshops in a mixed-methodology approach.

Physical vulnerability models develop relationships between the hazard intensity and its impact on infrastructure, referred to as the 'impact metric' (Wilson et al., 2017). For this study, we use a hazard threshold approach as it allows for the development of a relationship between the hazard intensity metrics (HIMs) and the theoretical thresholds at which functionality is likely to be impacted. To overcome an anticipated terminology barrier between volcanic risk scientists and petroleum engineers, a set of HIMs was agreed upon and mapped to different volcanic hazards (Table 2). An example of different terminology that required resolution is ash depth (routinely used by volcanic risk scientists as a HIM) compared to static pressure, used by engineers to design for snow-loading. Developing a set of common terminology was useful for enabling the engineers to understand the physical forces posed by volcanic hazards to petroleum infrastructure. We use the case study of Taranaki Mounga volcano in the Taranaki region of Aotearoa New Zealand. Expert workshop participants manage and operate petroleum sector infrastructure in the Taranaki region.

For the impact metric we chose to use impact states, which define discrete changes in functionality from tolerance to disruption to damage to complete destruction (Wilson et al., 2014). This approach works well for the theoretical approach required for the petroleum sector, where multiple volcanic hazards are considered. Here,

Article in Press

we use a simple four-tier damage level model (Table 2). We note that while six-level (D0-D5) damage state schema have been used elsewhere in risk modelling (e.g., Jenkins et al., 2014), a simpler version was more appropriate to this study given the lack of published information available on volcanic impacts on petroleum infrastructure.

2.2 Methodology stages

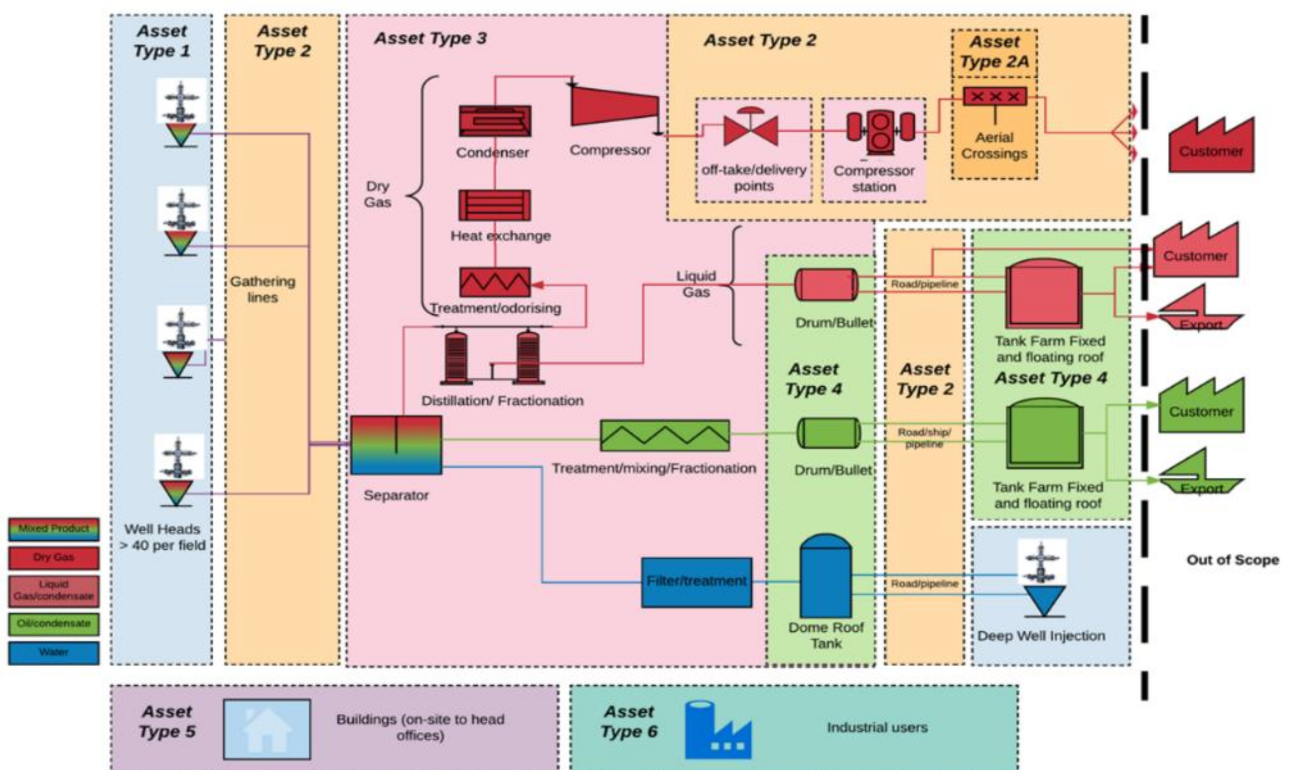
2.2.1 Stage 1: Literature review

The lack of documented volcanic impacts on the petroleum sector led us to carry out a literature search for examples where similar assets have been impacted by other hazards with analogous impacts, or where appropriate industry standards exist. For example, observations on washout and scouring from tsunami provide insight into dynamic pressure from lahars and PDCs. Corresponding to the four-tier damage level model (Table 3) this information has been used to define provisional thresholds (Table 4).

2.2.2 Stage 2: Petroleum sector assets: system mapping and spatial inventories

The petroleum sector is organisationally and technically complex, and mixed-methods approaches are likely to be required to identify, characterise, and map assets exposed to volcanic hazards. These methods may include reviews of published sources; expert workshops; site visits; and discussions with asset managers. The initial step in asset characterisation is the identification of any limitations and bounding factors that define the scope of work and level of detail. For example, it may be possible to exclude subsurface assets if the hazard assessment excludes magmatic intrusions or heat flow in the area of interest. Guidance from industry experts also suggested further scope limitations. For instance, exploration equipment such as drilling rigs may be excluded on the grounds that

le in Press



exploration activity would likely be shut down and equipment secured or even evacuated in the event of volcanic unrest.

Figure 3: Petroleum product life cycle, showing the six groups of asset types and their relationships.

245 The next step is mapping the assets as a system. A lifecycle system map is useful for visualising the assets involved in the petroleum sector from extraction and separation of component products through to transportation and delivery systems (Figure 3). The third step is the mapping of physical asset locations. Methods used to determine asset locations include Geographic Information Systems (GIS) (Remer, 2011; UNISDR, 2017); using existing open file datasets; reviewing satellite imagery; reviewing local authority consent information; interviewing industry 250 personnel and site visits. The final step is categorising petroleum assets according to their operational functionality. This categorisation step benefits from access to extensive expert knowledge, and where appropriate site visits. Asset categories for the petroleum sector include wells; pipelines; production facilities; storage tanks; buildings and industrial users (Table 1).

2.2.3 Stage 3: Petroleum sector expert workshop

255 An extensive group of petroleum industry representatives, regulators, emergency managers and local and regional authority staff and members of the volcanic impact science community were invited to an expert workshop held in the study area (27 October 2018). The aims of the workshop were to define the damage levels, refine the provisional thresholds (Table 4), and prioritise interdependencies of the various asset categories. The four asset classes considered were wells, pipelines (including aerial crossings), production facilities (excluding 260 buildings), and storage tanks. The key physical and systemic vulnerabilities identified during the expert workshop are outlined in Table 5. The resultant vulnerability models for each asset class, with threshold values for each HIM associated with damage states, are shown in Tables 6 (for wells), 7 (pipelines), 8 (production facilities excluding buildings) and 9 (storage tanks). The main discussion points are captured for each HIM as follows.

265 *Static pressure (loading):* Ashfall hazards were a critical concern for static loading, particularly for buildings and floating roof storage tanks. Pipelines and wells were not considered to be at risk from static loading. The expert group raised concerns about how floating roof storage tanks would cope with repeated ashfalls, with specific concerns raised about cleaning. Floating roof tanks are difficult to clean under normal circumstances and rely on rainwater drainage channels, which could be blocked by ashfall, further hindering ashfall clean-up efforts. The 270 expert group also agreed that snow-loading standards are a good analogue for static pressure thresholds and provide maximum design loads. As the Aotearoa New Zealand Standards (Standards New Zealand, 2003b) only consider roof design in alpine and subalpine settings, we adopted values from the American Petroleum Institute (API Standard 650; American Petroleum Institute, 2013) for snow-loading limits for welded oil storage tanks.

275 *Temperature:* Experts identified that seals and gaskets would be the components most vulnerable to thermal damage, and that the consequences of seal and gasket failure are critical and require their immediate replacement. In the event of thermal shock, inspections of all equipment would be required, which would delay

Article in Press

restarting production. The expert group estimated different temperature thresholds compared to the provisional estimates from the literature (Table 4), thus illustrating the value of expert input into this vulnerability assessment. Participants agreed that 60-80˚C heat exposure from PDCs would be the threshold above which minor damage would occur, with the onset of major damage at 150°C and destruction above 450°C. However, many participants noted high levels of uncertainty with these estimates and suggested that future laboratory-based research may be required to refine them. A further area of uncertainty concerns the duration of exposure to high temperatures, which is likely to vary by volcanic hazard.

Dynamic pressure: The group considered that dynamic forces of lahars and PDCs need to be treated separately as PDCs are a more uniformly distributed force while lahars are height-restricted and may impact only the bases of structures. For PDCs, wind loading was considered by attendees to be an analogous dynamic force to that of a PDC, and thus the group referred to the wind loading standards set out under AS/NZS 1170 (Standards New Zealand, 2002a). Design standards for wind loading used by the American Petroleum Institute were also referred to by the workshop attendees, and examples of extreme wind damage to storage tanks in the downstream petroleum sector from Hurricane Celia (1970), Hurricane Hugo (1989) and Hurricanes Rita and Katrina (2005) informed thresholds (American Society of Civil & Wind-Induced Forces Task, 2011). Some assets such as wellheads were identified as being highly resilient to dynamic pressures, based on internal pressure design standards which far exceed the dynamic pressures typical of PDCs. However, other assets such as flare stacks and control valves are likely to be less resilient. Flare stack design thresholds helped constrain the impact metric thresholds for the vulnerability model. The potential of lahars to cause scouring and erosional damage around storage tanks and pipelines was considered the most likely impact, particularly for hyper-concentrated lahars. The experts noted that while floating roof storage tanks typically require a bund (containment system) to be constructed to protect against any fuel spills, they are unlikely to be protective against very large, concentrated lahars.

Airborne ash: High concentrations of airborne ash were identified as a critical risk to production facilities, as many components have moving turbines or fans and rely on good quality air. As well as clogging filters which can lead to overheating, ash may also cause abrasion damage to turbines, which may require more frequent replacement, and may damage tank seals and gaskets. Petroleum sector attendees suggested that dust storms, which are routinely experienced in petroleum-producing areas of the Middle East, are an analogue for airborne ash, and noted that pre-emptive shutdowns during dust storms are common to protect assets. Volcanic risk attendees noted that ashfall events would likely be more damaging than dust storms due to the higher airborne concentrations reached and the abrasive and corrosive properties of volcanic ash. Furthermore, ash remobilisation can prolong the hazard (Wilson et al. 2011). The current plan for the petroleum industry in Taranaki is to shut down all equipment and production during an eruption to minimise the recovery period and restart production as rapidly as possible. However, the combination of airborne ash, high temperatures and dynamic pressure during an eruption would likely damage seals, gaskets and filters, which would then require a programme of inspection and replacement.

Article in Press

315 *2.2.4 Stage 4: Input by volcanic hazard, risk and petroleum sector experts on proposed physical vulnerability models*

The process to further inform the vulnerability thresholds, presented in Tables 6-9, was undertaken in two phases: 1) development of proposed vulnerability models based on literature and workshop findings, followed by 2) a critical review of these by subject matter experts (SMEs, e.g. airborne ash experts, surface flow experts,
320 petroleum sector experts). This process identified two problems with the outcomes of Stage 3 (expert workshop, Section 2.2.3). Firstly, the airborne ash concentrations discussed in the petroleum sector expert workshop was considered unrealistically high by the SMEs, casting doubt over the derived vulnerability functions. Further, the metric used (airborne ash concentration, in μg/m^3) did not capture the duration of exposure to ash concentrations, which is a crucial aspect of the damage mechanism from airborne ash. Future research could
325 consider impacts from airborne ash, but it is not considered further here. Secondly, the static loading threshold for damage state 3 (D3) for production facilities and storage tanks was deemed too high by SMEs and was modified during review to align with SME opinion for production facilities (Table 8) and the threshold observed in Milazzo et al. (2013) for storage tanks (7.0kPa; Table 9).

330

3 Case study: Application of physical vulnerability models to the petroleum sector in the Taranaki region, Aotearoa New Zealand

3.1 Risk context

Taranaki Mounga volcano is an active stratovolcano in the Taranaki region of Aotearoa New Zealand. Volcanism is characterised by cycles of cone growth and flank collapse (Lerner et al., 2019a; Cronin et al., 2021). Typical
335 hazards include PDCs, lahars, ashfall and edifice collapse. Last known activity occurred 1780 – 1800 AD, which produced many small effusive and explosive eruptions (Lerner et al., 2019b). Click or tap here to enter text. Damaschke et al. 2018 estimates a 33-42% chance of an eruption in the next 50 years.

The Taranaki region is the only petroleum-producing basin in Aotearoa New Zealand. Oil and gas products are
340 extracted, processed, and transported from key industrial sites distributed around Taranaki Mounga volcano. The energy sector supports in-region dairy farming and production, national electricity generation, and supplies industry, residential properties and business nationwide (PEPANZ, 2016). The petroleum sector contributes NZ$2.5 billion annually to Aotearoa New Zealand's Gross Domestic Product (GDP), including NZ$700 million in oil exports (Energy Futures Aotearoa, 2024). Aotearoa New Zealand's energy supply is from 40% renewable sources,
345 with the remaining 60% coming from fossil fuels. Approximately 30% of Taranaki's GDP is from oil and gas production, with this playing a significant role in the Taranaki region having the highest GDP per capita in Aotearoa New Zealand. Nearly all oil produced is for export, however natural gas is utilised locally for electricity generation (30%), industrial uses (including milk drying and timber processing; 15%), petrochemical and fertiliser production (45%), and household and commercial use (10%) (Energy Resources Aotearoa, 2024). As the only local source of

Article in Press

350 Liquefied Petroleum Gas (LPG) for the nation, the petroleum sector in the Taranaki region is highly systemically vulnerable to disruption (Weir et al. 2024a).

The Taranaki energy sector is a key dependency for critical infrastructure (New Zealand Lifelines Council 2020a). Whilst disaster resilience planning is considered for midstream and downstream usage (Ministry of Civil Defence 355 Emergency Management 2020), there is limited consideration for volcanic risk to upstream extraction and processing (WorleyParsons 2014). Several studies outline the potential direct, indirect and economic impact of energy disruption from Taranaki Mounga volcanism (Chapman et al. 2007; Johnston et al. 2011; Mcdonald et al. 2017; Taranaki Civil Defence and Emergency Management 2018a; Weir et al. 2024a). The lack of empirical evidence and available studies has limited the inclusion of this sector in volcanic impact and risk assessment. 360 Further, disruptions to the energy sector are typically considered for single-point discrete component failures (First Gas 2020), though volcanic eruptions are known to have complex spatio-temporal behaviours (Bebbington and Jenkins 2019).

3.2 Impact assessment framework

We follow a traditional impact assessment approach by spatially evaluating exposure using GIS software to locate 365 where hazard models and asset inventories intersect, then assessing the potential impact by applying vulnerability models to exposed assets (Figure 4; Jenkins et al. 2014; Weir et al. 2024b; Wilson et al. 2014;). Weir et al. (2022) presents a suite of scientifically credible and operationally relevant volcanic eruption scenarios for Taranaki Mounga volcano and are the only published eruption scenarios for Taranaki Mounga that spatially map the extent of volcanic hazards. Other available scenarios present credible eruption scenarios, but provide either 370 an illustrative (Torres-Orozco et al. 2018) or conceptual (Cronin et al. 2021) format. The Weir et al. (2022) scenarios are long-duration, multi-hazard multi-phase eruption scenarios that include ashfall loading and secondary lahars. Other hazards are included in the suite (PDCs, volcanic ballistic projectiles (VBPs), airborne ashfall, and lava flows) but these hazards are not mapped (Weir et al. 2022) as they are confined to Te Papakura o Taranaki (formerly Egmont National Park) and thus do not directly impact infrastructure of note. The nine 375 scenarios vary in eruption magnitude: there are three small (S1, S2, S3), three medium (M1, M2, M3) and three large (L1, L2, L3) scenarios. Each scenario has multiple phases, labelled: 1d, 2p, 3d, 4p, 5d and 6p, where *d* phases are discrete (1 day) and *p* phases are prolonged (multiple days).

380 **Figure 4:** The impact assessment approach used in this study. * denotes publicly available data and tools and ^ denotes novel data, methods or tools presented in this study.

We adopt the volcanic impact assessment framework developed in Weir et al. (2024a) for volcanic multi-hazards and multi-phase eruption scenarios. The Weir et al. (2024a) framework is traditional in its inclusion of physical 385 vulnerability models and HIMs, though it presents novel approaches for assessing multi-hazard impact through

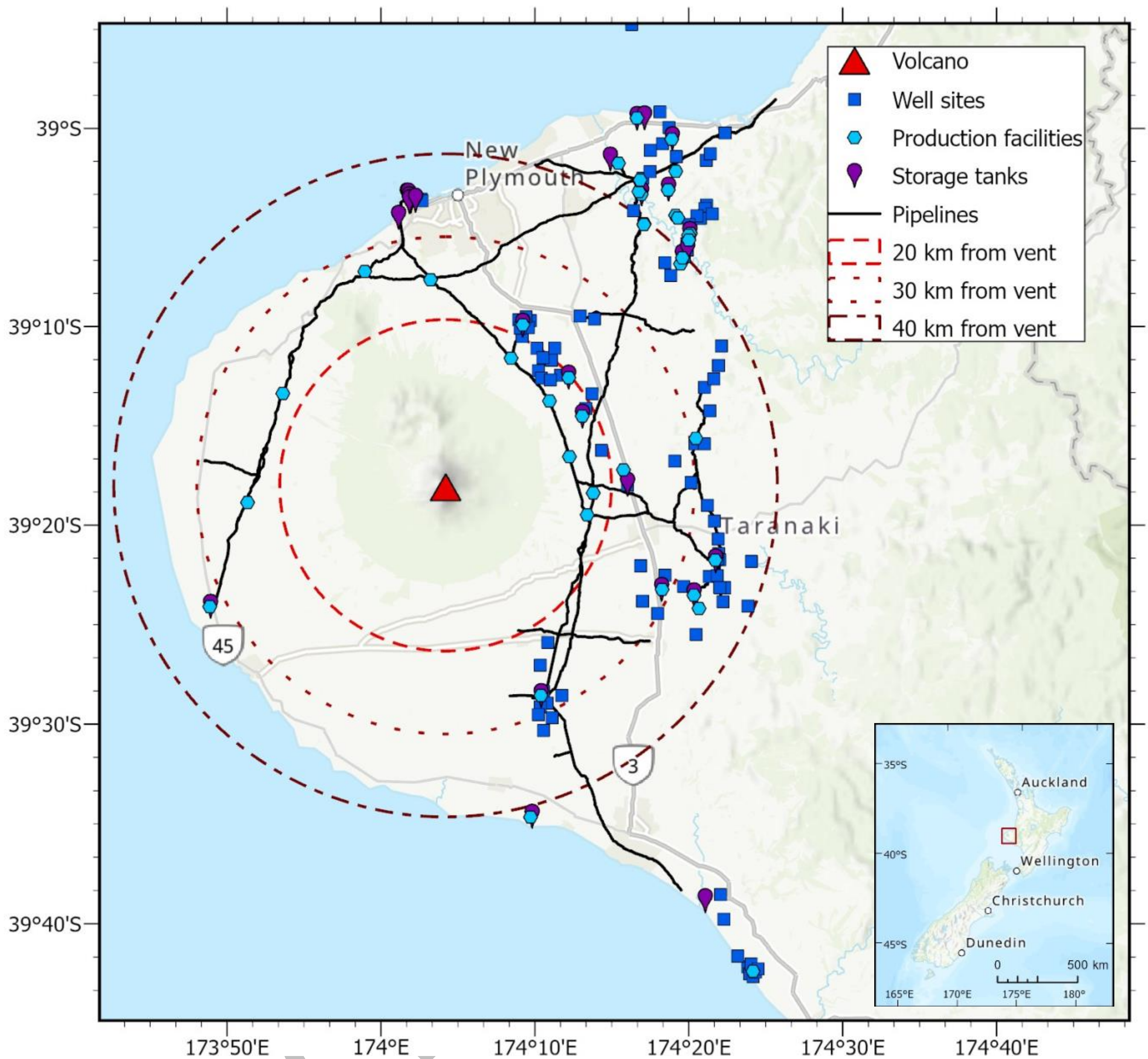
Article in Press

long-duration eruption scenarios and includes systemic disruption of critical infrastructure. The framework workflow begins with pre-defined volcanic eruption scenarios that explicitly describe multiple hazards (e.g. ashfall, lahars, PDCs) and their temporal evolution across discrete and prolonged phases. Each hazard is represented spatially using mapped hazard footprints and associated HIMs. Spatial inventories of infrastructure
390 assets are overlaid with the hazard footprints using GIS-based analysis. For each scenario phase, assets exposed to one or more hazards are identified and the corresponding HIM values are extracted at the asset location. Asset-specific physical vulnerability models define threshold-based relationships between hazard intensity metrics and damage states (e.g., no damage, minor damage, major damage, destruction). For each exposed asset, hazard intensities are compared against these thresholds to deterministically assign a damage state for that phase and
395 hazard. Where assets are exposed to multiple hazards and/or multiple phases, impacts are aggregated cumulatively, with damage states allowed to escalate but not recover during the eruption sequence. This enables assessment of how impacts compound over time rather than being treated as single, independent events. The framework also includes a systemic impact module that links physical damage to loss of functionality and cascading disruption across interdependent infrastructure networks (Weir et al. 2024a).
400

In this study, this impact assessment framework was implemented using hazard footprints from Weir et al. (2022) that were intersected with spatial petroleum asset inventories in GIS, hazard intensity values were extracted for each asset, and the vulnerability model thresholds developed here (Tables 6-9) were then applied deterministically to assign damage states for each scenario phase. We lack the data to support the inclusion of
405 the systemic impact module of Weir et al. (2024a). Here we apply the physical vulnerability models developed in Section 2 to a suite of multi-hazard, multi-phase eruption scenarios for Taranaki Mounga (Weir et al. 2022), using the Weir et al. (2024a) impact assessment approach for determining volcanic multi-hazard, multi-phase impact. Impacts were subsequently aggregated across phases following the cumulative approach described in Weir et al. (2024a).
410

We determine the potential impact to petroleum assets from a Taranaki Mounga eruption. We consider four asset types presented in Section 2: wells, pipelines, production facilities and storage tanks (respectively asset categories 1-4). Though volcanic vulnerability models for buildings are readily available (Maqsood et al. 2014), site-specific vulnerability assessments to determine building classes were beyond the scope of this study. Further,
415 the ‘industrial users’ category is highly complex and constitutes multiple asset types, so it is therefore excluded from the impact assessment. Consideration is given to disruption of industrial users in Section 3.3.1. Asset data were accessed through the publicly available spatial data platform Land Information New Zealand (LINZ) and was current as of 1 November 2018.

Article in Press



420

Figure 5: Petroleum sector assets in the Taranaki region, with inset map showing location in Aotearoa New Zealand (Land Information New Zeal and, 2018).

Petroleum sector assets (n = 247) in the Taranaki region were categorised as wells (n = 94), pipelines (n = 39), production facilities (n = 43), storage tanks (n = 28), buildings (n = 35) or industrial users (n = 8), in accordance with the definitions outlines in Table 1 (Figure 5). Several sites around the Taranaki region contain multiple asset category types due to the co-location of assets for operational expediency. Geospatial inventories were provided by workshop participants and local research partners (Figure 5).

425

3.3 Results

The impact to petroleum sector assets for all nine scenarios (S1 – L3) are presented in Figure 6. In Figure 6, the impact is shown for the final eruptive phase (6p) of each scenario in Weir et al. (2022), using the multi-hazard, cumulative impact assessment approach presented in Weir et al. (2024). Figure 7 shows the cumulative impact states of assets through the eruptive phases (1d – 6p) for Scenario L1. These multi-phase cumulative impact data are available for all scenarios.

430

Article

435 No physical impact to components occurs during Scenario S1, and in all others (S2 – L3) at least seven components are in Damage Level 3 (D3) (destruction). Impacts on pipelines and production facilities in lahar channels are principally driving the impact observed across all scenarios, highlighting not only the vulnerability of petroleum components to this hazard, but also the high exposure of petroleum assets in the Taranaki region to lahars. Lahars are generally channelised hazards, and petroleum sector assets in Taranaki are situated in river channels and in
440 known lahar plains (Neall and Alloway 1993, 1996). Generally, volcanic ashfall loading is not significant enough to cause impact across the scenarios; however, in Scenarios M2 and L1, several production facilities are in Damage Level 2 (D2) due to ashfall loading. PDCs in Weir et al. (2022) are not mapped, as they are thought not to extend beyond the Te Papakura o Taranaki National Park boundary, where there are no petroleum sector assets.

445 Several high-profile assets reach D3 across the eruption scenario suite. Pipelines and production facilities located in and around Hangatahua Stony River in northwest Taranaki reach D3 in 7 of the 9 scenarios. Pipelines, production facilities and storage tanks on the eastern side of Taranaki Mounga see high impact across the suite, with some assets reaching D3 in 7 of the 9 scenarios. Wells see no impact across the scenario suite, as anticipated from their high resilience to volcanic hazards in Table 6.

450

Article in Press

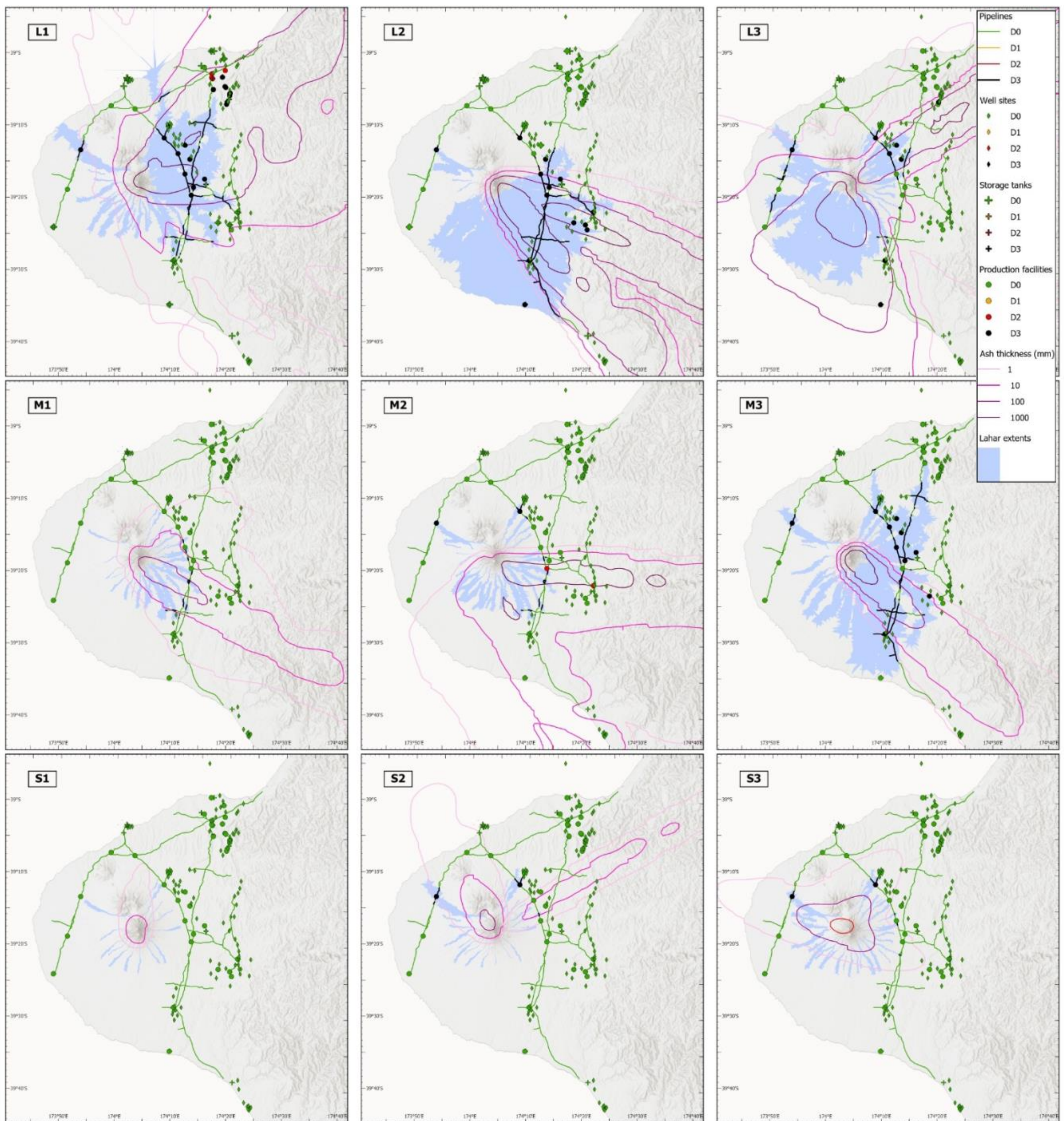


Figure 6: The cumulative impact to petroleum sector assets in the Taranaki region of Aotearoa New Zealand, for a suite of multi-hazard eruption scenarios (Weir et al. 2022). Results are shown for the 'small' eruption suite (S1 – S3), the 'medium' suite (M1 – M3) and the 'large' suite (L1 – L3).

455

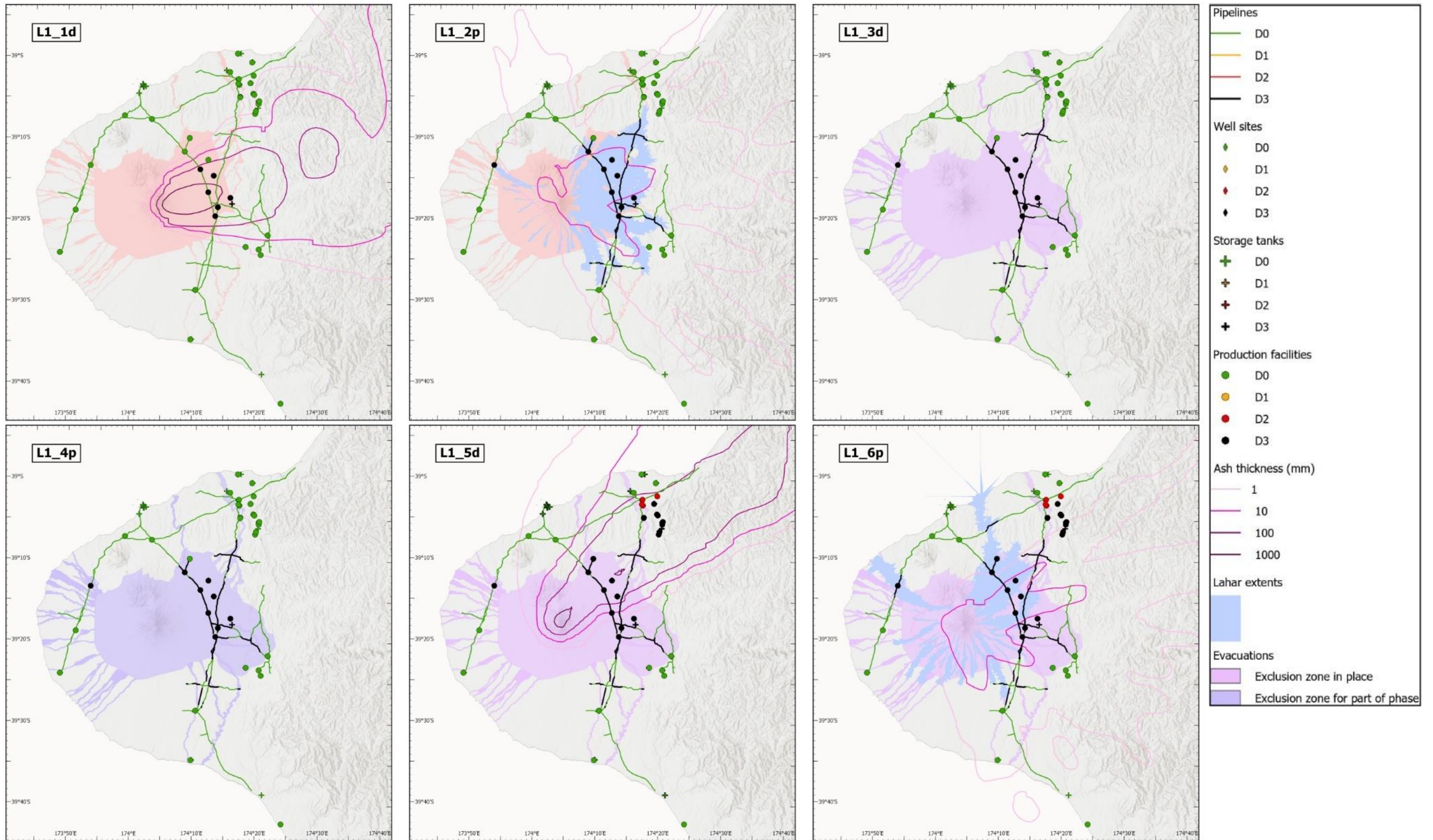


Figure 7: The impact to petroleum assets in the Taranaki region of Aotearoa New Zealand, for Scenario 'Large 1' (L1) in Weir et al. (2022). Scenario L1 has six phases: 1d , 2p, 3d, 4p, 5d and 6p. Phases 3d and 4p are quiescence phases, and thus, no further physical impact is incurred during these phases. Evacuation zones co-developed with Taranaki Civil Defence and Emergency Management (Coultas, 2024) are underlain to demonstrate access limitations for infrastructure operation and repairs.

4 Discussion

This study addresses a global research gap in the development of physical vulnerability models for petroleum sector assets exposed to volcanic hazards (Hayes et al. 2024). The petroleum sector is highly vulnerable to volcanic hazards, and despite global efforts to meet emissions reduction goals, it is still a fundamental essential service for modern society. Even with potential future energy transitions (i.e., away from fossil fuels), energy production systems may utilise similar, if not pre-existing, petroleum sector network components. Though the global exposure of petroleum sector assets to volcanic hazards is relatively low (Figure 1), in those contexts where there is high exposure (e.g., in Aotearoa New Zealand), there is often high dependence on local resources such as natural gas, and therefore if compromised, substantial regional and potentially national energy security and economic consequences. In Aotearoa, there is no established redundancy of supply for the petroleum sector, and disruption and damage to Taranaki assets can threaten national energy security. Further, petroleum sector networks are often subject to key interdependencies of national or transnational importance (e.g., gas for electricity generation, byproducts (e.g., CO_2) for medical, food sector and export uses). There is therefore a strong need to conceptualise, understand and quantify volcanic vulnerabilities and risk for this critical sector that this study begins to address.

Expert derived vulnerability thresholds, presented here, show that wells are likely the most resilient asset type within the petroleum system. Their subsurface design provides a degree of inherent protection from many volcanic hazards. However, associated wellhead infrastructure such as valves, electrical wiring, and in some cases air compressor units, introduce additional points of vulnerability. Pipelines are especially vulnerable where they are exposed, such as at aerial river crossings. In these locations, the erosional forces associated with lahar hazards pose the greatest risk. The high sediment loads and dynamic flow characteristics of lahars can undermine supports, scour foundations, and cause structural failure. Production facility assets encompass a diverse range of equipment, each with distinct hazard sensitivities. For dynamic pressure hazards, structures such as flare stacks are particularly exposed. In the case of suspended ash, equipment with air intake systems is especially vulnerable, as ash ingress can impair functionality and lead to operational shutdowns. Storage tank assets also vary considerably in design. Among these, floating roof tanks are perceived to be the most vulnerable to both static and dynamic pressure hazard HIMs, given their structural configuration and exposure. Finally, smaller components such as wiring and gaskets, although minor elements within larger systems, represent critical vulnerabilities across multiple asset categories. These components are sensitive to elevated temperatures and suspended ash, and their failure can significantly influence repair complexity and recovery timeframes. Lahars and other volcanic flow hazards, such as PDCs, represent the most consequential volcanic threats to the petroleum sector, therefore, their occurrence strongly governs overall volcanic risk. Production facilities and interdependent infrastructure networks (e.g., electricity and water supply, transport systems) are also susceptible to tephra fall. In contrast, wells, pipelines, and storage tanks tend to exhibit comparatively high levels of

Article in Press

495 resilience. These differences in vulnerability suggest that petroleum development in volcanic regions is not necessarily precluded, but it must be strategically planned. In particular, infrastructure siting should avoid mapped or potential volcanic flow paths, and critical interdependent networks must be designed or upgraded to withstand tephra and associated disruptions.

This study utilises the developed vulnerability models to assess the potential impact from nine eruption scenarios
500 of Taranaki Mounga volcano (Weir et al. 2022). These vulnerability models are exploratory in nature, with high and uncharacterised associated uncertainties largely due to a lack of available empirical impact data. While expert elicitation partially addresses this, we note this could be a priority for future research. The physical (direct) impact from volcanic multi-hazards is variable across the scenarios, with most of the asset damage attributed to extensive lahar flows in the larger eruption scenarios (M3 – L3, Figure 6). The physical (direct) impact accounts
505 for one dimension of volcanic impacts, and systemic (indirect) impacts due to this direct damage will be more spatially and temporally extensive. Weir et al. (2024) presents the indirect loss of service to interdependent critical infrastructure networks, including the petroleum sector, for the Taranaki eruption scenario suite. The petroleum sector is substantially disrupted in eight of the nine scenario applications, with complete destruction (D3) of some assets in seven of the scenarios) (Figure 6). The larger scenarios (M2 – L3) cause near-total disruption
510 of the regional network due to: (1) direct impacts to petroleum sector assets, (2) cascading disruption to petroleum sector network, (3) access restrictions due to evacuation management, and (4) disruption of servicing networks, such as electricity and transportation. The national implications of Taranaki petroleum sector disruption are severe and are the subject of much scrutiny in critical infrastructure studies (e.g. Taranaki Civil Defence and Emergency Management 2018b; New Zealand Lifelines Council 2020). The L1 scenario was selected
515 for each individual eruptive phase to be modelled as it represents a plausible, geologically supported eruptive sequence that produces the major hazards that drive impacts. This eruptive scenario has also been applied to model systemic infrastructure impacts (Weir et al. 2024a), water supply disruption (Porter et al. 2025), and transport connectivity (Lamb et al. 2025), therefore this study can contribute to this body of work and be used as a multi-sector planning tool.

520

Although documented volcanic impacts to petroleum infrastructure are rare, the global co-location of active volcanoes and hydrocarbon basins shows that Taranaki is not unique (Figure 1). Analogous configurations occur in the United States (Alaska), Russia (Kamchatka), Indonesia, Chile and Argentina (Patagonia), where pipelines, terminals, and processing facilities are situated downstream of active stratovolcanoes. The most illustrative
525 example is the Drift River Oil Terminal near Redoubt Volcano, where lahars in 1989–90 and 2009 inundated the facility and disrupted regional production (Brantley, 1990; Dorava & Meyer, 1994; Waythomas et al., 2013). Steep volcanic catchments draining toward industrial coastal zones in Kamchatka, lahar-prone river systems on Java associated with Mount Merapi, and Andean basins affected by volcanoes present geomorphological and infrastructural similarities to Taranaki, even where impacts have not yet been documented.

530

Article in Press

Global vulnerability is likely to be highest where channelised lahar systems intersect linear infrastructure (e.g., shallow-buried or aerial pipeline crossings) and where national or regional energy supply depends heavily on a single producing basin. Ice-rich stratovolcanoes in Alaska, Kamchatka, and the Andes may generate high-magnitude lahars capable of significant scour and dynamic loading (Vallance, 2024), while limited redundancy in
535 transmission networks can amplify systemic consequences. In contrast, regions with diversified supply networks may experience high physical exposure but lower national-level disruption due to built-in redundancy (Weir et al. 2024b).

Several design and planning strategies could reduce lahar-related pipeline vulnerability. These include routing
540 avoidance of mapped lahar corridors; deeper burial or armouring of river crossings (including horizontal directional drilling beneath channels); installation of sectionalising valves to limit cascading failures; bunding or diversion structures around tank farms; and formal integration of volcanic hazard maps into petroleum consenting and engineering standards. The Drift River experience demonstrates that relatively targeted physical mitigation (e.g., bund construction and elevation of critical components) can substantially reduce direct impact
545 (Waythomas et al., 2013). Embedding volcanic hazard considerations within existing Natech and critical infrastructure risk management frameworks represents a practical pathway for reducing future risk in analogous volcanic–petroleum settings worldwide.

4.1 Limitations and future directions

The relationship between damage state (e.g. Tables 6-9) and functional state (i.e. the level of service provided by
550 damaged assets) is not well characterised for critical infrastructure sectors, and Weir et al. (2024a) assumes a very simple relationship between physical damage and asset operation. Future work could investigate the relationship between physical and functional impact, across critical infrastructure network types. Further, though the systemic impact of the nine eruption scenarios may be largely consistent, the recovery time and cost are strongly influenced by the extent and severity of physical damage observed. The associated systemic disruption
555 (and cost) to industrial users and economic sectors will be inversely proportional to recovery duration. Future work could focus on recovery modelling and damage cost accounting for the Taranaki scenario suite to develop a better understanding of the systemic implications and total cost of asset damage.

Vulnerability modelling for petroleum assets requires significant further refinement through empirical post-event
560 studies after volcanic eruptions and other analogous events, such as wildfire and other flow hazards; destructive testing of components with regards to engineering standards; and numerical simulations demonstrating the relationships between damage, functionality, recovery and reestablishment.

The scenarios applied (Weir et al. 2022) had several limitations with respect to testing the vulnerability models
565 developed here. The HIMs presented in Weir et al. (2022) are not best aligned with those presented in Tables 6-9 or fit-for-purpose when assessing petroleum sector vulnerability. Therefore, adjustments had to be made to

Article in Press

apply the models to the scenario suite (Section 3.2). Weir et al. (2022) does not model offshore hazards (e.g., out-of-region ashfall), limiting our consideration of offshore petroleum sector assets here. Further, Weir et al. (2022) is devoid of unrest hazards (e.g. seismic activity, ground deformation) which can not only provoke damage, but present a highly challenging operational environment. The development of complementary unrest scenarios would highly complement infrastructure studies such as these in the future. Finally, the eruption scenario suite presented in Weir et al. (2022) consists of hypothetical, credible scenarios; however, a fully probabilistic volcanic hazard model, including higher resolution lahar hazard modelling, would allow for risk calculations to be undertaken.

The vulnerability models developed here exclude modules for airborne ash hazard, despite recognition as potentially damaging and disruptive for the petroleum sector (Tables 6-9). Airborne ash concentration was not deemed an acceptable HIM for this study, as the duration of exposure to airborne ash (i.e., ash dose) is highly important to capture. Accounting for the dose may also be crucial for other hazards, such as high temperature exposure on the fringes of volcanic surface flow hazards.

In many volcanic regions, petroleum production depends on coastal terminals and major port infrastructure located downstream of volcanic catchments or within ashfall-prone airspaces (Juniper, 2018). While shipping infrastructure was excluded from the present physical vulnerability assessment due to data and scope constraints, future systemic risk assessments could explicitly incorporate port functionality, maritime exclusion zones, and sedimentation impacts to capture the full petroleum supply-chain exposure in volcanic regions.

The petroleum sector in Taranaki is highly exposed and vulnerable to volcanic unrest and eruption hazards, though there is limited consideration of volcanic risk management in publicly available documentation. However, increasing domestic regulation of the sector is provoking increased consideration of risk management protocols in accordance with Australia/New Zealand Standards, which are reviewed regularly as part of an iterative improvement process. These vulnerability models and impact assessment provide an additional tool to aid in the review and revision of existing standards and practices, contributing towards better risk management and resilience-building procedures.

5 Conclusions

We present world-first volcanic physical vulnerability models for the four key asset classes of the petroleum sector: wells, pipelines, production facilities and storage tanks. The vulnerability models are developed for four volcanic hazard intensity metrics (burial thickness, static load, temperature and dynamic pressure) and are thus applicable to multiple volcanic hazards. We apply these models to pre-existing multi-hazard eruption scenarios for Taranaki Mounga volcano in Aotearoa New Zealand, using an available impact assessment framework to demonstrate their usability in impact and risk modelling. Across the nine eruption scenarios assessed, no physical damage is modelled in the smallest scenario (S1), whereas in all remaining scenarios (S2–L3) multiple petroleum sector assets reach complete destruction (D3). Pipelines and production facilities located within mapped lahar

Article in Press

604 pathways are the most consistently affected, with several high-exposure assets reaching D3 in seven of the nine
605 eruption scenarios, while wells remain undamaged across all scenarios due to their high physical resilience. Overall, the results demonstrate that moderate-to-large eruptions are sufficient to cause widespread, system-critical damage to key petroleum infrastructure, with impacts concentrated in a small number of highly exposed locations. Our impact assessment indicates that a future eruption of Taranaki Mounga volcano could cause widespread impacts to the petroleum sector, which could in turn create a significant and prolonged national
610 energy crisis. The impact assessment results allow the investigation of effective and feasible risk management strategies to aid in reducing future volcanic impacts of volcanism in the Taranaki region, and across Aotearoa NZ. The vulnerability models may be applied in other volcanic regions worldwide to assess potential volcanic impacts, and inform risk reduction and readiness actions.

615 **Author contributions**

ZJ and TMW conceptualised the study. ZJ developed the physical vulnerability models for her Master of Science (MSc) degree at the University of Canterbury Te Whare Wānanga o Waitaha, under the supervision of TMW, NID and JP. AW conducted volcanic physical impact modelling, systemic impact modelling and developed and applied the impact assessment framework. ZJ, AW and NID created the figures. AW, CS and HC drafted the manuscript,
620 and all authors read and approved it. CCS and RF provided expert advice. HC, JW and EC assisted with data acquisition, analysis and presentation during the development of the manuscript.

Acknowledgements

The authors thank GNS Science for hosting ZJ, and staff members Brad Scott, Graham Leonard, Sally Potter, S
625 Uma, Kirsten Garbett, Katy Kelly and Nick Horspool for their interest and support. We gratefully thank and acknowledge the following companies that provided input into the project: Shell Taranaki Ltd, Todd Energy Ltd, TAG Oil (NZ) Ltd, First Gas Ltd, the Petroleum Exploration & Production Association of New Zealand, Taranaki Civil Defence and Emergency Management, and Taranaki Regional Council. The authors thank Matthew Hughes and Jim Cole for their co-supervision of ZJ during her thesis. We gratefully acknowledge funding support from the
630 Natural Hazard Research Platform (NHRP) (Grant 2015-MAU-01-NHRP), the He Mounga Puia Transitioning Taranaki to a Volcanic Future programme (Grant UOAX1913), the Resilience to Nature's Challenges Volcano Programme (Grant GNS-RNC047) and the GNS Science Core Research Programme (NID). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

635 **Data availability**

The volcanic hazard scenarios used in this study are derived from Weir et al. (2022) (https://doi.org/10.1016/j.jvolgeores.2022.107557) and are publicly available. Petroleum infrastructure spatial data used in the analysis are subject to proprietary and confidentiality restrictions and cannot be shared openly.

Article in Press

Access to these data, and the resulting impact assessment outputs that depend on them, may be requested from
640 the authors, subject to appropriate permissions and data-sharing agreements with the data providers.

Article in Press

References

Aitsi-Selmi, A., Egawa, S., Sasaki, H., Wannous, C., & Murray, V. (2015). The Sendai framework for disaster risk reduction: Renewing the global commitment to people's resilience, health, and well-being. International Journal of Disaster Risk Science, 6(2), 164-176. doi:10.1007/s13753-015-0050-9

Allen, P. A., & Allen, J. R. (2013). Basin analysis: Principles and application to petroleum play assessment: John Wiley & Sons.

Alloway, B. V., McComb, P., Neall, V. E., Vucetich, C. G., Gibb, J., Sherburn, S., & Stirling, M. (2005). Stratigraphy, age, and correlation of voluminous debris-avalanche events from an ancestral Egmont Volcano: implications for coastal plain construction and regional hazard assessment. Journal of the Royal Society of New Zealand, 35(1-2), 229-267.

Alloway, B. V., Neall, V. E., & Vucetich, C. G. (1995). Late Quaternary (post 28,000 year B.P.) tephrostratigraphy of northeast and central Taranaki, New Zealand. Journal of the Royal Society of New Zealand, 25(4), 385-458. doi:10.1080/03014223.1995.9517496

American Petroleum Institute. (2013). API STD 650. In Welded Tanks for Oil Storage, Twelfth Edition (pp. 498). Washington, D.C.: American Petroleum Institute.

American Society of Civil, E., & Wind-Induced Forces Task, C. (2011). Wind Loads for Petrochemical and Other Industrial Facilities. Reston, VA: American Society of Civil Engineers.

Arguden, A. T., & Rodolfo, K. S. (1990). Sedimentologic and dynamic differences between hot and cold laharic debris flows of Mayon Volcano, Philippines. GSA Bulletin, 102(7), 865-876. doi:10.1130/0016-7606(1990)102<0865:SADDBH>2.3.CO;2

Ancione G., Milazzo M.F., Lisi R., Maschio G. (2015) Consequences of liquid tank explosions caused by lava flow, Chemical Engineering Transactions, 43, 2071-2076 DOI: 10.3303/CET1543346

Aspinall, W. P., Charbonnier, S., Connor, C. B., Connor, L. J. C., Costa, A., Courtland, L. M., . . . Watanabe, K. (2016). Volcanic hazard assessments for nuclear installations: Methods and examples in site evaluation (9201049161). Retrieved from Vienna, Austria: http://www-pub.iaea.org/MTCD/publications/PDF/TE1795web.pdf

Australian Energy Market Operator Limited. (2014). Gas quality guidelines; Operating procedure. Retrieved from Australia: http://www.aemo.com.au/media/Files/Other/consultations/gas/Gas_Quality_Guidelines_Version_9_0_Official_2.pdf

Baek, J.-h., Kim, Y.-p., Kim, W.-s., Koo, J.-m., & Seok, C.-s. (2012). Load bearing capacity of API X65 pipe with dent defect under internal pressure and in-plane bending. Materials Science and Engineering: A, 540, 70-82. doi:10.1016/j.msea.2012.01.078

Baxter, P. J., Boyle, R., Cole, P., Neri, A., Spence, R. J. S., & Zuccaro, G. (2005). The impacts of pyroclastic surges on buildings at the eruption of the Soufrière Hills volcano, Montserrat. Bulletin of Volcanology, 67(4), 292-313. doi:10.1007/s00445-004-0365-7

Bebbington, M., Cronin, S. J., Chapman, I., & Turner, M. B. (2008). Quantifying volcanic ash fall hazard to electricity infrastructure. Journal of Volcanology and Geothermal Research, 177(4), 1055-1062. doi:10.1016/j.jvolgeores.2008.07.023

Bebbington MS, Jenkins SF (2019) Intra-eruption forecasting. 81:34. https://doi.org/https://doi.org/10.1007/s00445-019-1294-9

Belousov, A., Voight, B., & Belousova, M. (2007). Directed blasts and blast-generated pyroclastic density currents: a comparison of the Bezymianny 1956, Mount St Helens 1980, and Soufrière Hills, Montserrat 1997 eruptions and deposits. Bulletin of Volcanology, 69(7), 701. doi:10.1007/s00445-006-0109-y

Article in Press

Birkmann, J., Buckle, P., Jaeger, J., Pelling, M., Setiadi, N., Garschagen, M., . . . Kropp, J. (2010). Extreme events and disasters: A window of opportunity for change? Analysis of organizational, institutional and political changes, formal and informal responses after mega-disasters. Natural Hazards, 55(3), 637-655. doi:10.1007/s11069-008-9319-2

Blake, D. M. (2017). Impacts of volcanic ash on surface transportation networks: considerations for Auckland City, New
685 Zealand. (Doctor of Philosophy in Disaster Risk and Resilience), University of Canterbury, Christchurch, New Zealand. Retrieved from https://ir.canterbury.ac.nz/handle/10092/13282

Blake, D. M., Wilson, G., Stewart, C., Craig, H. M., Hayes, J. L., Jenkins, S. F., . . . Cronin, S. J. (2015). The 2014 eruption of Kelud volcano, Indonesia: impacts on infrastructure, utilities, agriculture and health (GNS Science report 2015/15 x, 130 p.). Retrieved from Lower Hutt, New Zealand:

690 Blong, R. J., Grasso, P., Jenkins, S. F., Magill, C. R., Wilson, T. M., McMullan, K., & Kandlbauer, J. (2017). Estimating building vulnerability to volcanic ash fall for insurance and other purposes. Journal of Applied Volcanology, 6(1), 2. doi:10.1186/s13617-017-0054-9

Bonadonna, C., & Houghton, B. F. (2005). Total grain-size distribution and volume of tephra-fall deposits. Bulletin of Volcanology, 67(5), 441-456. doi:10.1007/s00445-004-0386-2

695 Brantley, S. R. (1990). The eruption of Redoubt Volcano, Alaska, December 14, 1989-August 31, 1990. Washington, DC: United States Government Printing Office.

Bratspies, R. M. (2011). A regulatory wake-up call: Lessons from BP's Deepwater Horizon Disaster. Golden Gate U. Envtl. LJ, 5, 7.

Bredero Shaw. (n.d.). Yellow jacket: High density two layer polyethylene coating. Houston, TX. Retrieved from
700 http://www.brederoshaw.com/non_html/pds/BrederoShaw_PDS_YellowJacket.pdf

Brinkley, D. (2007). The Great Deluge : Hurricane Katrina, New Orleans, and the Mississippi Gulf Coast (1st, Harper Perennial ed.). New York: Harper Perennial.

Brown, S. K., Loughlin, S. C., Sparks, R. S. J., & Vye-Brown, C. (2014). Global volcanic hazards and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015. Retrieved from

705 Brown, S. K., Sparks, R. S. J., Mee, K., Vye-Brown, C., Ilyinskaya, E., Jenkins, S. F., & Loughlin, S. C. (2015). Global volcanic hazards and risk: Regional and country profiles of volcanic hazard and risk. Report IV of the GVM/IAVCEI contribution to the Global Assessment Report on Disaster Risk Reduction 2015. In.

Bull, K. F., & Buurman, H. (2013). An overview of the 2009 eruption of Redoubt Volcano, Alaska. Journal of Volcanology and Geothermal Research, 259, 2-15. doi:10.1016/j.jvolgeores.2012.06.024

710 Chapman, I., Bebbington, M., Cronin, S. J., & Turner, M. B. (2007). Vulnerability analysis of the power-distribution infrastructure in Western North Island of New Zealand to ashfall from Mt Taranaki/Egmont. Paper presented at the Cities on Volcanoes 5 Shimabara, Japan. http://www.eri.u-tokyo.ac.jp/people/nakada/cov5_hp/documents/abstract_e.pdf

Civil Defence Emergency Management Act 2002, (2017, August 8). Retrieved from http://www.legislation.govt.nz

715 Clemens, P. L. (1993). Fault tree analysis. JE Jacobs Severdurup. Retrieved from http://rischioatmosfereesplosive.studiomarigo.it/profiles/marigo2/images/file/1736612536.pdf

Cook Inletkeeper. (2009). Drift River oil terminal; Timeline, issues & questions 2009. Retrieved from Inlet Keeper website: https://inletkeeper.org/issues/drift-river

Coppola, D. P. (2011). Introduction to international disaster management: Butterworth-Heinemann, second edition.

720 Coultas, E. K. (2024). Identifying Evacuation Planning Considerations for Complex Volcanic Crises: A Case Study from Taranaki, Aotearoa New Zealand. MSc Thesis, University of Canterbury.

Article in Press

Craig, H., Wilson, T. M., Stewart, C., Outes, V., Villarosa, G., & Baxter, P. J. (2016). Impacts to agriculture and critical infrastructure in Argentina after ashfall from the 2011 eruption of the Cordón Caulle volcanic complex: an assessment of published damage and function thresholds. Journal of Applied Volcanology, 5(1), 7. doi:10.1186/s13617-016-0046-1

Craig, H., Wilson, T. M., Stewart, C., Villarosa, G., Outes, V., Cronin, S. J., & Jenkins, S. F. (2016). Agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America. Natural Hazards, 82(2), 1167-1229. doi:10.1007/s11069-016-2240-1

Cronin SJ, Zernack A V, Ukstins IA, et al (2021) The geological history and hazards of a long-lived stratovolcano, Mt. Taranaki, New Zealand. New Zeal J Geol Geophys 0:1–23. https://doi.org/10.1080/00288306.2021.1895231

Critical Contingency Operator. (2017). CCO information guide. Retrieved from CCO Website: http://www.cco.org.nz/publications

Cronin, S. J. (2012). Faster rebuilds with MRCGE: Simulating socio-economic rebuild following volcanic event. Retrieved from Wellington, New Zealand: https://www.naturalhazards.org.nz/haz/content/download/11396/60959/file/NHRP%20Contest%202012%20Cronin.pdf

Cronin, S. J., Stewart, R. B., Neall, V. E., Platz, T., & Gaylord, D. (2003). The AD1040 to present Maero Eruptive Period of Egmont Volcano, Taranaki, New Zealand. Geol Soc NZ Misc Publ A, 116, 43.

Cruz, A.M and Suarez-Paba, M.C. (2019) Advances in Natech research: an overview. Progress in Disaster Science 1, 100013. https://doi.org/10.1016/j.pdisas.2019.100013

Damaschke, M., Cronin, S. J., & Bebbington, M. S. (2017). A volcanic event forecasting model for multiple tephra records, demonstrated on Mt. Taranaki, New Zealand. Bulletin of Volcanology, 80(1), 9. doi:10.1007/s00445-017-1184-y

Damaschke, M., Cronin, S. J., Holt, K. A., Bebbington, M., & Hogg, A. G. (2017). A 30,000 yr high-precision eruption history for the andesitic Mt. Taranaki, North Island, New Zealand. Quaternary Research, 87(1), 1-23.

Deligne, N. I. (2016). Developing volcanic hazard and risk models for the Auckland Volcanic Field as part of the DEVORA project. Retrieved from Wellington, New Zealand: https://www.eqc.govt.nz/sites/public_files/4620-Developing-volcanic-hazard-and%20risk-models-Auckland-Volcanic-Field.pdf

Deligne, N. I., Fitzgerald, R. H., Blake, D. M., Davies, A. J., Hayes, J. L., Stewart, C., . . . Woods, R. (2017). Investigating the consequences of urban volcanism using a scenario approach I: Development and application of a hypothetical eruption in the Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research, 336, 192-208. doi:10.1016/j.jvolgeores.2017.02.023

Deligne NI, Jenkins SF, Meredith ES, et al (2022) From anecdotes to quantification: advances in characterizing volcanic eruption impacts on the built environment. Bull Volcanol 84:7. https://doi.org/10.1007/s00445-021-01506-8

Deligne, N. I., & Wilson, G. (2015). Architecture and hazard intensity metrics for RiskScape volcano. Retrieved from Lower Hutt, New Zealand:

Della-Pasqua, F. N., Massey, C. I., McSaveney, M. J., & Townsend, D. B. (2016). Preliminary assessment of some flank-failure scenarios for Mount Taranaki and recommendations for future assessment of the risk from such hazards. Retrieved from Wellington, Lower Hutt: http://shop.gns.cri.nz/preliminary-assessment-of-some-flank-failure-scenarios-for-mount-taranaki-and-recommendations-for-future-assessment-of-the-risk-from-such-hazards/

Dorava, J. M., & Meyer, D. F. (1994). Hydrologic hazards in the lower Drift River basin associated with the 1989–1990 eruptions of Redoubt Volcano, Alaska. Journal of Volcanology and Geothermal Research, 62(1), 387-407. doi:10.1016/0377-0273(94)90044-2

Article in Press

Doronzo, D. M., Martí, J., Dellino, P., Giordano, G., & Sulpizio, R. (2016). Dust storms, volcanic ash hurricanes, and turbidity currents: physical similarities and differences with emphasis on flow temperature. Arabian Journal of Geosciences, 9(4), 290. doi:10.1007/s12517-016-2351-8

Dussaillant, A., Russell, A., Meier, C., Rivera, A., Mella, M., Garrido, N., . . . Gonzalez, C. (2016). Causes, Dynamics and Impacts of Lahar Mass Flows due to the April 2015 Eruption of Calbuco Volcano, Chile. Paper presented at the EGU General Assembly Conference Abstracts.

Efford, J. T., Clarkson, B. D., & Bylsma, R. J. (2014). Persistent effects of a tephra eruption (AD 1655) on treeline composition and structure, Mt Taranaki, New Zealand. New Zealand Journal of Botany, 52(2), 245-261. doi:10.1080/0028825X.2014.886599

Energy Education. (n.d.). Representation of upstream, midstream, and downstream industry. Retrieved from http://energyeducation.ca/encyclopedia/Downstream_oil_and_gas_industry

Energy Resources Aotearoa (2024). Our energy resources. Retrieved from https://www.energyresources.org.nz/oil-and-gas-new-zealand/our-energy-mix/ Accessed 20 March 2025.

Evans, J. (2013). Introduction to structured expert elicitation: A risk analysis perspective. Methods for Research Synthesis: A Cross-Disciplinary Approach. Harvard Center for Risk Analysis. Retrieved from https://cdn1.sph.harvard.edu/wp-content/uploads/sites/1273/2013/09/Evans-abstract-Sept-2013.pdf

Finnis, K., Johnston, D. M., & Paton, D. (2004). iolcanic hazard risk perceptions in New Zealand. Tephra, 21(September 2004), 1-5.

First Gas (2020) Critical Contingency Management Plan

FirstGas. (n.d). Network map of the FirstGas transmission pipelines. Retrieved from http://firstgas.co.nz/our-network/network-map/

Fitzgerald, R. H., Wilson, T. M., Hayes, J. L., Weir, A. M., Williams, J. H., & Leonard, G. S. (2023). A stocktake of global volcanic vulnerability models to inform future volcanic risk research in Aotearoa New Zealand: GNS Science. doi: 10.21420. *NQ3E-9M78*.

Fletcher, A., & Nicholas, D. (2014). Fusion bonded polyethylene coatings – 40 years on. http://www.steelmains.com/. Retrieved from http://www.steelmains.com/files/FBPE%20Coatings%20-%2040%20years%20on%20Corrosion%20Australasia%20February%202015.pdf

Freire S, Florczyk A, Pesaresi M, Sliuzas R (2019). An improved global analysis of population distribution in proximity to active volcanoes, 1975-2015. ISPRS International Journal of Geo-Information 8(8)

Gehl, P., Desramaut, N., Réveillère, A., & Modaressi, H. (2014). Fragility functions of gas and oil networks. In K. Pitilakis, H. Crowley, & A. M. Kaynia (Eds.), SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk: Buildings, Lifelines, Transportation Networks and Critical Facilities (pp. 187-220). Dordrecht: Springer Netherlands.

Gehl, P., Quinet, C., Le Cozannet, G., Kouokam, E., & Thierry, P. (2013). Potential and limitations of risk scenario tools in volcanic areas through an example at Mount Cameroon. Natural Hazards and Earth System Sciences, 13, 2409-2424. doi:10.5194/nhess-13-2409-2013

Gerstenberger, M., McVerry, G., Rhoades, D., & Stirling, M. (2014). Seismic Hazard Modeling for the Recovery of Christchurch. Earthquake Spectra, 30(1), 17-29. doi:10.1193/021913eqs037m

Giovinazzi, S., Brown, C., Seville, E., Stevenson, J. R., Hatton, T., & Vargo, J. J. (2016). Criticality of infrastructures for organisations. International Journal of Critical Infrastructures, 12(4), 331-363. doi:10.1504/ijcis.2016.081303

Article in Press

Global Facility for Disaster Reduction and Recovery (2014). Guide to developing disaster recovery frameworks: World reconstruction conference version. Global Facility for Disaster Reduction and Recovery, International Recovery
805 Platform

Global Volcanism Program, 2023. [Database] Volcanoes of the World (v. 5.1.0; 9 Jun 2023). Distributed by Smithsonian Institution, compiled by Venzke, E. https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1

GNS Science. (n.d.). Petroleum Basin Explorer. Retrieved from https://data.gns.cri.nz/pbe

Global Volcanism Program, 2001. Report on Nyiragongo (DR Congo) (Wunderman, R., ed.). Bulletin of the Global Volcanism
810 Network, 26:12. Smithsonian Institution. https://doi.org/10.5479/si.GVP.BGVN200112-223030.

GNS Science, & NIWA. (n.d.). RiskScape user technical documentation wiki. Retrieved from https://wiki.riskscape.org.nz/index.php/RiskScape_User_Technical_Documentation_Wiki

Green, R. M., Bebbington, M., Cronin, S. J., & Jones, G. (2013). Geochemical precursors for eruption repose length. Geophysical Journal International, 193(2), 855-873. doi:10.1093/gji/ggt044

815 Hayes, J. L., Wilson, T. M., Deligne, N. I., Cole, J. W., & Hughes, M. W. (2017). A model to assess tephra clean-up requirements in urban environments. Journal of Applied Volcanology, 6(1), 1. doi:10.1186/s13617-016-0052-3

Hayes, J. L., Wilson, T. M., & Magill, C. R. (2015). Tephra fall clean-up in urban environments. Journal of Volcanology and Geothermal Research, 304, 359-377. doi:10.1016/j.jvolgeores.2015.09.014

Horspool, N., Cousins, W. J., & Power, W. L. (2015). Review of Tsunami risk facing New Zealand: A 2015 update. Retrieved
820 from http://www.eqc.govt.nz/sites/public_files/GNS%202015%20Update.pdf

Houghton, B. F., Bonadonna, C., Gregg, C. E., Johnston, D. M., Cousins, W. J., Cole, J. W., & Del Carlo, P. (2006). Proximal tephra hazards: Recent eruption studies applied to volcanic risk in the Auckland volcanic field, New Zealand. Journal of Volcanology and Geothermal Research, 155(1), 138-149. doi:https://doi.org/10.1016/j.jvolgeores.2006.02.006

Hull, A. (1996). Earthquake and volcanic hazards in Taranaki: potential threats to oil and gas production and distribution
825 infrastructure. Paper presented at the 1996 New Zealand Petroleum Conference Proceedings. Wellington, Ministry of Commerce: 261Á271.

Hurst, A. W. (1994). ASHFALL—a computer program for estimating volcanic ash fallout. Report and users guide. Institute of Geological & Nuclear Sciences Science Report, 94(23), 22.

Hurst, A. W., & Davis, C. (2017). Forecasting volcanic ash deposition using HYSPLIT. Journal of Applied Volcanology, 6(1), 5.
830 doi:10.1186/s13617-017-0056-7

Hurst, A. W., Jolly, A. D., & Sherburn, S. (2014). Precursory characteristics of the seismicity before the 6 August 2012 eruption of Tongariro volcano, North Island, New Zealand. Journal of Volcanology and Geothermal Research, 286, 294-302. doi:10.1016/j.jvolgeores.2014.03.004

Hurst, A. W., & Smith, W. (2010). Volcanic ashfall in New Zealand – probabilistic hazard modelling for multiple sources. New
835 Zealand Journal of Geology and Geophysics, 53(1), 1-14. doi:10.1080/00288301003631129

International Energy Agency. (2021). Key World Energy Statistics 2021. Retrieved from https://www.iea.org/reports/key-world-energy-statistics-2021

International Energy Agency. (2017). World Energy Outlook 2017 Retrieved from Paris, France: http://www.iea.org/weo2017/

840 Intertek. (n.d.). Intelligent pigging pipeline inspection diagram. Retrieved from http://www.intertek.com/pipeline-inline-inspection/

Jenkins, S.F., Day, S.J., Faria, B.V.E. et al. Damage from lava flows: insights from the 2014–2015 eruption of Fogo, Cape Verde. J Appl. Volcanol. 6, 6 (2017). https://doi.org/10.1186/s13617-017-0057-6

Article in Press

Jenkins, S. F., Komorowski, J. C., Baxter, P. J., Spence, R. J. S., Picquout, A., Lavigne, F., & Surono. (2013). The Merapi 2010 eruption: An interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics. Journal of Volcanology and Geothermal Research, 261, 316-329. doi:10.1016/j.jvolgeores.2013.02.012

Jenkins, S. F., Magill, C. R., McAneney, J., & Blong, R. J. (2012). Regional ash fall hazard I: a probabilistic assessment methodology. Bulletin of Volcanology, 74(7), 1699-1712. doi:10.1007/s00445-012-0627-8

Jenkins, S. F., McAneney, J., Magill, C. R., & Blong, R. J. (2012). Regional ash fall hazard II: Asia-Pacific modelling results and implications. Bulletin of Volcanology, 74(7), 1713-1727. doi:10.1007/s00445-012-0628-7

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. Journal of Volcanology and Geothermal Research, 276, 105-120. doi:10.1016/j.jvolgeores.2014.03.002

Jenkins, S. F., Wilson, T. M., Magill, C. R., Miller, V., Stewart, C., Marzocchi, W., & Boulton, M. (2014). Volcanic ash fall hazard and risk: Technical background paper for the UN-ISDR 2015 global assessment report on disaster risk reduction. Retrieved from

Jérôme, L., & Neall, V. E. (n.d.). A Scenario for Volcanic Unrest at Mt Taranaki. Retrieved from http://volcanic.massey.ac.nz/research/2005-11-volcanic-unrest.php

JFE Steel Corporation. (n.d.). Pipe coatings. www.jfe-steel.co.jp. Retrieved from http://www.jfe-steel.co.jp/en/products/pipes/catalog/e1e-009.pdf

Johnston, D. M., Becker, J. S., Jolly, G. E., Potter, S. H., Wilson, T. M., Stewart, C., & Cronin, S. (2011). Volcanic hazards management at Taranaki volcano: Information source book. Retrieved from Wellington, New Zealand: http://shop.gns.cri.nz/volcanic-hazards-management-at-taranaki-volcano-information-source-book/

Johnston, D. M., Stewart, C., Leonard, G., Hoverd, J., Thordarsson, T., & Cronin, S. (2004). Impacts of volcanic ash on water supplies in Auckland: Part I. GNS Science Report, 25.

Juniper, Z. (2018). Risk assessment of the petroleum exploration and production industry from volcanic hazards in the Taranaki region, New Zealand. Master of Science thesis. University of Canterbury, Christchurch, New Zealand. http://dx.doi.org/10.26021/6738

Kissell, J. R., & Myers, P. (2003). Revision addresses new approaches for storage tank loads. Oil & Gas Journal. Retrieved from http://www.ogj.com/ website: http://www.ogj.com/articles/print/volume-101/issue-47/transportation/revision-addresses-new-approaches-for-storage-tank-loads.html

Kongar, I., Giovinazzi, S., & Rossetto, T. (2016). Seismic performance of buried electrical cables: evidence-based repair rates and fragility functions. Bulletin of Earthquake Engineering, 1-31. doi:10.1007/s10518-016-0077-3

Krausmann, E., Cozzani, V., Salzano, E., & Renni, E. (2011a). Industrial accidents triggered by natural hazards: an emerging risk issue. Natural Hazards and Earth System Sciences, 11(3), 921. doi:10.5194/nhess-11-921-2011

Krausmann, E., Renni, E., Campedel, M. and Cozzani, V. (2011b Industrial accidents triggered by earthquakes, floods and lightning: lessons learned from a database analysis. Nat Hazards 59, 285–300. https://doi.org/10.1007/s11069-011-9754-3

Krausmann, E. and Salzano, E. (2017). Lessons learned from Natech events. In: Krausmann, E., Cruz, A.M. and Salzano, E. (2017) Natech risk assessment and management: reducing the risk of natural-hazard impact on hazardous installations. Elsevier, The Netherlands. ISBN: 978-0-12-803807-9.

Krausmann, E., Girgin, S. and Necci, A. (2019) Natural hazard impacts on industry and critical infrastructure: Natech risk drivers and risk management performance indicators. International Journal of Disaster Risk Reduction 40, 101163. https://doi.org/10.1016/j.ijdrr.2019.101163

Article in Press

885 Lamb, J., Craig, H. M., Thomas, K. L., Wilson, T. M., & Bowbrick, Z. (2025). Multi-hazard impact assessment of regional rural transport networks for a large eruption of Taranaki Mounga, Aotearoa New Zealand. *New Zealand Journal of Geology and Geophysics*, *68*(4), 773-793. https://doi.org/10.1080/00288306.2025.2461522

Land Information New Zealand, 2018. [Database] (1 Nov 2018).

Larsen, W. F. (1974). Fault tree analysis. Retrieved from

890 Lavigne, F. (2002). Lahar Front in the Curah Lengkong river, Semeru volcano, Indonesia. Retrieved from https://www.youtube.com/watch?v=KwsA2XNWk2k

Lerner GA, Cronin SJ, Bebbington MS, Platz T (2019a) The characteristics of a multi-episode volcanic regime: the post-AD 960 Maero Eruptive Period of Mt. Taranaki (New Zealand). Bull Volcanol 81:. https://doi.org/10.1007/s00445-019-1327-4

895 Lerner GA, Cronin SJ, Turner GM, Rowe MC (2019b) Paleomagnetic determination of the age and properties of the 1780–1800 AD dome effusion/collapse episode of Mt. Taranaki, New Zealand. Bull Volcanol 81:. https://doi.org/10.1007/s00445-019-1275-z

Loughlin, S. C., Sparks, S., Brown, S. K., Vye-Brown, C., & Jenkins, S. F. (2015). Global Volcanic Hazards and Risk: Cambridge University Press.

900 Lujala, P., Rod, J. K., & Thieme, N. (2007). Fighting over oil: Introducing a new dataset: Location of the world's petroleum fields (PETRODATA) [Dataset]. Retrieved from: http://worldmap.harvard.edu/data/geonode:location_of_the_worlds_petroleum_fields__xtl

Lund, K. A., & Benediktsson, K. (2011). Inhabiting a risky earth: The Eyjafjallajökull eruption in 2010 and its impacts (Respond to this article at http://www.therai.org.uk/at/debate). Anthropology Today, 27(1), 6-9. doi:10.1111/j.1467-
905 8322.2011.00781.x

Macedonio, G., Costa, A., & Folch, A. (2008). Ash fallout scenarios at Vesuvius: Numerical simulations and implications for hazard assessment. Journal of Volcanology and Geothermal Research, 178(3), 366-377. doi:10.1016/j.jvolgeores.2008.08.014

Maqsood T, Wehner M, Ryu H, et al (2014) GAR15 Vulnerability Functions. Report UNISDR/GA SE Asian Reg Work Struct
910 Vulnerability Model GAR Glob Risk Assessment, 11–14 November, 2013, Geosci Aust Canberra, Aust 38:. https://doi.org/http://dx.doi.org/10.11636/Record.2014.038.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M. L., & Di Ruocco, A. (2012). Basic principles of multi-risk assessment: A case study in Italy. Natural Hazards, 62(2), 551-573. doi:10.1007/s11069-012-0092-x

Marzocchi, W., & Jordan, T. H. (2014). Testing for ontological errors in probabilistic forecasting models of natural systems.
915 Proceedings of the National Academy of Sciences, 111(33), 11973-11978. doi:10.1073/pnas.1410183111

Mathieu, L., van Wyk de Vries, B., Holohan, E. P., & Troll, V. R. (2008). Dykes, cups, saucers and sills: Analogue experiments on magma intrusion into brittle rocks. Earth and Planetary Science Letters, 271(1), 1-13. doi:https://doi.org/10.1016/j.epsl.2008.02.020

McBirney, A., & Godoy, A. (2003). Notes on the IAEA guidelines for assessing volcanic hazards at nuclear facilities. Journal of
920 Volcanology and Geothermal Research, 126(1), 1-9.

MCDEM. (2016). National Disaster Resilience Strategy: Update for National Lifelines Forum [Presented by Paul Bagg]. Wellington, New Zealand Retrieved from http://www.aelg.org.nz/.

MCDEM. (2017). National Lifelines Programme [presented by Paul Bagg]. Paper presented at the National Lifelines Forum 2017, Auckland, New Zealand. http://www.aelg.org.nz/

925 MCDEM. (n.d.). CDEM Framework [Webpages]. Retrieved from https://www.civildefence.govt.nz/

Article in Press

MCDEM (2020) National Fuel Plan

McDonald, G. W., Cronin, S. J., Kim, J.-H., Smith, N. J., Murray, C. A., & Procter, J. N. (2017). Computable general equilibrium modelling of economic impacts from volcanic event scenarios at regional and national scale, Mt. Taranaki, New Zealand. Bulletin of Volcanology, 79(12), 87. doi:10.1007/s00445-017-1171-3

930 Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., . . . Viavattene, C. (2013). Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. Natural Hazards and Earth System Science, 13(5), 1351-1373. doi:10.5194/nhess-13-1351-2013

Milazzo, M. F., Ancionea, G., Listera, D. G., Bascob, A., Salzanob, E., & Maschio, G. (2012). Analysis of the effects due to ash fallout from Mt. Etna on industrial installations. Chemical Engineering Transactions 26. doi:10.3303/CET1226021

935 Milazzo, M. F., Ancione, G., Basco, A., Lister, D. G., Salzano, E., & Maschio, G. (2013a). Potential loading damage to industrial storage tanks due to volcanic ash fallout. Natural Hazards, 66(2), 939-953. doi:10.1007/s11069-012-0518-5

Milazzo, M.F., Ancione, G., Salzano, E. and Maschio, G. (2013b) Vulnerability of Industrial Facilities to Potential Volcanic Ash Fallouts. Chemical Engineering Transactions 31, 901-907. DOI: 10.3303/CET1331151

Milazzo M.F., Primerano P., Ancione G., Salzano E., Maschio G. (2014) Potential damages of atmospheric storage tanks due 940 to volcanic ash aggregations in presence of water, Chemical Engineering Transactions 36, 487-492 DOI: 10.3303/CET1436082

Ministry of Business, I. E. (2012). Review of the Maui pipeline outage of October 2011. Retrieved from Wellington, New Zealand: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-security/documents-image-library/Review-Maui-pipeline-outage-october-2011.pdf

945 Mitchell, T., & Harris, K. (2012). Resilience: A risk management approach. Retrieved from London, England:

Mullineaux, D. R., & Crandell, D. R. (1962). Recent Lahars from Mount St. Helens, Washington. GSA Bulletin, 73(7), 855-870. doi:10.1130/0016-7606(1962)73[855:RLFMSH]2.0.CO;2

Myers, P. (2017, 5-9 November 2017). [Email discussion of floating tank impacts].

Neall, V. E. (2011, July 2011). Rain-triggered debris flows (lahars) on Mt Taranaki/Mt Egmont, New Zealand. Paper presented 950 at the International Union for Quaternary Research conference, Bern, Switzerland.

Neall, V. E., & Alloway, B. V. (1993). Volcanic hazards at Egmont volcano (2nd ed.). Palmerston North, New Zealand.

Neall, V. E., & Alloway, B. V. (1996). Volcanic hazard map of Western Taranaki. In Massey University Department of Soil Science Occasional Report 12.

Neall, V. E., Stewart, R. B., & Smith, I. E. M. (1986). History and petrology of the Taranaki volcanoes. In I. Smith & T. Webb 955 (Eds.), Late Cenozoic volcanism in New Zealand: A collection of papers dealing with the nature and distribution of Late Cenozoic volcanic activity in New Zealand, published in the centennial year of the 1886 eruption of Tarawera (Vol. 23, pp. 251-263). Wellington, New Zealand: Royal Society of New Zealand Bulletin.

Neri, A., Aspinall, W. P., Cioni, R., Bertagnini, A., Baxter, P. J., Zuccaro, G., . . . Woo, G. (2008). Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. Journal of Volcanology and Geothermal Research, 178(3), 397- 960 415. doi:10.1016/j.jvolgeores.2008.05.014

New Zealand Government. (2016). Energy in New Zealand 2016. Retrieved from Wellington, New Zealand: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications

New Zealand Government. (2017). Energy in New Zealand 2017. Retrieved from Wellington, New Zealand: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-in- 965 new-zealand/documents-images/energy-in-nz-2017.pdf

Article in Press

New Zealand Lifelines Council. (2017). New Zealand lifelines infrastructure vulnerability assessment: Stage 1 Retrieved from Auckland, New Zealand: http://www.aelg.org.nz/document-library/other-documents/

New Zealand Lifelines Council (2020) New Zealand Critical Lifelines Infrastructure National Vulnerability Assessment

Newhall, C. G., & Hoblitt, R. (2002). Constructing event trees for volcanic crises. Bulletin of Volcanology, 64(1), 3-20.

970 Newhall, C. G., & Self, S. (1982). The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism. Journal of Geophysical Research: Oceans, 87(C2), 1231-1238. doi:10.1029/JC087iC02p01231

Nolan, D. P. (2014). Handbook of fire and explosion protection engineering principles: for oil, gas, chemical and related facilities: William Andrew.

Normile, D. (2017, 27 November). Scientists watching volcanic eruption on Bali minute by minute. Science Magazine, 358.

975 Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. American Journal of Community Psychology, 41(1-2), 127-150. doi:10.1007/s10464-007-9156-6

O'Rourke, T. D. (2007). Critical infrastructure, interdependencies, and resilience. BRIDGE-WASHINGTON-NATIONAL ACADEMY OF ENGINEERING-, 37(1), 22.

980 Ogiso, M., Matsubayashi, H., & Yamamoto, T. (2015). Descent of tremor source locations before the 2014 phreatic eruption of Ontake volcano, Japan. Earth, Planets and Space, 67(1), 1-12. doi:10.1186/s40623-015-0376-y

Papale, P. (2017). Rational volcanic hazard forecasts and the use of volcanic alert levels. Journal of Applied Volcanology, 6(1), 13. doi:10.1186/s13617-017-0064-7

Pattillo, A. (2017). Facilitating with confidence workshop [Notes]. In Pattillo (Ed.).

985 PEPANZ (2016) An introduction to New Zealand's Oil and Gas Industry

Petroleum Exploration and Production Association of New Zealand. (2017). Year in Review 2016. Retrieved from Wellington, New Zealand: http://www.pepanz.com/

Pilcher, C., & Sexton, D. (1993). Effects of the Gulf War oil spills and well-head fires on the avifauna and environment of Kuwait. Sandgrouse, 15, 6-17.

990 Platt, R. H. (1991). Lifelines: An Emergency Management Priority for the United States in the 1990s. Disasters, 15(2), 172-176. doi:10.1111/j.1467-7717.1991.tb00446.x

Platz, T., Cronin, S. J., Cashman, K. V., Stewart, R. B., & Smith, I. E. M. (2007). Transition from effusive to explosive phases in andesite eruptions—A case-study from the AD1655 eruption of Mt. Taranaki, New Zealand. Journal of Volcanology and Geothermal Research, 161(1), 15-34. doi:10.1016/j.jvolgeores.2006.11.005

995 Platz, T., Cronin, S. J., Procter, J. N., Neall, V. E., & Foley, S. F. (2012). Non-explosive, dome-forming eruptions at Mt. Taranaki, New Zealand. Geomorphology, 136(1), 15-30. doi:10.1016/j.geomorph.2011.06.016

Polteau, S., Mazzini, A., Galland, O., Planke, S., & Malthe-Sørenssen, A. (2008). Saucer-shaped intrusions: Occurrences, emplacement and implications. Earth and Planetary Science Letters, 266(1), 195-204. doi:https://doi.org/10.1016/j.epsl.2007.11.015

1000 Porter, H., Wilson, T. M., Weir, A., Stewart, C., Craig, H. M., Wild, A. J., ... & Buzzella, M. (2025). A new volcanic multi-hazard impact model for water supply systems: Application at Taranaki Mounga, Aotearoa New Zealand. *International Journal of Disaster Risk Reduction*, *116*, 105113. https://doi.org/10.1016/j.ijdrr.2024.105113

Potter, S. H., Jolly, G. E., Neall, V. E., Johnston, D. M., & Scott, B. J. (2014). Communicating the status of volcanic activity: Revising New Zealand's volcanic alert level system. Journal of Applied Volcanology, 3(1), 1-16. doi:10.1186/s13617-

1005 014-0013-7

Article in Press

Procter, J. N., Cronin, S. J., Platz, T., Patra, A., Dalbey, K., Sheridan, M., & Neall, V. E. (2010). Mapping block-and-ash flow hazards based on Titan 2D simulations: a case study from Mt. Taranaki, NZ. Natural Hazards, 53(3), 483-501. doi:10.1007/s11069-009-9440-x

Procter, J. N., Cronin, S. J., & Zernack, A. V. (2009). Landscape and sedimentary response to catastrophic debris avalanches, western Taranaki, New Zealand. Sedimentary Geology, 220(3–4), 271-287. doi:10.1016/j.sedgeo.2009.04.027

Querol, X., Tobías, A., Pérez, N., Karanasiou, A., Amato, F., M. Stafoggia, M., Pérez García-Pando, C., Ginoux, P., Forastiere, F., Gumy, S., Mudu, P., Alastuey, A. (2019) Monitoring the impact of desert dust outbreaks for air quality for health studies Environment International, 130, 104867. https://doi.org/10.1016/j.envint.2019.05.061

Ramasamy, A., Hill, A.-M., Hepper, A., Bull, A. M., & Clasper, J. (2009). Blast mines: physics, injury mechanisms and vehicle protection. Journal of the Royal Army Medical Corps, 155(4), 258-264.

Rattenbury, M. S., & Isaac, M. J. (2012). The QMAP 1:250 000 Geological Map of New Zealand project. New Zealand Journal of Geology and Geophysics, 55(4), 393-405. doi:10.1080/00288306.2012.725417

Reader, T. W., & O'Connor, P. (2014). The Deepwater Horizon explosion: Non-technical skills, safety culture, and system complexity. Journal of Risk Research, 17(3), 405-424. doi:10.1080/13669877.2013.815652

Reed, D. A., Kapur, K. C., & Christie, R. D. (2009). Methodology for assessing the resilience of networked infrastructure. IEEE Systems Journal, 3(2), 174-180. doi:10.1109/JSYST.2009.2017396

Relifweb. (n.d.). Indonesia: Mt. Agung Volcano - Sep 2017. Retrieved from https://reliefweb.int/disaster/vo-2017-000141-idn

Remer, A. (2011). GIS as a tool for assessing volcanic hazards, vulnerability, and at risk areas of the Three Sisters Volcanic Region, Oregon. Papers in Resource Analysis. University of Minnesota. Winona, MN. Retrieved from http://www.gis.smumn.edu/GradProjects/RemerA.pdf

Robertson, R. E. A., Aspinall, W. P., Herd, R. A., Norton, G. E., Sparks, R. S. J., & Young, S. R. (2000). The 1995–1998 eruption of the Soufriére Hills volcano, Montserrat, WI. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 358(1770), 1619.

Robinson, T., & Rosser, N. (2017). Rapid landslide risk assessment of transport infrastructure following the 13 November 2016 Kaikoura, New Zealand, earthquake. Paper presented at the EGU General Assembly Conference Abstracts.

Rovins, J. E., Wilson, T. M., Hayes, J. L., Jensen, S. J., Dohaney, J., Mitchell, J., . . . Davies, A. (2015). Risk Assessment Handbook (GNS Science Miscellaneous Series, 84. 71p). Retrieved from

Schlumberger. (n.d). Oilfield Glossary. Retrieved from http://www.glossary.oilfield.slb.com/

Safari, A., Das, N., Langhelle, O., Roy, J. and Assadi, M. (2019) Natural gas: a transition fuel for sustainable energy system transformation? Energy Science and Engineering 7, 1075-1094. DOI: 10.1002/ese3.380

Searl, A., Nicholl, A., Baxter, P.J. (2002) Assessment of the exposure of islanders to ash from the Soufriere Hills volcano, Montserrat, British West Indies. Occupational and Environmental Medicine 59, 523-531.

Shaw Pipe. (2010). Pipeline coating solutions. Technical Literature_2010. www.shawpipe.ca. Retrieved from https://www.google.co.nz/url?sa=t&rct=j&q=&esrc=s&source=web&cd=10&cad=rja&uact=8&ved=0ahUKEwjytN-tx_3VAhXIUrwKHcYoDqcQFghYMAk&url=https%3A%2F%2Fapps.neb-one.gc.ca%2FREGDOCS%2FFile%2FDownload%2F690029&usg=AFQjCNHTtdgSqzeqQzql7jF7ZEBzSSrp0g

Sigurdsson, H., Houghton, B. F., McNutt, S., Rymer, H., & Stix, J. (2015). The Encyclopedia of Volcanoes (H. Sigurdsson Ed. Second Edition ed.). Amsterdam, Netherlands: Academic Press.

Skogdalen, J. E., & Vinnem, J. E. (2012). Quantitative risk analysis of oil and gas drilling, using Deepwater Horizon as case study. Reliability Engineering & System Safety, 100(Supplement C), 58-66. doi:10.1016/j.ress.2011.12.002

Article in Press

Sparks, R. S. J. (2003). Forecasting volcanic eruptions. Earth and Planetary Science Letters, 210(1), 1-15. doi:10.1016/S0012-821X(03)00124-9

Sparks, R. S. J., Aspinall, W. P., Crosweller, H. S., & Hincks, T. K. (2012). Risk and uncertainty assessment of volcanic hazards. In J. Rougier, S. Sparks, & L. J. Hill (Eds.), Risk and Uncertainty Assessment for Natural Hazards. Cambridge: Cambridge University Press.

Sparks, R. S. J., & Cashman, K. V. (2013). How volcanoes work: A 25 year perspective. GSA Bulletin, 125(5-6), 664-690. doi:10.1130/B30720.1

Spence, R. J. S., Baxter, P. J., & Zuccaro, G. (2004). Building vulnerability and human casualty estimation for a pyroclastic flow: a model and its application to Vesuvius. Journal of Volcanology and Geothermal Research, 133(1), 321-343. doi:10.1016/S0377-0273(03)00405-0

Spence, R. J. S., Kelman, I., Baxter, P. J., Zuccaro, G., & Petrazzuoli, S. (2005). Residential building and occupant vulnerability to tephra fall. Natural Hazards and Earth System Science, 5(4), 477-494. doi:https://hal.archives-ouvertes.fr/hal-00299218

Spence, R. J. S., Kelman, I., Calogero, E., Toyos, G. P., Baxter, P. J., & Komorowski, J. C. (2005). Modelling expected physical impacts and human casualties from explosive volcanic eruptions. Natural Hazards and Earth System Science, 5(6), 1003-1015. doi:https://hal.archives-ouvertes.fr/hal-00330913

Spence, R. J. S., Zuccaro, G., Petrazzuoli, S., & Baxter, P. J. (2004). Resistance of buildings to pyroclastic flows: Analytical and experimental studies and their application to Vesuvius. Natural Hazards Review, 5(1), 48-59. doi:10.1061/(ASCE)1527-6988(2004)5:1(48)

Standards Australia & Standards New Zealand. (2009a). AS/NZS 1170.5:2004. Welington, New Zealand: Standards New Zealand Retrieved from https://shop.standards.govt.nz/default.htm?action=viewProductPack&mod=catalog&pid=4028828607b5ba7a0107d4b4ea840003§orId=I1.

Standards Australia & Standards New Zealand. (2009b). AS/NZS ISO 31000: 2009. Welington, New Zealand: Standards New Zealand Retrieved from https://www.standards.govt.nz/search-and-buy-standards/standards-information/risk-managment/.

Standards New Zealand. (2002a). AS/NZS 1170.0 Supplement 1:2002. In Structural design actions - Part 0: General principles - Commentary (pp. 25). Wellington, New Zealand.

Standards New Zealand. (2002b). AS/NZS 1170.0:2002. In Structural design actions - Part 0: General principles (pp. 40). Wellington, New Zealand.

Standards New Zealand. (2003a). AS/NZS 1170.3 Supplement 1:2003. In Structural design actions - Part 3: Snow and ice actions - Commentary (Supplement to AS/NZS 1170.3:2003) (pp. 68). Wellington, New Zealand.

Standards New Zealand. (2003b). AS/NZS 1170.3:2003. In Structural design actions - Part 3: Snow and ice actions (pp. 40). Wellington, New Zealand.

Standards New Zealand. (2004). NZS 1170.5:2004. In Structural design actions - Part 5: Earthquake actions - New Zealand (pp. 86). Wellington, New Zealand.

Standards New Zealand. (2011). AS/NZS 1170.2:2011. In Structural design actions - Part 2: Wind actions (pp. 100). Wellington, New Zealand.

Stewart, C., Johnston, D. M., Leonard, G. S., Horwell, C. J., Thordarson, T., & Cronin, S. J. (2006). Contamination of water supplies by volcanic ashfall: A literature review and simple impact modelling. Journal of Volcanology and Geothermal Research, 158(3–4), 296-306. doi:10.1016/j.jvolgeores.2006.07.002

Article in Press

Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Van Dissen, R., Berryman, K., . . . Langridge, R. (2012). National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America, 102(4), 1514-1542. doi:10.1785/0120110170

Taranaki Civil Defence & Emergency Management. (2015). Mt Taranaki volcanic unrest response plan (1300423 (Version 7)). Retrieved from Stratford, New Zealand:

Taranaki Civil Defence and Emergency Management (2018) Taranaki Lifelines Vulnerability Study: V1.0 October 2018 Page 1. 1–59

Taylor, J., Chang, S., Elwood, K., Seville, E., & Brunsdon, D. (2012). Learning from Christchurch: technical decisions and societal consequences in post-earthquake recovery (Research Report 2012/08). Retrieved from Resilient Organisations http://www.resorgs.org.nz/images/stories/pdfs/critical_decisions_in_the_recovery_of_christchurch.pdf

Torres-Orozco, R., Cronin, S. J., Pardo, N., & Palmer, A. S. (2017). New insights into Holocene eruption episodes from proximal deposit sequences at Mt. Taranaki (Egmont), New Zealand. Bulletin of Volcanology, 79(1), 3. doi:10.1007/s00445-016-1085-5

Tedesco, D., Vaselli, O., Papale, P., Carn, S.A., Voltaggio, M., Sawyer, G.M., Durieux, J., Kasareka, M. and Tassi, F. (2007) January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo. Journal of Geophysical Research 11, B09202, doi:10.1029/2006JB004762.

Townsend, D., Vonk, A., & Kamp, P. (2008). Geology of the Taranaki Area, QMAP 1: 250000 Geological Map. GNS Science, Lower Hutt, New Zealand, 86.

Turner, M. B. (2008). Eruption cycles and magmatic processes at a reawakening volcano, Mt. Taranaki, New Zealand: a thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Earth Science at Massey University, Palmerston North, New Zealand.

Turner, M. B., Bebbington, M., Cronin, S. J., & Stewart, R. B. (2009). Merging eruption datasets: building an integrated Holocene eruptive record for Mt Taranaki, New Zealand. Bulletin of Volcanology, 71(8), 903-918. doi:10.1007/s00445-009-0274-x

Turner, M. B., Cronin, S. J., Bebbington, M., & Platz, T. (2008). Developing probabilistic eruption forecasts for dormant volcanoes: a case study from Mt Taranaki, New Zealand. Bulletin of Volcanology, 70(4), 507-515. doi:10.1007/s00445-007-0151-4

Turner, M. B., Cronin, S. J., Bebbington, M., Smith, I. E. M., & Stewart, R. B. (2011). Integrating records of explosive and effusive activity from proximal and distal sequences: Mt. Taranaki, New Zealand. Quaternary International, 246(1–2), 364-373. doi:10.1016/j.quaint.2011.07.006

Turner, M. B., Cronin, S. J., Smith, I. E., Stewart, R. B., & Neall, V. E. (2008). Eruption episodes and magma recharge events in andesitic systems: Mt Taranaki, New Zealand. Journal of Volcanology and Geothermal Research, 177(4), 1063-1076. doi:10.1016/j.jvolgeores.2008.08.001

UNDRR (2019) Global Assessment Report on Disaster Risk Reduction

UNISDR. (2009). UNISDR Terminology for Disaster Risk Redution. Retrieved from Geneva, Switzerland:

UNISDR. (2015). The Sendai framework for disaster risk reduction 2015 - 2030. Retrieved from http://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

UNISDR. (2017). Words into action guidelines: National disaster risk assessment. Retrieved from Geneva, Switzerland: http://www.unisdr.org/files/52828_nationaldisasterriskassessmentwiagu.pdf

Urlainis, A., Shohet, I. M., & Levy, R. (2015). Probabilistic risk assessment of oil and gas infrastructures for seismic extreme events. Procedia Engineering, 123, 590-598. doi:10.1016/j.proeng.2015.10.112

Article In Press

U.S.G.S. (n.d.). What Are Volcano Hazards? In U.S. Geological Survey Fact Sheet 002-97 (Ed.).

1130 Valentine, G. A. (1998). Damage to structures by pyroclastic flows and surges, inferred from nuclear weapons effects. Journal of Volcanology and Geothermal Research, 87(1), 117-140. doi:10.1016/S0377-0273(98)00094-8

Vallance, J.W. (2024). Lahars: Origins, Behavior and Hazards. In: Jakob, M., McDougall, S., Santi, P. (eds) Advances in Debris-flow Science and Practice. Geoenvironmental Disaster Reduction. Springer, Cham. https://doi.org/10.1007/978-3-031-48691-3_12

1135 Vector Gas Limited. (2012). 2011 Maui pipeline failure technical investigation report. Retrieved from Wellington, New Zealand: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-security/documents-image-library/2011%20Maui%20Pipeline%20Failure%20Technical%20Investigation%20Report.pdf

Voight, B., & Davis, M. J. (2000). Emplacement temperatures of the November 22, 1994 nuée ardente deposits, Merapi Volcano, Java. Journal of Volcanology and Geothermal Research, 100(1), 371-377. doi:10.1016/S0377-

1140 0273(00)00146-3

Wahlström, M. (2015). New sendai framework strengthens focus on reducing disaster risk. International Journal of Disaster Risk Science, 6(2), 200-201. doi:10.1007/s13753-015-0057-2

Waythomas, C. F., Dorava, J. M., Miller, T. P., Neal, C. A., & McGimsey, R. G. (1997). Preliminary volcano-hazard assessment for Redoubt Volcano, Alaska (2331-1258). Retrieved from USGS:

1145 https://volcanoes.usgs.gov/vhp/hazard_assessments.html

Waythomas, C. F., Pierson, T. C., Major, J. J., & Scott, W. E. (2013). Voluminous ice-rich and water-rich lahars generated during the 2009 eruption of Redoubt Volcano, Alaska. Journal of Volcanology and Geothermal Research, 259, 389-413. doi:10.1016/j.jvolgeores.2012.05.012

Weir AM, Wilson TM, Bebbington MS, et al (2024a) Approaching the challenge of multi-phase, multi-hazard volcanic impact

1150 assessment through the lens of systemic risk: application to Taranaki Mounga. Natural Hazards. https://doi.org/10.1007/s11069-023-06386-z

Weir AM, Mead S, Bebbington MS, et al (2022) A modular framework for the development of multi-hazard, multi-phase volcanic eruption scenario suites. J Volcanol Geotherm Res 427:107557. https://doi.org/10.1016/j.jvolgeores.2022.107557

1155 Weir AM, Wilson TM, Bebbington MS, et al (2024b) Quantifying systemic vulnerability of interdependent critical infrastructure networks: a case study for volcanic hazards. International Journal of Disaster Risk Science 114: 104997. https://doi.org/10.1016/j.ijdrr.2024.104997

Wellington Lifelines Group. (2012). Lifeline utilities restoration times for metropolitan Wellington following a Wellington Fault earthquake. Retrieved from http://www.getprepared.org.nz/

1160 Wild, A. J. (2016). A volcanic tephra fall hazard evacuation decision support tool for Taranaki dairy livestock using probabilistic modelling. (Masters), University of Canterbury, Canterbury, New Zealand. Retrieved from https://ir.canterbury.ac.nz/handle/10092/11924

Wilkinson, B., Crampton, E., & Krupp, J. (2018). Recipe for disaster: Building policy on shaky ground. Retrieved from Wellington, New Zealand: https://nzinitiative.org.nz/reports-and-media/reports/recipe-for-disaster-building-

1165 policy-on-shaky-ground/

Williams, G., & Wilson, T. M. (2017). Volcanic ash fall impacts to diesel generators: Results from the lab [Powerpoint]. Retrieved from Canterbury, New Zealand: http://www.aelg.org.nz/document-library/volcanic-ash-impacts/

Wilson, G. (2015). Vulnerability of critical infrastructure to volcanic hazards. (Doctor of Philosphy in Hazard and Disaster Management), University of Canterbury,

Article in Press

1170 Wilson, G., Wilson, T. M., Deligne, N. I., Blake, D. M., & Cole, J. W. (2017). Framework for developing volcanic fragility and vulnerability functions for critical infrastructure. Journal of Applied Volcanology, 6(1), 14. doi:10.1186/s13617-017-0065-6

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research, 286, 148-182. doi:10.1016/j.jvolgeores.2014.08.030

1175 Wilson TM, Cole JW, Stewart C, et al (2011) Ash storms: Impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bull Volcanol 73:223–239. https://doi.org/10.1007/s00445-010-0396-1

Wilson, T. M., & Kaye, G. D. (2007). Agricultural fragility estimates for volcanic ash fall hazards. In: GNS Science.

Wilson, T. M., Kaye, G. D., Stewart, C., & Cole, J. W. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on
1180 agriculture and infrastructure.

Wilson, T. M., Stewart, C., Bickerton, H., Baxter, P. J., Outes, V., Villarosa, G., & Rovere, E. (2013). Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastructure, agriculture and public health: GNS Science.

Wilson, T. M., Stewart, C., Cole, J. W., Dewar, D. J., Johnston, D. M., & Cronin, S. J. (2009). The 1991 eruption of Volcan
1185 Hudson, Chile: Impacts on agriculture and rural communities and long-term recovery. Retrieved from Lower Hutt, New Zealand:

Wilson, T. M., Stewart, C., Sword-Daniels, V., Leonard, G. S., Johnston, D. M., Cole, J. W., . . . Barnard, S. T. (2012). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, Parts A/B/C, 45–46, 5-23. doi:10.1016/j.pce.2011.06.006

1190 Wilson, T. M., Stewart, C., Wardman, J. B., Wilson, G., Johnston, D. M., Hill, D. P., . . . Roberts, L. (2014). Volcanic ashfall preparedness poster series: A collaborative process for reducing the vulnerability of critical infrastructure. Journal of Applied Volcanology, 3(1), 10. doi:10.1186/s13617-014-0010-x

World Bank (2014) Global Facility for Disaster Reduction and Recovery. Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment. 329:1086–1086

1195 WorleyParsons. (2014). Gas disruption study: Report on the potential impacts of the NZ gas market. Retrieved from Christchurch, New Zealand: http://www.mbie.govt.nz/info-services/sectors-industries/energy/gas-market/documents-image-library/gas-disruption-study.pdf

Zernack, A. V., Cronin, S. J., Bebbington, M., Price, R. C., Smith, I. E. M., Stewart, R. B., & Procter, J. N. (2012). Forecasting catastrophic stratovolcano collapse: A model based on Mount Taranaki, New Zealand. Geology, 40(11), 983-986.
1200 doi:10.1130/g33277.1

Zernack, A. V., Cronin, S. J., Neall, V. E., & Procter, J. N. (2011). A medial to distal volcaniclastic record of an andesite stratovolcano: detailed stratigraphy of the ring-plain succession of south-west Taranaki, New Zealand. International Journal of Earth Sciences, 100(8), 1937-1966. doi:10.1007/s00531-010-0610-6

Zernack, A. V., Procter, J. N., & Cronin, S. J. (2009). Sedimentary signatures of cyclic growth and destruction of
1205 stratovolcanoes: A case study from Mt. Taranaki, New Zealand. Sedimentary Geology, 220(3–4), 288-305. doi:10.1016/j.sedgeo.2009.04.024

Zuccaro, G., Cacace, F., Spence, R. J. S., & Baxter, P. J. (2008). Impact of explosive eruption scenarios at Vesuvius. Journal of Volcanology and Geothermal Research, 178(3), 416-453. doi:10.1016/j.jvolgeores.2008.01.005

Article in Press

1210

Article in Press

1215

Tables

Table 1: Physical asset categories for the petroleum industry for volcanic risk assessment.

Asset type	Asset category	Description
1	Wells	Standalone well pads, where the well may be producing, injecting or have been shut-in, suspended or abandoned. Some pads will have a small amount of associated equipment such as compressors or flares and may or may not have onsite staffing.
2	Pipelines	Multiple types, diameters and burial depths and contents, from mixed product gathering lines to high pressure gas lines, low pressure gas lines or water. A subcategory includes pipelines exposed at the surface at aerial crossings, generally over rivers, or risers where tie-in points occur.
3	Production facilities	These are the most diverse class of assets, often comprising many kilometres of pipeline; cooling and separating towers where the raw hydrocarbon product is separated into its components of water, gas, oil and condensate. However, can also be valve stations for isolating sections of pipeline with an above-ground station compound. Other onsite equipment can include local storage tanks, flares, operations offices and water pits for fire safety. Staff are usually onsite.
4	Storage tanks	Storage tanks comprise a wide range of construction types and sizes. The two main subcategories are fixed and floating roof tanks.
5	Buildings	Building types can range from converted shipping containers and Portacabins to purpose-designed office buildings.
6	Industrial users	End users include methanol plants, Liquefied Petroleum Gas (LPG) bottling stations, dairy processing and fertiliser factories.

Table 2: Relationship between volcanic hazards (rows) and hazard intensity metrics (HIMs; columns), with black squares where relationship has been established.

	Dynamic pressure (kPa)	Temperature (˚C)	Loading/static pressure (kPa)
Debris avalanches (flank failure)	■		
Lahars (volcanic mudflows)	■		■
Pyroclastic Density Currents (PDCs)	■	■	■
Ashfall			■

1220

Table 3: Damage level definitions for petroleum assets applied in this study.

Damage levels	Definition
D0	No physical damage
D1	Minor (no structural) damage
D2	Major (structural) damage
D3	Total physical asset destruction, i.e. catastrophic failure (full replacement rather than repair)

Article in Press

1225 **Table 4: Summary of literature review deriving provisional vulnerability thresholds for** hazard intensity metrics (**HIMs) from similar events and hazards, related to the damage states presented in Table 3.**

HIMs	Example relevant asset types	Relevant phenomena	Examples of analogous events	Provisional thresholds	References
Loading/ static pressure (kPa)	Storage tanks (floating roof designs)	Snow loading; rainfall	Laboratory studies; snow-loading design standards; rainfall and ashfall industry standards	< 1 kPa 1-1.25 kPa 1.25 – 2 kPa > 2 kPa	American Petroleum Institute, 2013; Efford, Clarkson, & Bylsma, 2014; Gehl, Quinet, Le Cozannet, Kouokam, & Thierry, 2013; Macedonio, Costa, & Folch, 2008; Milazzo et al., 2013; Milazzo et al., 2012; Neall, 2011; Standards New Zealand, 2003b
Temperature (°C)	Pipelines (aerial crossings)	Pyroclastic density currents (PDCs); extreme weather events	Merapi eruption, 2010; Montserrat eruption, 1995 - present; Mount Redoubt 1991, 2009; Volcan de Colima eruption, 2015; Mount St. Helens eruption, 1980	< 45 ˚C 45-55 ˚C 55-500 ˚C > 500 ˚C	Arguden & Rodolfo, 1990; Australian Energy Market Operator Limited, 2014; Bredero Shaw, n.d.; Fletcher & Nicholas, 2014; Jenkins et al., 2013; JFE Steel Corporation, n.d.; Mullineaux & Crandell, 1962; Nolan, 2014; Shaw Pipe, 2010; Voight & Davis, 2000
Dynamic pressure (kPa)	Pipelines (aerial crossings)	Extreme weather events; tsunamis; explosions; scouring from tsunamis or lahars; PDCs (fringe effects and central zones)	Great Japan Earthquake & Tsunami 2011; Chile Tsunami 2015; Gulf War 1991; Merapi eruption, 2010; Montserrat eruption, 1995 - present; Mount Redoubt 1991, 2009; Volcan de Colima eruption, 2015; Mount St. Helens eruption, 1980; laboratory studies; New Zealand Maui Pipeline failure (2011)	< 0.5 kPa 0.5-1 kPa 1-2 kPa > 2 kPa	American Society of Civil & Wind-Induced Forces Task, 2011; Baek, Kim, Kim, Koo, & Seok, 2012; Baxter et al., 2005; Belousov, Voight, & Belousova, 2007; Dorava & Meyer, 1994; Jenkins et al., 2013; Meyer et al., 2013; Ministry of Business, 2012; Pilcher & Sexton, 1993; Ramasamy, Hill, Hepper, Bull, & Clasper, 2009; Spence, Baxter, & Zuccaro, 2004; Spence, Zuccaro, et al., 2004; Vector Gas Limited, 2012

Article in Press

Table 5: The key physical and systemic vulnerabilities identified during the expert workshop for each asset type.

Asset class	High-level overview of physical vulnerability	Systemic issues identified
Wells and wellheads Asset category 1	Likely the most physically resilient asset types with respect to volcanic hazards. Associated well stacks, including electrical wiring and air compressors will be more vulnerable, particularly to dynamic pressure from PDCs.	Dependent on electricity for operation, road access for maintenance, and telecommunications for remote operations. Though these assets are generally physically resilient to volcanic hazards, disruption of interdependent critical infrastructure, and burial of subsurface infrastructure from volcanic surface flows can disrupt production.
Pipelines Asset category 2	Pipelines are most vulnerable when exposed in aerial river crossings. Channel bed scouring by lahars is likely to be the most damaging hazard/HIM for this asset type.	Systemically vulnerable to production disruption The location of pipeline break(s) dictates the functionality of the network. High repair cost (multiple breaks) and low repair cost (one or two break) can produce the same systemic disruption, though the recovery time may vary. Disrupted access (road damage, impassability, evacuations) will impede recovery.
Production facilities Asset category 3	Production facilities depend on a large range of equipment of varying vulnerability to different hazards. Flare stacks are highly vulnerable to dynamic pressure from PDCs, and all equipment with an air intake is vulnerable to airborne ash.	Highly systemically vulnerable. Dependent on electricity for operation, road access for maintenance, telecommunications for remote operations, and water for component cooling.
Storage tanks Asset category 4	Floating roof storage tanks are vulnerable to static pressure from ashfall loading.	
Building Asset category 5	Due to the high variability in building construction type in both operational and infrastructure-housing buildings, site-specific surveys of physical vulnerability to volcanic hazards are recommended. The physical vulnerability of buildings relevant to the petroleum sector are not considered in this study, beyond acknowledging they are a key asset class in the network.	Damage to buildings that house infrastructure (e.g. production facilities) may contribute to damage and disruption of asset categories 1, 2, 3, 4 and 6.
Industrial Users Asset category 6	Due to the high variability in industrial use types and asset configurations, site-specific surveys of physical vulnerability to volcanic hazards are recommended. The physical vulnerability of industrial users relevant to the petroleum sector are not considered in this study, beyond acknowledging they are a key asset class in the network.	
All assets Asset categories 1-6	Seal and gaskets are common across many asset classes and are likely to be vulnerable to a combination of dynamic pressure,	

Article in Press

Classification: In-Confidence

temperature and airborne ash. Widespread damage to these components is likely to delay recovery from an eruption.

1230

Article in Press

Classification: In-Confidence

Table 6: Vulnerability model for wells. ♣ denotes values elicited from petroleum sector expert workshop. ♦ denotes values that were initially elicited from petroleum sector expert workshop and were subsequently modified by volcanic impact experts.

Wells					
Hazard Intensity Metric (HIM)		D0	D1	D2	D3
		No damage	Minor damage	Major damage	Destroyed
Loading/static pressure (kPa)	Example of damage	-			
	Threshold	n/a			
Temperature (˚C)	Example of damage		Seals damaged	Seals destroyed	Well head destroyed
	Threshold	0 - 80 ♣	80 - 121 ♣	121 – 1000 ♣	> 1000 ♣
Dynamic pressure (kPa)	Example of damage	-	-	-	-
	Threshold	0 - 13,000 ♣	n/a	13,000 - 34,000 ♣	> 34,000 ♣

1235

Table 7: Vulnerability model for pipelines. ♣ denotes values elicited from petroleum sector expert workshop. ♦ denotes values that were initially elicited from petroleum sector expert workshop and were subsequently modified by volcanic impact experts.

Pipelines (including aerial crossings and pipelines buried to a maximum depth of 700 mm)					
Hazard Intensity Metric (HIM)		D0	D1	D2	D3
		No damage	Minor damage	Major damage	Destroyed
Loading/static pressure (kPa)	Example of damage	-			
	Threshold	n/a			
Temperature (˚C)	Example of damage	-	Gasket failures	Loss of steel strength	Pipeline/struts destroyed
	Threshold	< 150 ♣	150 - 450 ♣	450 - 600 ♣	> 600 ♣
Dynamic pressure (kPa)	Example of damage	-	-	-	Pipeline/struts destroyed
	Threshold	0 - 0.05 ♣	0.05 - 1 ♣	1 - 2 ♣	> 2 ♣

1240

Classification: In-Confidence

Article in Press

Table 8: Vulnerability model for production facilities, excluding buildings. ♣ denotes values elicited from petroleum sector expert workshop. ♦ denotes values that were initially elicited from petroleum sector expert workshop and were subsequently modified by volcanic impact experts.

Production facilities (excluding buildings)					
Hazard Intensity Metric (HIM)		**D0**	**D1**	**D2**	**D3**
		No damage	**Minor damage**	**Major damage**	**Destroyed**
Loading/static pressure (kPa)	Example of damage	-	-	-	-
	Threshold	0 - 1.2 ♦	n/a	1.2 - 3.0 ♦	> 3.0 ♦
Temperature (˚C)	Example of damage	-	Seals damaged	Seals destroyed	-
	Threshold	0 - 80 ♣	80 - 121 ♣	121 - 150 ♣	> 150 ♣
Dynamic pressure (kPa)	Example of damage	-	-	-	Assets crumple
	Threshold	0 - 0.05 ♣	n/a	0.05 - 1 ♣	>1 ♣

1245

Table 9: Vulnerability model for storage tanks. ♣ denotes values elicited from petroleum sector expert workshop. ♦ denotes values that were initially elicited from petroleum sector expert workshop and were subsequently modified by volcanic impact experts.

Storage tanks					
Hazard Intensity Metric (HIM)		**D0**	**D1**	**D2**	**D3**
		No damage	**Minor damage**	**Major damage**	**Destroyed**
Loading/static pressure (kPa)	Example of damage	-	n/a	-	-
	Threshold	0 - 1.2 ♦	n/a	1.2 - 7.0 ♦	> 7.0 ♦
Temperature (˚C)	Example of damage	-	Seals damaged	Seals destroyed	-
	Threshold	0 - 80 ♣	80 - 150 ♣	150 - 200 ♣	> 200 ♣
Dynamic pressure (kPa)	Example of damage	-	-	-	Tanks crumple/rupture
	Threshold	0 - 0.05 ♣	n/a	0.05 - 1 ♣	> 1 ♣

Article in Press

1250

Article in Press

Classification: In-Confidence