RESEARCH ARTICLE

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

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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 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.

Keywords: Impact assessment; Volcanic risk assessment; Energy sector; Expert workshop; Mt. Taranaki; Critical infrastructure.

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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 [United Nations Office for Disaster Risk Reduction 2019]. Volcanic eruptions can generate hazards such as ashfall, pyroclastic density currents (PDCs), and 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 Group 2017; United Nations Office for Disaster Risk Reduction 2019].

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 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 [United Nations Office for Disaster Risk Reduction 2015] refers to the need to 'ensure access to affordable, reliable, sustainable and modern energy' for all. However, at 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^{-1} compared to 25.8 kg GJ^{-1} for coking

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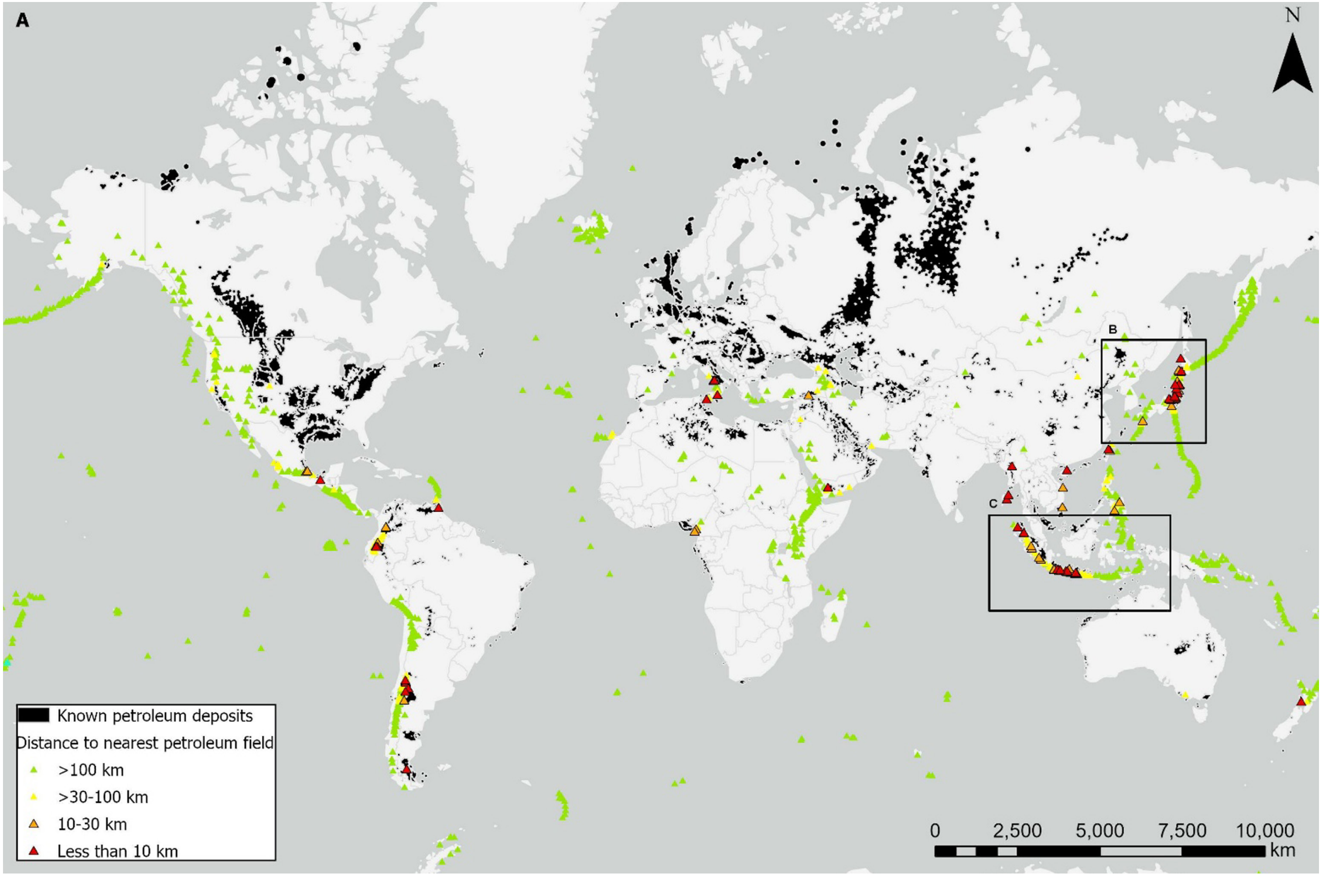

Figure 1: [A] Global distribution of Holocene volcanoes (triangles) [Global Volcanism Program 2025] and known oil and gas deposits (black) [Lujala et al. 2007]. Volcanoes within 10 km of any part of an oil and/or gas field are indicated with red triangles; those within 10 km are indicated with red triangles; 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.

coal, 26.2 kg GJ^{-1} for non-coking coal and 20 kg GJ^{-1} for crude oil) [Safari et al. 2019]. Though energy transition planning is under development, there will be a reliance 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 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 [Hull 1996; Brinkley 2007; Bratspies 2011; Task Committee on Wind-Induced Forces of the Petrochemical Committee of Energy Division 2011; Skogdalen and Vinnem 2012; Reader and O'Connor 2013]. 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 [Krausmann 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. 2021]. Globally, over one billion people are estimated to live within 100 km of an active volcano [Freire et al. 2019]. While

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.

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).

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* volcano (Aotearoa New Zealand) using an available volcanic impact assessment framework.

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

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 [Casadevall et al. 1990; Dorava and 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 [Cook Inletkeeper 2009; Bull and Buurman 2013].

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 2024]. 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

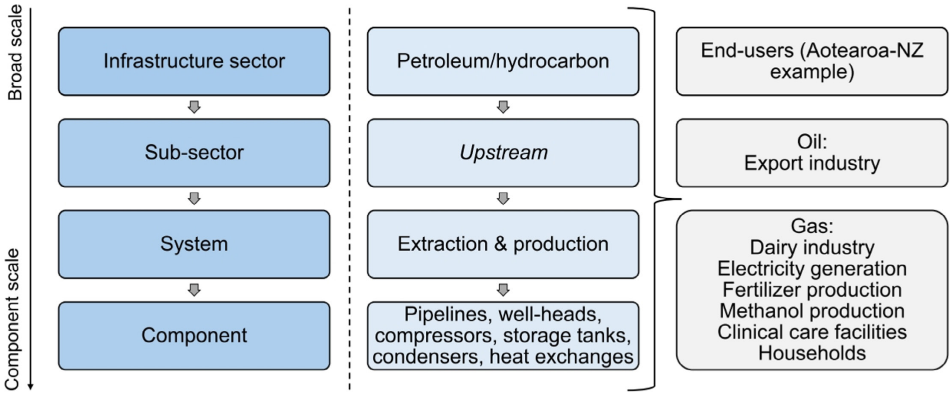

Figure 2: Conceptual critical infrastructure tier scheme, adapted from Wilson [2015] applied to the petroleum sector. The left column illustrates the generic hierarchy from broad infrastructure sector to sub-sector, system, and component scales. The central column applies this structure to the petroleum/hydrocarbon 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.

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			■

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 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.

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 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].

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 [Wilson et al. 2017; Fitzgerald et al. 2023; Hayes et al. 2024]. 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. 2017]. 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 example.

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 [O'Hagan 2019]. Expert workshops require careful planning. Aims need to be clearly defined, and appropriate attendees invited [Barton et al. 2020]. 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. 2014b; Wilson et al. 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. 2014a]. This approach works well for the theoretical approach required for the petroleum sector, where multiple volcanic hazards are considered. Here, 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. 2014b], 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 exploration activity would likely be shut down and equipment secured or even evacuated in the event of volcanic unrest.

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; United Nations Office for Disaster Risk Reduction 2017]; using existing open file datasets; reviewing satellite imagery; reviewing local authority consent information; interviewing industry 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).

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)

2.2.3 *Stage 3: Petroleum sector expert workshop*

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 as-

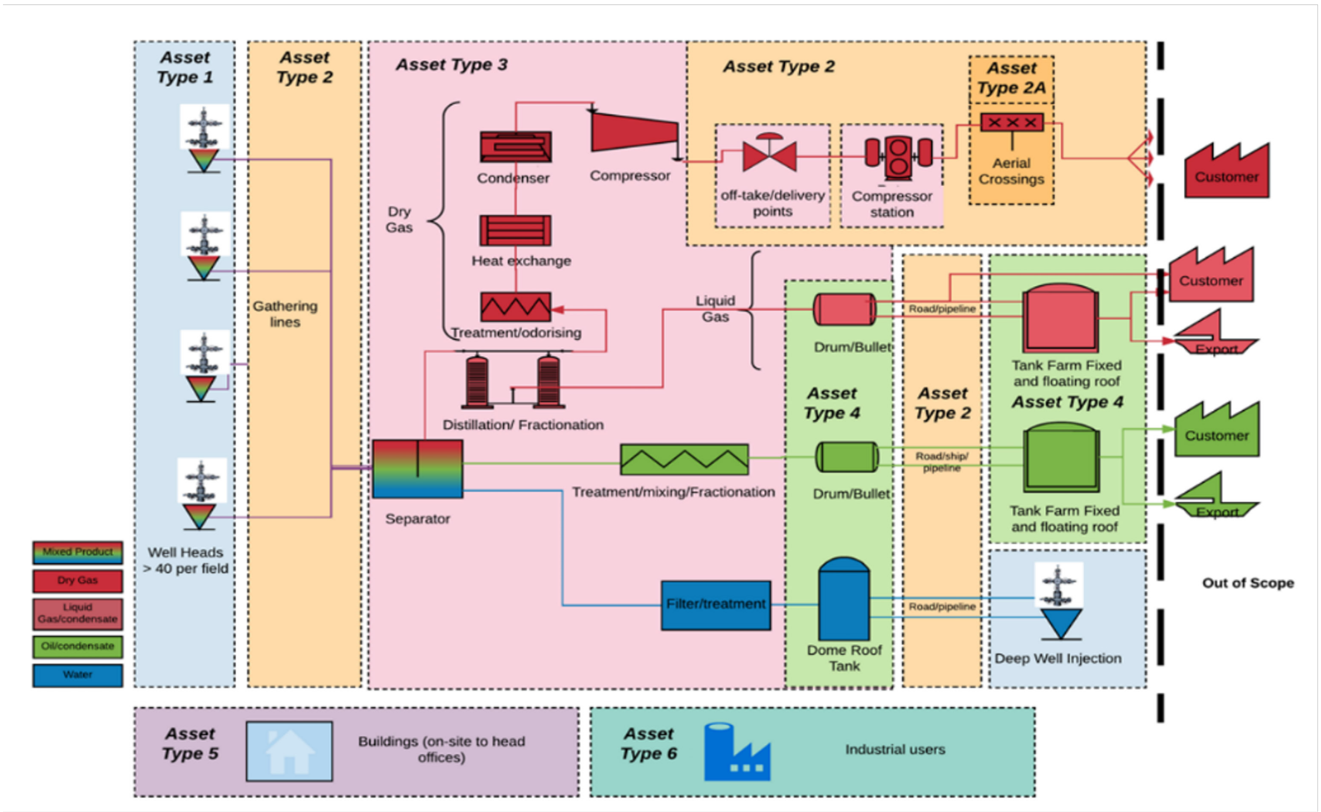

Figure 3: Petroleum product life cycle, showing the six groups of asset types and their relationships.

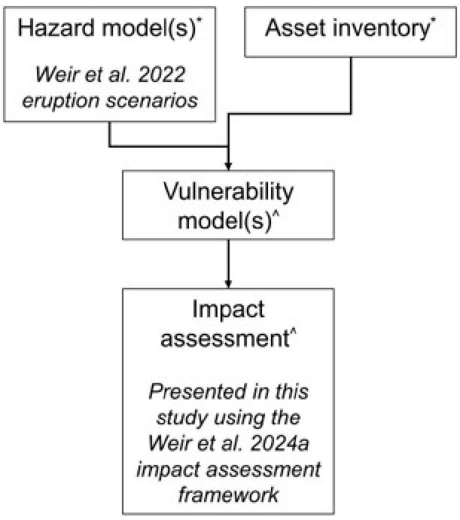

Figure 4: The impact assessment approach used in this study. * denotes publicly available data and tools and ˆ denotes novel data, methods or tools presented in this study.

set categories. The four asset classes considered were wells, pipelines (including aerial crossings), production facilities (excluding 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 Table 6 for wells, pipelines, productions facilities excluding buildings and storage tanks. The main discussion points are captured for each HIM as follows.

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 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 2003] 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.

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 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 2002]. 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 [Task Committee on Wind-Induced Forces of the Petrochemical Committee of Energy Division 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 hyperconcentrated 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. 2010]. 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.

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

The process to further inform the vulnerability thresholds, presented in Table 6, 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, 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 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 6) and the threshold observed in Milazzo et al. [2013b] for storage tanks (7.0 kPa; Table 6).

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 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]. 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 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 [Samuelson 2008]. 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 Resources Aotearoa 2024]. Aotearoa New Zealand's energy supply is from 40 % renewable sources, 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

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	D0: <1 kPa, D1: 1–1.25 kPa, D2: 1.25–2 kPa, D3: >2 kPa	Standards New Zealand [2003], Macedonio et al. [2008], Milazzo et al. [2012], Neall [2012], American Petroleum Institute [2013], Gehl et al. [2013], Milazzo et al. [2013a,b], and Efford et al. [2014]
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	D0: <45 °C, D1: 45–55 °C, D2: 55-500 °C, D3: >500 °C	Mullineaux and Crandell [1962], Arguden and Rodolfo [1990], Voight and Davis [2000], Bredero Shaw [2004], Shaw Pipe [2010], Jenkins et al. [2013], Australian Energy Market Operator Ltd [2014], Fletcher and Nicholas [2014], and Nolan [2014]
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)	D0: <0.5 kPa, D1: 0.5–1 kPa, D2: 1–2 kPa, D3: >2 kPa	Pilcher and Sexton [1993], Dorava and Meyer [1994], Spence et al. [2004a,b], Baxter et al. [2005], Belousov et al. [2007], Ramasamy et al. [2009], Task Committee on Wind-Induced Forces of the Petrochemical Committee of Energy Division [2011], Baek et al. [2012], Ministry of Business, Innovation and Employment [2012], Jenkins et al. [2013], and Meyer et al. [2013]

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 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 2020]. Whilst disaster resilience planning is considered for midstream and downstream usage [National Emergency Management Agency 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 Emergency Management Office 2018; 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. Further, disruptions to the energy sector are typically considered for single-point discrete component failures [FirstGas 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 where hazard models and asset inventories intersect, then assessing the potential impact by applying vulnerability models to exposed assets (Figure 4) [Jenkins et al. 2014a; Wilson et al. 2014a; Weir et al. 2024b]. 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 an illustrative [Torres-Orozco et al. 2017] 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 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).

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

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 vulnerability models and HIMs, though it presents novel approaches for assessing multi-hazard impact through 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 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 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].

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 (Table 6) were then applied deterministically to assign damage states for each scenario phase. We lack the data to support the inclusion of 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].

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, the 'industrial users' category is highly complex and constitutes multiple asset types, so it is therefore excluded from the impact assessment. Asset data were accessed through the publicly available spatial data platform Land Information New Zealand (LINZ) and was current as of 1 November 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).

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. [2024a,b]. 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.

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 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.

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.

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.

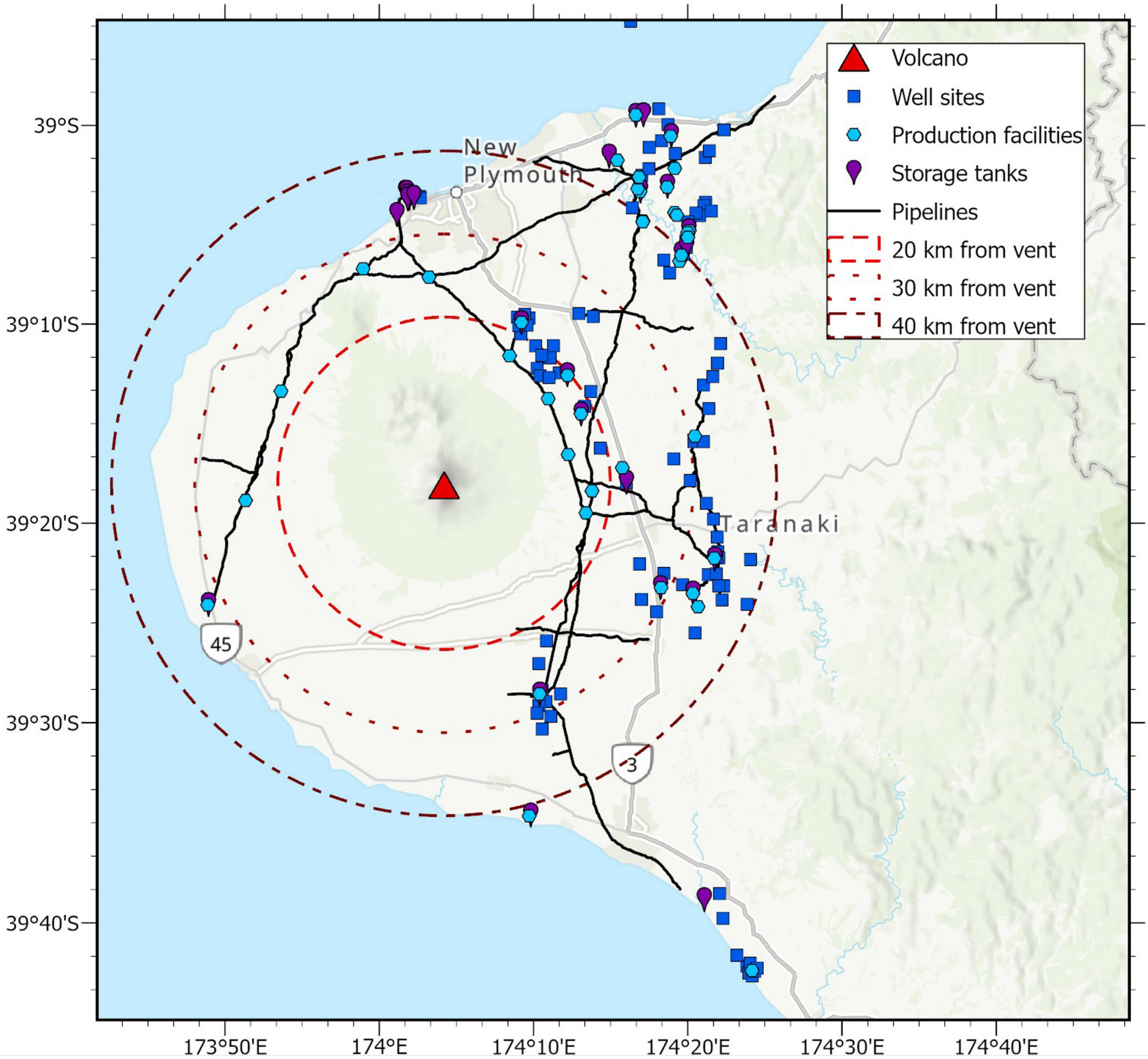

Figure 5: Petroleum sector assets in the Taranaki region, with inset map showing location in Aotearoa New Zealand [Land Information New Zealand 2018].

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 resilience. These differences in vulnerability suggest that petroleum development in volcanic

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

Hazard Intensity Metric (HIM)		D0 No damage	D1 Minor damage	D2 Major damage	D3 Destroyed
WELLS					
Loading/static pressure (kPa)	Example of damage	-	-	-	-
	Threshold	n/a	n/a	n/a	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 ♣
PIPELINES [a]					
Loading/static pressure (kPa)	Example of damage	-	-	-	-
	Threshold	n/a	n/a	n/a	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 ♣
PRODUCTION FACILITIES [b]					
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 ♣
STORAGE TANKS					
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 ♣

[a] including aerial crossings and pipelines buried to a maximum depth of 700 mm; [b] excluding buildings

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 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 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. [2024b] 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 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 Emergency Management Office 2018; New Zealand Lifelines Council 2020]. The L1 scenario was selected 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.

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 example is the Drift River Oil Terminal near Redoubt Volcano, where lahars in 1989–90 and 2009 inundated the facility and disrupted regional production [Casadevall et al. 1990; Dorava and 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.

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 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 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 [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. Table 6) and functional state (i.e. the level of service provided by 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 (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 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 developed here. The HIMs presented in Weir et al. [2022] are not best aligned with those presented in Table 6 or fit-for-purpose when assessing petroleum sector vulnerability. Therefore, adjustments had to be made to 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 (Table 6). 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

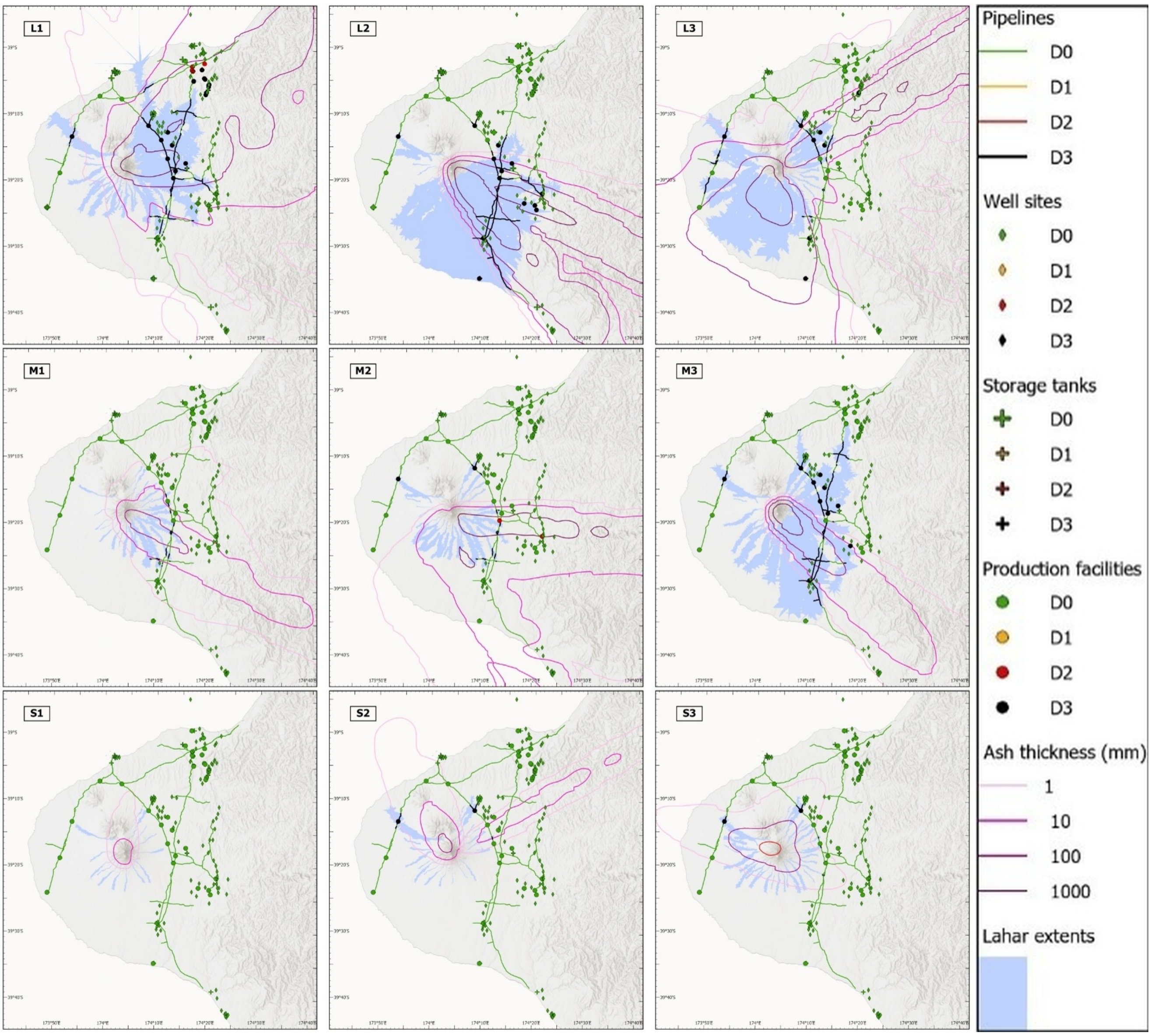

Figure 6: The cumulative impact to petroleum sector assets in the Taranaki region of Aotearoa New Zealand, for a suite of multi-hazard eruption scenarios [Weir et al. 2022]. Results are shown for the 'small' eruption suite (S1–S3), the 'medium' suite (M1–M3) and the 'large' suite (L1–L3).

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.

4.2 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 pathways are the most consistently affected, with several high-exposure assets reaching D3 in seven of the nine 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

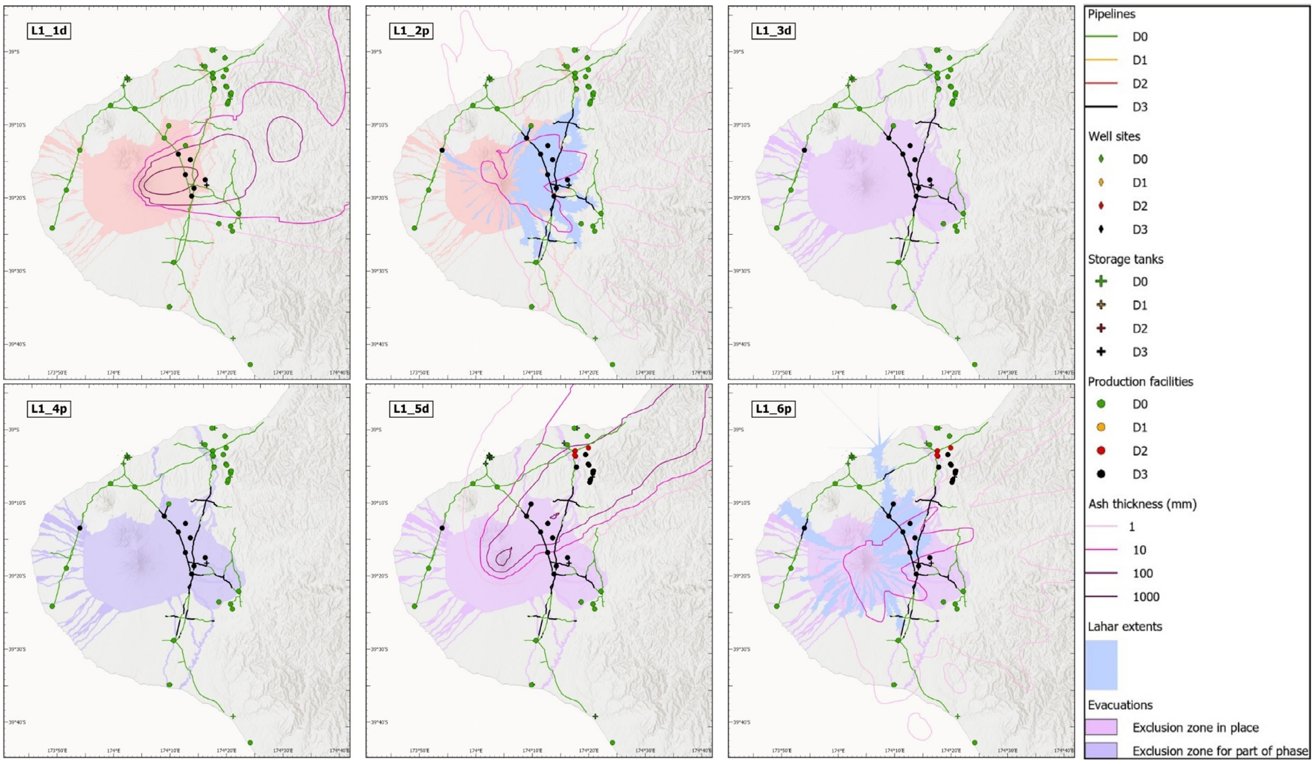

Figure 7: The impact to petroleum assets in the Taranaki region of Aotearoa New Zealand, for Scenario 'Large 1' (L1) in Weir et al. [2022]. Scenario L1 has six phases: 1d , 2p, 3d, 4p, 5d and 6p. Phases 3d and 4p are quiescence phases, and thus, no further physical impact is incurred during these phases.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

turn create a significant and prolonged national 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.

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, 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.

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

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