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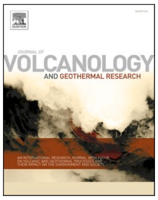

A modular framework for the development of multi-hazard, multi-phase volcanic eruption scenario suites

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ABSTRACT

Understanding future volcanic eruptions and their potential impact is a critical component of disaster risk reduction, and necessitates the production of salient, robust hazard information for decision-makers and end-users. Volcanic eruptions are inherently multi-phase, multi-hazard events, and the uncertainty and complexity surrounding potential future hazard behaviour is exceedingly hard to communicate to decision-makers. Volcanic eruption scenarios are recognised to be an effective knowledge-sharing mechanism between scientists and practitioners, and recent hybrid scenario suites partially address the limitations surrounding the traditional deterministic scenario approach. Despite advances in scenario suite development, there is still a gap in the international knowledge base concerning the synthesis of multi-phase, multi-hazard volcano science and end-user needs. In this study we present a new modular framework for the development of complex, long-duration, multi-phase, multi-hazard volcanic eruption scenario suites. The framework was developed in collaboration with volcanic risk management agencies and researchers in Aotearoa-New Zealand, and is applied to Taranaki Mounga volcano, an area of high volcanic risk. This collaborative process aimed to meet end-user requirements, as well as the need for scientific rigour. This new scenario framework development process could be applied at other volcanic settings to produce robust, credible and relevant scenario suites that are demonstrative of the complex, varying-duration and multi-hazard nature of volcanic eruptions. In addressing this gap, the value of volcanic scenario development is enhanced by advancing multi-hazard assessment capabilities and cross-sector collaboration between scientists and practitioners for disaster risk reduction planning.

1. Introduction

Volcanic eruptions are inherently complex phenomena, varying in intensity, style and duration. Meteorological and hydrological controls on volcanic phenomena are equally diverse, though with a more advanced capability for prediction (Marzocchi and Woo, 2007). The diversity and complexity of volcanic hazard dynamics makes them challenging and uncertain drivers of disaster risk. When combined with other drivers which can increase exposure (e.g. population growth) and vulnerability (e.g. social inequities), and therefore risk to communities in volcanic areas, the diversity and complexity of volcanic hazards require scientifically informed disaster risk reduction strategies (Bretton et al., 2018a, 2018b; Donovan, 2019; Doyle and Paton, 2018; Fearnley, 2013; Fearnley and Beaven, 2018). Increasingly, complex multi-scale challenges of this kind are being addressed by bringing scientists and practitioners together to collaborate in the production of both disaster risk reduction (DRR) knowledge and disaster risk management (DRM) strategies (Barton et al., 2020; Davies et al., 2015a; Hayes et al., 2020; Mach et al., 2020; Wyborn et al., 2017).

Interactions between science, policy and practice are often termed the ‘science-policy-practice interface’ (SPPI), which has been defined as the processes and settings in which decision makers ‘use, misuse, or reject scientific research in their thinking, analyses or decision-making’ (p.4, Wyborn et al. (2017)). Well-managed collaborations across this interface have been found to result in enduring, partnerships that contribute to scientifically robust knowledge that meets the

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requirements of the decision-makers (Barton et al., 2020; Fearnley and Beaven, 2018; Mach et al., 2020; Wyborn et al., 2017). The collaborative development and management of hazard scenarios can facilitate this knowledge sharing, contributing to increases in the relevance and uptake of scientific information (Davies et al., 2015b; Barton et al., 2020), the empowerment of decision-makers and community members to better prepare for a disaster (Hicks et al., 2014) and increases in awareness and understanding of volcanic uncertainty (Hicks et al., 2014). When developed and managed in this way, hazard scenarios serve as 'boundary objects,' a sociological concept originally defined by Star and Griesemer (1989) as 'scientific objects that inhabit several intersecting social worlds and satisfy the information requirements of each of them' (p.393, Star and Griesemer (1989)). Effective DRM relies on knowledge sharing between scientists and practitioners to co-develop an understanding of what is legitimate (fair and appropriate), relevant (meets the needs of end-users) and credible (meets international peer-reviewed scientific standards) for the local risk context (Barton et al., 2020; Cash et al., 2003; Davies et al., 2015b; Fearnley and Beaven, 2018). Boundary objects are 'more likely to produce relevant, useable information because they engage end-users early' (p.8089, Cash et al., 2003), 'can increase scientific credibility by involving different types of expertise' (p.8089, Cash et al., 2003), and can 'enhance legitimacy by providing transparent access to the processes of information to multiple stakeholders' (p.8090, Cash et al., 2003). Volcanic hazard scenarios are increasingly being utilized as boundary objects, and are commonly developed by hazard scientists to aid decision-makers in response planning and resilience-building initiatives (Davies et al., 2015b; Hayes et al., 2016, 2020; Keough and Shanahan, 2008).

Volcanic hazard assessment began to emerge as an essential component of volcanology and disaster science as a result of increasing interest and awareness following the 1980s volcanic disasters of Mt St Helens, USA (1980), El Chichón, Mexico (1982), Galunggung, Indonesia (1982) and Nevado del Ruíz, Colombia (1985) (Tilling, 1989). Volcanic monitoring agencies and other scientific authorities began to develop hazard assessment techniques to improve the predictive capacity of volcano science, and to communicate hazard and risk potential to communities and stakeholders in volcanic regions (Ronan et al., 2000; Tilling, 1989). Generally, early approaches were deterministic in nature, often taking the form of a single-phase volcanic eruption event of a determined intensity and style (Barclay et al., 2008; Hudson-Doyle et al., 2014b). Whilst deterministic hazard information has proven useful for communication and planning purposes (Barclay et al., 2008; Haynes et al., 2007; Hudson-Doyle et al., 2014a), they are commonly considered to not fully capture the complexity and uncertainty associated with volcanic eruptions. To address the recognised need to demonstrate uncertainty in volcanic hazard assessment, as analytical and technological methods improved, sophisticated probabilistic, statistically-informed hazard assessment approaches found favour (Hudson-Doyle et al., 2014a; Marzocchi et al., 2008, 2010; Sandri et al., 2012; Sparks et al., 2012). However, due to the uncertainty and complexity of probabilistic approaches, they have proven to be exceedingly hard to adopt in any meaningful way in disaster management (Davies and Davies, 2018; Haynes et al., 2008; Hudson-Doyle et al., 2014b).

Both approaches have value for scientists and end-users, but the tendency to produce either deterministic or probabilistic hazard assessment information has limited the potential value offered by integrating elements of both approaches to develop scientifically credible, operationally-relevant hazard assessment products (Barclay et al., 2008; Donovan, 2019; Hayes et al., 2020; Hicks et al., 2014; Leonard et al., 2014; Maier et al., 2016; Marzocchi and Jordan, 2013; Sparks et al., 2012). This is a concern for decision-makers who need salient, relevant, robust hazard information to inform long-term planning (Johnston et al., 1999; Mach et al., 2020). Attempts to bridge deterministic (scenario) and probabilistic approaches are finding increasing favour (Ang et al., 2020; Hayes et al., 2020; Thompson et al., 2017a), especially in settings where scientists and users have attempted to collaboratively partner in DRR activities that aim to distil the complexity of potential hazard behaviour in a credible, yet useable way (Ang et al., 2020; Barclay et al., 2008; Hayes et al., 2020; Haynes et al., 2008; Hudson-Doyle et al., 2015). Despite the relevance of recent hazard assessment and scenario suite development methodologies, there is a growing desire from end-users for dynamic, iterative disaster risk management tools that demonstrate the spatio-temporal intensity of hazard footprints and the resultant impacts (Davies et al., 2015b; Davies and Davies, 2018; Global Facility for Disaster Reduction and Recovery (GFDRR), 2016; Thompson et al., 2017b).

Volcanic eruptions are multi-phase, cascading, often prolonged events where current volcanic behaviour is dictated by preceding activity (Bebbington and Jenkins, 2019; Jenkins et al., 2007; Lindsay et al., 2010; Marzocchi et al., 2010; Sandri et al., 2014). Despite this recognition, there is a relative lack in the literature of scenario development approaches for multi-hazard and multi-phase eruptions (Hayes et al., 2020; Torres-Orozco et al., 2018). A suite of eruption scenarios that recognises the spatial and temporal dependencies between phase type and hazard occurrences could allow decision-makers to better explore the complexity of volcanic eruptions and volcanic uncertainty, and arguably better prepares emergency managers and end-users for an evolving volcanic crisis (Ang et al., 2020; Kappes et al., 2012).

In this study we present a modular framework for the development of multi-hazard, multi-phase eruption scenarios, meeting stakeholder requirements, and with the capacity for adaptation and flexibility that emergency planning and response necessitates. We apply this modular volcanic scenario development framework to Taranaki Mounga[1] volcano, Aotearoa-New Zealand, and present a suite of nine complex eruption scenarios that are scientifically robust, and relevant to the needs of operational end-users. The scenarios were developed to cover the range of possible eruption scales expected at Taranaki Mounga, in a process that was informed at each stage by end-user needs and requirements (e.g. evacuation planning, resource allocation planning, loss-modelling risk management etc.). In the following sections, we discuss the local risk context, previous scenario development for Taranaki Mounga, and the co-creative approach adopted in this study, highlighting the current knowledge and operational gaps and therefore the drivers of this research. This is followed by a discussion of the scenario framework methodology, which justifies all inclusions and exclusions to the framework and highlights the transferability of this methodology to other volcanoes. We then present the nine-member eruption scenario suite for Taranaki Mounga, including a subsidiary 'X' suite that includes low-probability but very high consequence debris avalanche events. The article closes with a discussion of the potential applications, limitations and future research direction of this study.

2. Case study: Taranaki Mounga, Aotearoa-New Zealand

2.1. *Eruption history and future eruption potential of Taranaki Mounga*

Taranaki Mounga is an active stratovolcano in the Taranaki region, on the west coast of the North Island of Aotearoa-New Zealand (Fig. 1B). Taranaki Mounga volcanism is characterized by cycles of cone growth followed by edifice collapse (Cronin et al., 2021; Lerner et al., 2019a; Zernack et al., 2011). Periods of cone growth incorporate effusive and dome-forming activity, and are interspersed with episodes of explosive activity in the form of sub-Plinian to Plinian volcanism (Cronin et al., 2021; Lerner et al., 2019a; Platz et al., 2007; Turner et al., 2011). Typical hazards produced by Taranaki Mounga volcanism include pyroclastic density currents (PDCs) caused by dome or column collapse, tephra dispersal associated with explosive eruptions, debris avalanches caused by edifice collapse, and remobilisation of volcanic debris in the

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[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*.

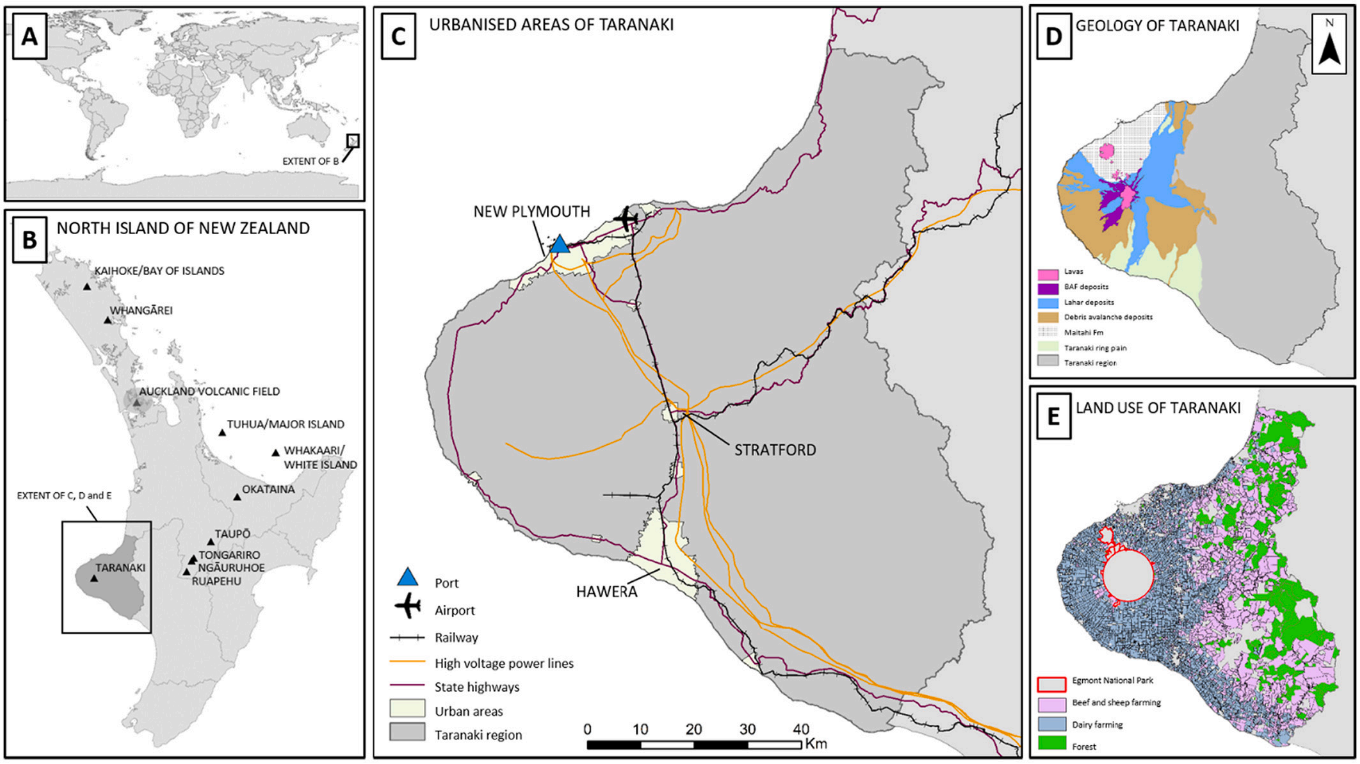

Fig. 1. A) The location of Aotearoa-New Zealand; B) the location of the Taranaki region and volcanic centres of Aotearoa-New Zealand; C) urban centres and selected critical infrastructure of the region; D) simplified geology of the Taranaki volcanic complex (modified from Zernack et al., 2009); E) land use of the Taranaki region.

form of lahars (Fig. 1D). Several studies have compiled detailed Taranaki Mounga eruption records, finding that there exists an average recurrence time of between 300 and 500 years for explosive sub-Plinian to Plinian events (Alloway et al., 1995; Cronin et al., 2021; Damaschke et al., 2017; Turner, 2008). The most recent sub-Plinian eruption is thought to have occurred in 1655 AD (Platz, 2007; Platz et al., 2007). Lerner et al. (2019b) dated the last known activity at Taranaki to 1780-1800 AD. This activity consisted of many small effusive and explosive eruptions, and a final dome-building event (Neall, 1972; Platz et al., 2012). Damaschke et al. (2018) estimated there to be a 33-42% chance of an eruption at Taranaki within the next 50 years.

2.2. Risk context

The 2018 Aotearoa-New Zealand census counted 117,561 people living in the Taranaki region (2.5% of NZ's population) and counted 45,444 occupied private dwellings (Stats, 2018). The region is home to more than eight iwi (Māori tribes; Māori are the indigenous people of Aotearoa-New Zealand), many marae (Māori communal and/or sacred meeting grounds) and sites of significant cultural interest. The Taranaki region has the second highest Gross Domestic Product (GDP) per capita in Aotearoa-New Zealand (NZD $68,427 in 2018; NZD $58,778 was the national average)(Stats, 2018). Due to the volcanically dominated topography of the Taranaki region critical infrastructure circumnavigates the volcanic cone. There are 530 named rivers in the Taranaki region, the vast majority of which extend radially from the volcanic edifice. As a result critical infrastructure, such as water pipes and telecommunication lines, are often bound to the underside of road bridges (or pass over as pipe bridges), exposing them to surface flow hazards such as PDCs and lahars. The bulk of the Taranaki Mounga volcanic edifice sits within the Te Papakura o Taranaki (Egmont National Park (National Park)), which is managed by the Department of Conservation (DoC) Te Papa Atawhai (Fig. 1E). Te Papakura o Taranaki is of cultural, environmental and touristic importance to the region, and DoC are actively engaged with the regional civil defence authority to manage risk within the park. The National Park boundary sits at approximately a 10 km radius from Taranaki Mounga's summit. This ensures minimal asset exposure within close proximity (<10 km) to the vent, and limits future development close to the volcano, unless for DoC-sanctioned purposes.

2.3. Volcanic risk management in the Taranaki region

Within the current Aotearoa-New Zealand Civil Defence and Emergency Management (CDEM) structure, regional CDEM groups are tasked with tailoring plans and strategies to manage the hazards, exposure and vulnerabilities applicable for their region, and facilitating conversation and knowledge transfer between local stakeholders, groups and agencies (MCDEM, 2015, 2010, 2005). The Taranaki CDEM group is responsible for planning and responding to volcanic activity in the region of interest. Fostering strong relationships with researchers is a key element of the Taranaki CDEM group's approach to hazard and risk management (New Zealand Government, 2015). Effective disaster risk reduction and disaster resilience initiatives rely increasingly on collaboration between scientists and policy-makers (UNISDR, 2015). Volcanic eruption scenarios are commonly viewed as effective tools (or boundary objects) for facilitating conversation and collaboration across the science-policy and practice divide (Donovan, 2019; Donovan and Oppenheimer, 2015; Hudson-Doyle et al., 2014b), and can be a vital tool for emergency management authorities to direct and prioritise future disaster risk management activities.

2.4. Previous volcanic scenario development at Taranaki Mounga

Whilst a few studies present information on the hazard potential at Taranaki Mounga (Neall, 2011; Procter et al., 2010; Zernack et al., 2009, 2012), very few have produced volcanic hazard scenarios for a future awakening of the Taranaki volcanic complex (Neall and Alloway, 1993;

Torres-Orozco et al., 2018), summarized in Table 1. Eruption scenarios customised for CDEM exercises (‘Taranaki Awakens!’, ‘Exercise Billow’, ‘Taranaki Blowout’, ‘Exercise Pahu’) have been useful for specific response planning purposes. Since these scenarios are often bespoke, and have required minimal scientific input, they do not attempt to reproduce the range of likely future volcanic activity at Taranaki Mounga. The Torres-Orozco et al. (2018) scenario suite is demonstrative of a variety of possible volcanic futures at Taranaki Mounga. This suite is multi-hazard and multi-phase, and well illustrates and articulates potential future activity. However, the scenario suite is limited by a narrow eruption intensity range (exclusively Plinian eruptions; magnitudes 4-5), a qualitative temporal scale, and a lack of data that can be applied in an emergency management context (e.g. multi-phase spatial data for each scenario). The summation of volcanic eruption scenario studies at Taranaki Mounga (Table 1) shows a marked lack of multi-hazard, multi-phase volcanic eruption scenario suites, particularly those that are relevant to decision-makers, accessible to stakeholders, and adaptable for operational use.

3. Methodology

Three mechanisms facilitated the co-production of this study: embedding the lead science author of this study (Weir) in the most appropriate policy and practice agency (the local emergency management authority) for several weeks (1), regular semi-structured meetings between actors either side of the SPPI (2), and iterative ongoing validation of the outcomes with the emergency management agency's wider stakeholder networks (3). These mechanisms were used to establish the key objectives of this study (1), clearly identify the scope of the scenario suite (1, 2), and ensure that the format and content of the scenario suite was relevant and applicable (1, 2, 3).

The first author (Weir) was embedded in the agency responsible for coordinating disaster risk reduction and emergency response in the Taranaki region (Taranaki CDEM) from 12th Feb 2018 to 23rd March 2018. The aim of embedment was for the first author to build on and work through established science/practitioner networks in the region to facilitate a focused collaboration between researchers and Taranaki CDEM practitioners. There is growing evidence that embedding scientists within policy and practice organisations can increase the likelihood of addressing priority knowledge gaps (Bruce and O’Callaghan, 2016; Cvitanovic et al., 2018). The lead author was based in the agency every day and participated in routine weekly agency meetings as well as meetings with the wider stakeholder groups such as advisory, planning and disaster response groups. While embedded in Taranaki CDEM Group the lead author also visited other stakeholder agencies in the region, such as regional and local councils, infrastructure managers and rural interest groups to gain an understanding of how volcanic eruption scenarios could be operationalised in different contexts. While embedded in Taranaki CDEM the lead author actively participated in the disaster response and recovery activities associated with Ex-Cyclone Gita (20th Feb 2018). This experience greatly enhanced the author's understanding of operational requirements during a disaster, and contributed to building trust and shared understanding between scientists and practitioners during this study.

Throughout the embedment period, and for approximately the 6 months following, the lead author facilitated semi-structured monthly meetings between the scientists and practitioners involved in this study to identify and work through key issues regarding Taranaki Mounga hazard assessment in sequence. This process involved 7 key stages of methodological development (Table 2). Each stage involved the identification of a key issue, and the exploration of possible actions to address it. While each of these stages was driven by commitment and motivation from both scientists and practitioners, some were more strongly motivated by scientists to develop new, more sophisticated and applicable volcanic eruption scenarios (credibility), while others were primarily driven by practitioner need for the development of tools to support risk management and response planning (relevance) (Table 2). Balancing these motivations in order to achieve a scenario that was useful, as well as scientifically robust contributed to the legitimacy of the outcomes, in that they reflected and balanced the input, interests and needs of both practitioners and scientists, as well as those of communities in the region.

Motivations for the first stages of methodological development (Stages 1-4 (Table 2)) were shared across the SPPI, which led to

Table 1
Previous volcanic unrest or eruption scenario development for the Taranaki volcanic complex, displaying a lack of multi-part, multi-hazard, multi-phase volcanic eruption scenarios, and particularly those of operational relevance.

Study	Type	Purpose of scenario development	Approach used to develop scenarios	Single- or multi-scenario suite	Single- or multi-hazard	Single- or multi-phase
Weir et al., (this study)	*Peer-reviewed publication*	*Scenario development for future research and emergency management planning*	*Statistical model, expert judgement and empirical data*	*Multi- (9)*	*Multi-*	*Multi-*
Wild et al., 2019	Peer-reviewed publication	Impact assessment of dairy infrastructure and livestock evacuation modelling	Bayesian Event Tree for Volcanic Hazards (BET_VH), expert judgement and empirical data	Multi- (6)	Single-	Single-
Juniper, 2018	MSc thesis	Impact assessment of petroleum infrastructure	Empirical data (Tahurangi and Kahui eruption deposits)	Multi- (2)	Multi-	Single-
Torres-Orozco et al., 2018	Peer-reviewed publication	Scenario development for future research	Empirical data and lithofacies analysis	Multi- (3)	Multi-	Multi-
Mcdonald et al., 2017	Peer-reviewed publication	Regional and national scale economic impact assessment	Empirical data (Tahurangi block-and-ash flow, Inglewood tephra and Opua debris avalanche deposits)	Multi- (3)	Single-	Single-
“Exercise Pahu”, 2013	Emergency management exercise	Testing emergency management response capabilities	Expert judgement and empirical data (Tahurangi eruption deposits)	Single-	Multi-	Multi-
“Taranaki Blowout”, 2010	Online community/ emergency management exercise	Increase resident's awareness and understanding of volcanic hazards	Expert judgement and empirical data (Tahurangi eruption deposits)	Single-	Multi-	Multi-
Wilson et al., 2009	Peer-reviewed publication	Livestock evacuation modelling	Empirical data (Inglewood tephra deposit)	Single-	Single-	Single-
“Exercise Billow”, 2008	Emergency management exercise	Testing emergency management response capabilities	Expert judgement and empirical data (Tahurangi eruption deposits)	Single-	Multi-	Multi-
“Taranaki Awakens!”, 2006	Emergency management exercise	Testing emergency management response capabilities and highlight key infrastructural vulnerabilities	Expert judgement and empirical data	Single-	Multi-	Multi-

Table 2
The key stages in the decision-making process in this scenario development framework (Stages 1- 7). The table shows the issue identified by Taranaki CDEM and the authors, and the resultant action taken, documented in this study. The black dots show the relative motivation expressed by Taranaki CDEM Group (based on the relevance of research outcomes to their needs) and informing the author's contributions (based on concern to ensure that the scenario provided a high value contribution to scenario science).

	Motivation		Issue identified	Action
	Taranaki CDEM Group	Authors		
Stage 1	●	●	The lack of operationally useful volcanic hazard information for planning and response purposes	To develop volcanic eruption scenario(s) for planning and response purposes
Stage 2	●	●	The lack of understanding of the possible future eruption style and intensity, and the associated uncertainty	To develop a suite of volcanic eruption scenarios, demonstrative of the credible range of eruption styles and intensities
Stage 3	●	●	The lack of understanding of the possible impacts of a future volcanic eruption	To develop a scenario suite that is impact-led and suitable for impact assessment purposes, whilst remaining credible
Stage 4	●	●	The lack of understanding of the possible complexity of the potential future eruption	To develop a suite of volcanic eruptions that are multi-hazard, multi-phase and long-duration
Stage 5	⬤	•	The need for a an adaptable, flexible tool that can be modified before, during and after an event	To develop a modular scenario development framework
Stage 6	⬤	•	The need for the development of a relevant, applicable volcanic eruption scenario suite over a short time frame	The exclusion of spatial hazard mapping within the Te Papakura o Taranaki National Park, the adoption of a hydrological catchment-led methodology and the limiting of the scenario suite to a 6 month eruption duration
Stage 7	⬤	●	The need to produce a scenario suite that is demonstrative of all credible volcanic behaviour, but is also feasible to plan for and respond to	The exclusion of debris avalanche events in the main scenario suite (S1 – L3) and the creation of a subsidiary ‘X’ suite

agreement that a suite of multi-phase, multi-hazard, impact-led credible eruption scenarios would best suit both operational and scientific purposes. Stages 5 and 6 (Table 2) were strongly driven by practitioner motivation, and led to building flexibility and adaptability into the framework. Stage 7 (Table 2) informed the development of a subsidiary ‘X’ suite that includes a low-likelihood, high-impact debris avalanche event. As a debris avalanche event vastly exceeds the hazard modelling and operational response capacity of scientists and practitioners respectively, following lengthy discussion, we concluded that debris avalanche events were to be excluded from the main scenario suite, but included in a subsidiary ‘X’ suite, to recognise the plausibility of low-probability high-impact hazard events.

4. Scenario development

With consideration for the issues identified in Table 2, we developed an approach that is modular, statistically informed and inherently adaptable. The scenario development framework consists of a suite of nine scenarios, consisting of a ‘small’ magnitude sub-suite (S1, S2 and S3), a ‘medium’ magnitude sub-suite (M1, M2 and M3) and a ‘large’ magnitude sub-suite (L1, L2, and L3) (Fig. 2). The scenarios increase in volcanic magnitude (Pyle, 2015) as you progress through the suite, i.e. scenario M2 is of a smaller eruption magnitude than scenario M3, for example (Fig. 2). The scenario framework is composed of four modules; the eruption location (Module 1), the eruptive phase type (Module 2), the phase duration (Module 3) and the hazard occurrence and frequency in each phase (Module 4) (Fig. 2).

In the following sections we apply the scenario development framework to Taranaki Mounga volcano, using relevant studies and data to devise the four principal modules of the scenario framework (eruption location, phase type, phase duration and hazard occurrence and frequency). The selection of input parameters, empirical and numerical models can be easily substituted for other data and tools more appropriate for the risk context of a given volcanic area.

4.1. Module 1: eruption location

Volcanic settings are diverse. Volcanic fields see multiple, small short-lived volcanic events, whereas stratovolcanoes can produce complex, prolonged events, generally sourced from the same (or nearby) vent. To accommodate this diversity, the modular framework allows for multiple eruption locations across the scenario suite. It is important to consider that different eruption locations could mean different activity styles and associated hazard products.

Taranaki volcanism has migrated south-eastwards over time, resulting in the recently active topographic features of Taranaki Mounga summit and the subsidiary vent of Fanthams Peak. Accordingly, the scenarios presented in this study occur at both Fanthams Peak (S1 and S2) and the summit of Taranaki Mounga (S3 – L3) (Fig. 3). Eruptive activity at Fanthams Peak tends towards basaltic, effusive, lava flow-producing volcanism, as exemplified in scenarios S1 and S2 in the framework. Contrastingly, Taranaki Mounga summit volcanism tends towards andesitic, explosive, ash-bearing and pyroclastic flow producing, as exemplified in the framework (S3 – L3) (Fig. 3). As volcanism has migrated throughout the history of the Taranaki volcanic complex, it is not inconceivable that the next period of volcanic activity in the region will occur at a new location, likely close to the current summit. The emergence of a new area of volcanic activity carries with it considerable uncertainty; the precise vent location, eruption intensity, style, magma composition and associated volcanic hazards are all undetermined and unrepresented in the stratigraphic record. However, a major shift in volcanic activity at the Taranaki volcanic complex, e.g. a new subsidiary peak, will result in much the same style and hazard footprints as a summit or Fanthams Peak eruption. It is therefore considered inconsequential in this context, and is excluded from the current application of the framework. Torres-Orozco et al. (2018) followed a similar logic in justifying the exclusion of a new vent location, and considering activity only from Taranaki Mounga's summit and Fanthams Peak.

4.2. Module 2: eruptive phase types

Using the Smithsonian Institute's Global Volcanism Program (GVP) database, Bebbington and Jenkins (2019) deconstructed past volcanic eruptions into sequences from among nine phase types (Table 3). The study then used Markov chain analysis to quantify the probability of transitioning from one phase type to another, considering the current state and preceding state of the volcano. The probability of transitioning

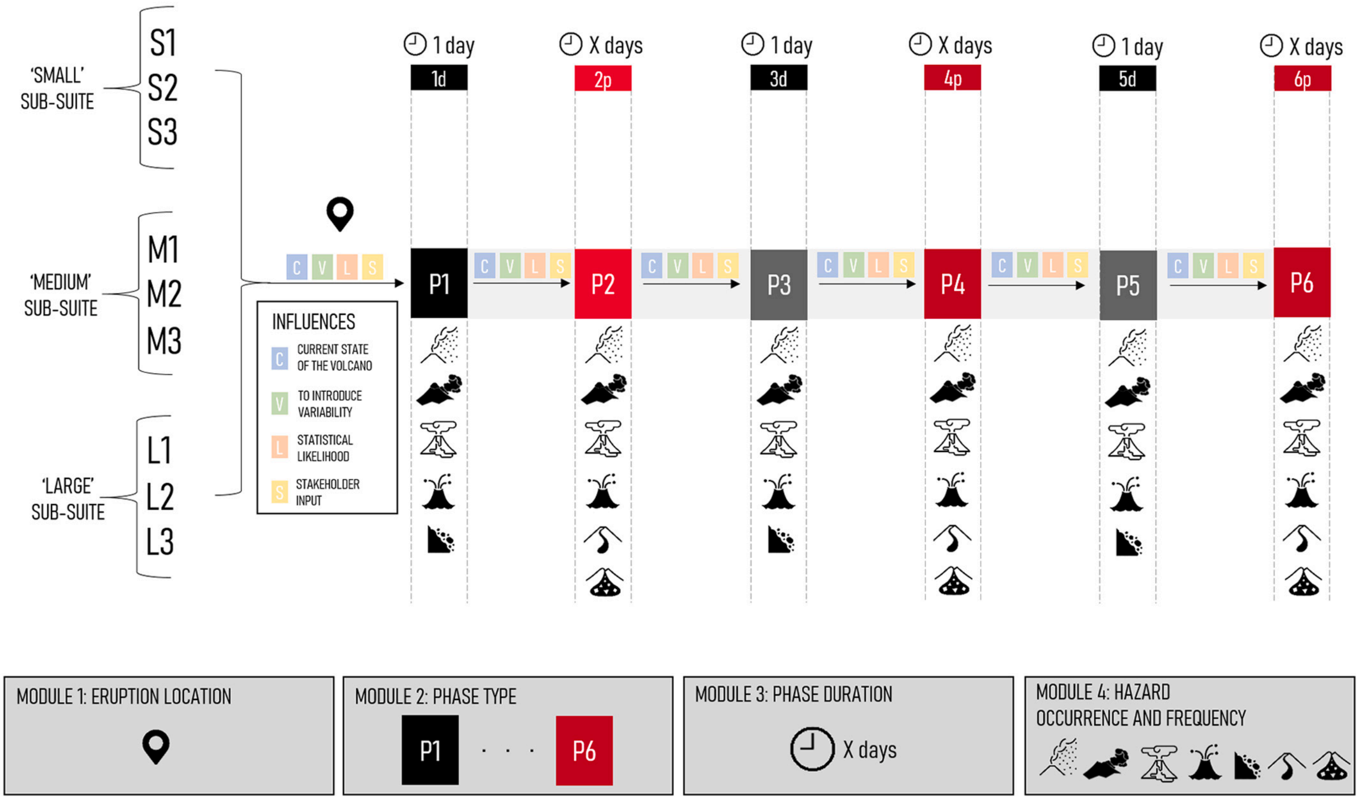

Fig. 2. The modular scenario development framework, comprised of four modules; eruption location (Module 1), phase type (Module 2), phase duration (Module 3) and hazard occurrence and frequency (Module 4). The main suite comprised of three sub-suites, the 'small', 'medium' and 'large' sub-suites. Phase transitions are dictated by four main influencing factors, shown in the 'influences' box.

between phase types is displayed in Table 4.

The starting phase type should be selected with due consideration given to the current state of the volcano and previous activity observed or recorded. In the case of Taranaki Mounga, an initial explosive phase type of 5, 6 or 7 can be assumed, since a high-intensity explosive phase is needed to clear the current closed conduit and offload the summit dome (Lerner et al., 2019a, 2019b; Platz et al., 2007; Procter et al., 2010; Torres-Orozco et al., 2017a, 2017b, 2018; Zernack et al., 2012). Similarly, activity at Fanthams Peak is limited to phase types 1-5, given its largely effusive, basaltic eruptive history. All scenarios open with discrete, explosive phases (phase types 3 (Fanthams Peak), 5 (Fanthams Peak and summit) or 6 (summit)) (Fig. 3). The succeeding phase types must be determined by balancing the likelihood of transitioning to the next phase (Bebbington and Jenkins, 2019) (Table 4) with end-user requirements (Fig. 4).

The most likely phase transition is not necessarily the optimal phase transition for the end-users applying the scenario suite in an operational context. Following the determination of phase types in each scenario, certain assumptions could be made about the phase duration and hazard occurrence and frequency. On many occasions, the most likely phase transition resulted in the replication of another scenario in the suite (Fig. 4). In these instances, usually the second or third most likely phase transition was selected in order to introduce variability into the suite. On a few occasions, low-likelihood phase transitions were selected, either to demonstrate the wide variety of potential future activity at the Taranaki complex, or to introduce further variability into the suite.

In Bebbington and Jenkins (2019), the deformation phase is 'suppressed' in much of the statistical analysis, due to a lack of recorded incidences of phase type 8 in the GVP database. Only 10 deformation phases (c. 0.25% of total) were identified, and as such, the deformation phase is also excluded in this analysis. Similarly, the quiescence phase type (phase type 9) is largely excluded from this analysis due to suppression in Bebbington and Jenkins (2019), and due to the need to introduce complexity into this scenario suite. Further iterations of this framework application will consider the inclusion of phase types 8 and 9 (Section 7.2).

4.3. *Module 3: phase duration*

Following Bebbington and Jenkins (2019), phase types can be considered either discrete or prolonged. Phase types 5-7 are considered discrete, with c. <2-day duration, and phase types 1-4, 8 and 9 are considered prolonged (Bebbington and Jenkins, 2019). Minor, major and Plinian eruptions (phase types 5, 6 and 7 respectively) record rapid onset explosive eruptions, where associated hazards (e.g. pyroclastic density currents (PDCs) and proximal ash) are emplaced very shortly after the activity begins. Periods of effusion and low intensity explosivity (phase types 1-4), deformation (phase type 8) and quiescence (phase type 9) occur on longer time frames. Time is measured in whole days, with discrete phases lasting 1-day, although the actual eruption may be a fraction of this, and prolonged phases lasting for a user-determined amount of time. This temporal metric of 'days' is consistent with complimentary volcanic studies (Bebbington and Jenkins, 2019), and is also consistent with the temporal metric used by emergency managers and decision-makers in response and recovery planning and operations. The modular framework alternates between discrete and prolonged phases through time, with the phase labelled as such (*d* for discrete and *p* for prolonged; 1d, 2p, 3d, 4p, 5d, 6p…) (Fig. 2). Though prolonged–prolonged phase transitions are common at other case study volcanoes present in the Bebbington and Jenkins (2019) study, given the initial conditions (summit-dome blocking closed conduit), this was not considered likely at Taranaki Mounga. This alternating modular structure allows for varying activity type between scenarios, whilst ensuring consistency and simplicity within the suite.

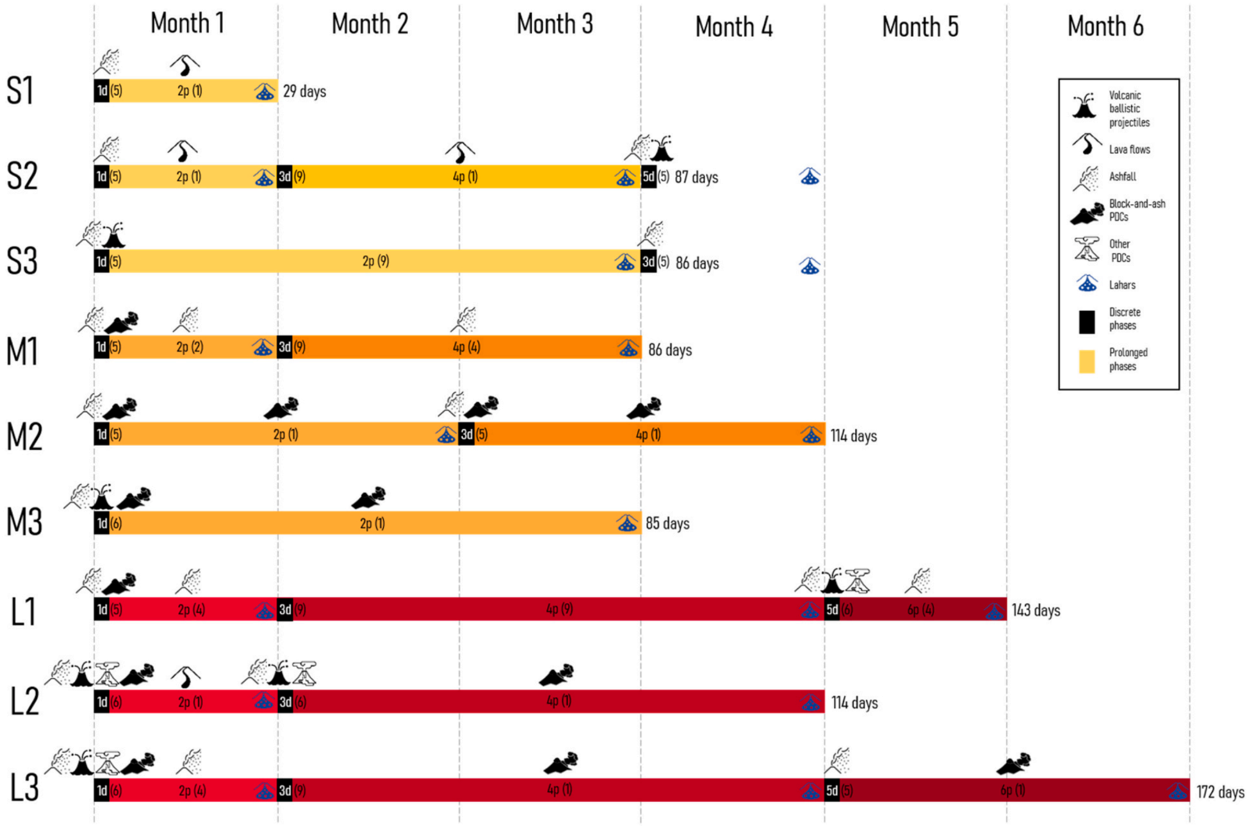

Fig. 3. The modular scenario framework as applied to the Taranaki volcanic complex. The nine-member scenario suite has a duration of 6 months, due to time and computational constraints (Table 2), with discrete (d) phases lasting 1 day, and prolonged (p) phases lasting from weeks to months. Volcanic hazards associated with each phase are shown above the phases, and total scenario length is displayed at the end of each scenario bar. For each phase, the phase number (e.g. 1d, 2p, 3d, 4p, 5d, 6p) is followed by the phase type (1-9 (Bebbington and Jenkins, 2019)).

Table 3
Volcanic activity phase (1-9) definitions, modified from Bebbington and Jenkins (2019). Phase type 8 (deformation) is excluded from this analysis.

Phase/ State	Description	Notes
1	Effusive	Solely effusive activity, including lava extrusions (domes), lava effusions (flow), fountains and spatter cones.
2	Effusive and explosive	Activity that specifically describes an effusive and explosive component, but cannot be further divided into discrete phases. Includes effusive activity in Phase/State 1, and phreatic through magmatic explosive activity.
3	Continuously explosive	Explosive activity described as continuous or Strombolian.
4	Intermittently explosive	Explosive activity described as intermittent or Vulcanian, or with a date range exceeding 2 days without mention of a major explosion.
5	Minor explosive eruption	c. < 10 km column height.
6	Major explosive eruption	c. 10–20 km column height. Many VEI 3 and most VEI 4 eruptions will have at least one.
7	Plinian explosive eruption	c. >20 km column height. Most VEI 5 and all VEI 6+ eruptions will have at least one.
8	*Deformation*	*No eruptive activity, but explicit mention of deformation.*
9	Quiescence	More than 1 day between states 1-8

The duration of discrete phases is inherent in the activity type and dictated by the framework. The duration of prolonged phases for the application to Taranaki varies from 7- to 84-days (i.e. 1–12 weeks) (Fig. 3). Prolonged phase durations were informed by Bebbington and Jenkins (2019), analogue studies (Carrara et al., 2019; Loughlin et al., 2010; Platz et al., 2007), and was also impact-led. Prolonged phase durations differ between scenarios, ensuring varying total length across the suite, therefore introducing variability into the scenario suite outputs for emergency management planning purposes.

4.4. *Module 4: hazard occurrence and frequency*

The volcanic hazards included in this modular framework are shown in Fig. 3. These hazards were chosen as they are of particular relevance for Taranaki Mounga, but other hazards (such as volcanic gas, volcanic earthquakes, blast-type PDCs, syn-eruptive lahars etc.) can be incorporated into the framework when applied to a different volcanic context. Volcanic ash (A) is assumed to occur during every explosive phase type (phase types 2-7). PDCs (P) can occur during high-intensity explosive phases (phase types 5-7) and block-and-ash pyroclastic flows (PBaf) can occur during explosive phases that have the potential to offset the summit dome (phase types 5-7), and during effusive phases (phase types 1 and 2), which allow cycles of lava-dome growth and gravitational collapse (Fig. 5).

Fig. 5 shows the possible hazards associated with each phase type, and their spatial constraints in a Taranaki context. Depending on the volcanic context, the expected hazards in each phase type could differ. For example, phase type 1 at Fanthams Peak (a subsidiary vent in the Taranaki volcanic complex) is more likely to result in a lava flow due to the basaltic nature of the subsidiary peak, however, an instance of phase type 1 at Taranaki Mounga's summit is likely to result in a dome-building event, possibly accompanied by instances of pyroclastic block-and-ash flows.

During phase types 3 and 4, explosive eruptions are frequent, and are

Table 4
The estimated transition matrix between eruptive states, where Eff = Effusive, Exp = Explosion(s), Cts = Continuous, Int = Intermittent and E = Eruption (as described in Table 3). Modified from Bebbington and Jenkins (2019).

		Start	Eff (1)	Eff + Exp (2)	Cts Exp (3)	Int Exp (4)	Minor E (5)	Major E (6)	Plinian E (7)	End
P =	Start	0	0.12	0.10	0.04	0.33	0.33	0.05	0.01	0
	Eff (1)	0	0.39	0.13	0.05	0.12	0.05	0.01	0.00	0.24
	Eff + Exp (2)	0	0.13	0.24	0.07	0.20	0.05	0.05	0.00	0.25
	Cts Exp (3)	0	0.15	0.21	0.10	0.21	0.05	0.06	0.00	0.23
	Int Exp (4)	0	0.09	0.13	0.03	0.27	0.14	0.05	0.01	0.28
	Minor E (5)	0	0.04	0.03	0.01	0.16	0.46	0.03	0.00	0.27
	Major E (6)	0	0.17	0.13	0.03	0.38	0.12	0.04	0.04	0.08
	Plinian E (7)	0	0.11	0.04	0.07	0.52	0.07	0.11	0.07	0.00
	End	0	0	0	0	0	0	0	0	1

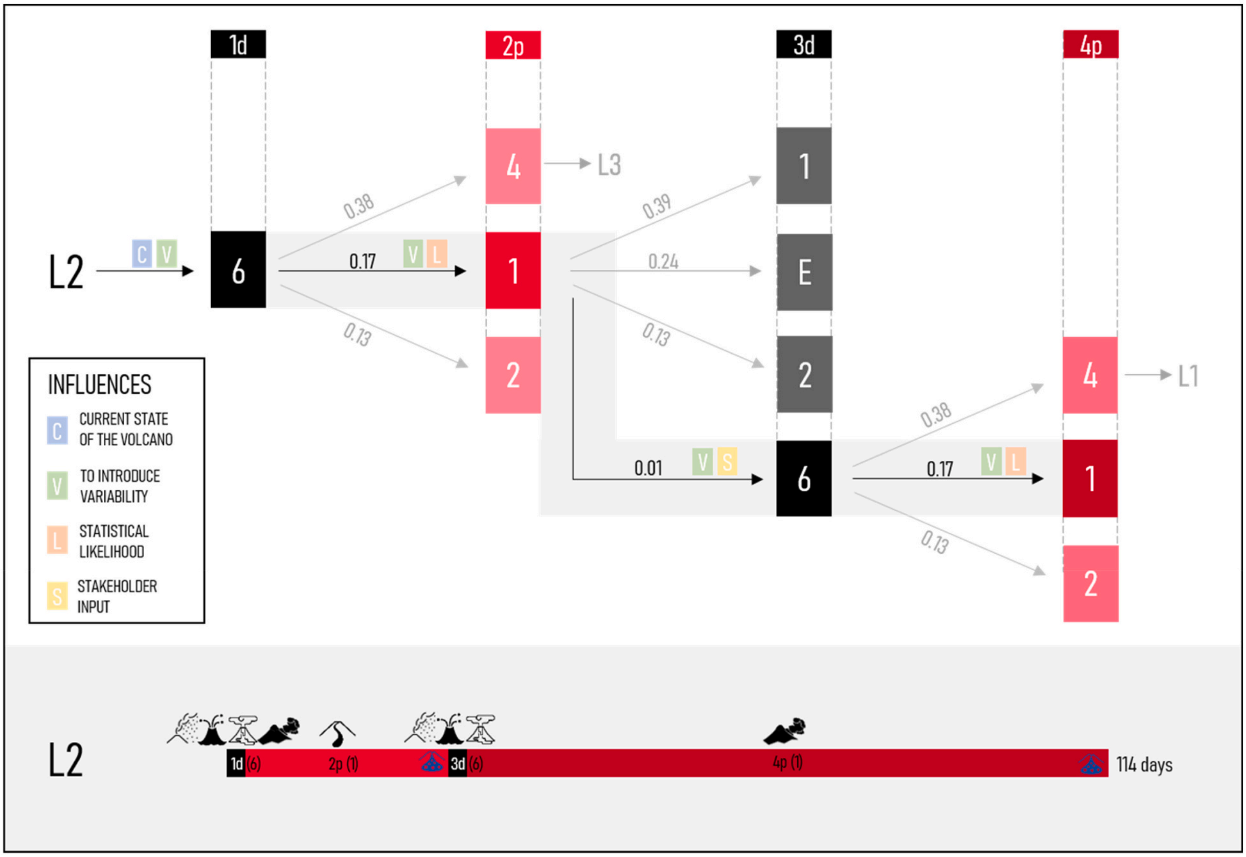

Fig. 4. The factors influencing decisions around phase transitions for scenario L2. The probability of transitioning between phase types (1-9, 'E' = End) is shown next to the arrows (Bebbington and Jenkins, 2019). Influencing factors are shown above the arrows linking the phase types selected. Below, scenario L2 is shown, as in Fig. 3. The need for variability in the scenario suite (V) was a strong determinator of the phase transitions. Where the most likely transition resulted in a duplication of a prior scenario, V and stakeholder input (S) were strong influencing factors of phase selection.

therefore assumed to be relatively small, low-volume events (Bebbington and Jenkins, 2019). Phase types 5, 6 and 7 are considered to be of increasing intensity, with phase type 5 (Minor explosive eruption) an analogue for a small sub-Plinian event, phase type 6 (Major explosive eruption) a large sub-Plinian event, and phase type 7 a Plinian eruption (Bebbington and Jenkins, 2019). The physical parameters and frequency (for prolonged phases) of hazard instances will be deduced differently for each hazard. Generally, decisions around hazard instances and frequency were impact-led and grounded in scientific credibility, using past volcanic deposits, analogue studies and expert judgement.

4.4.1. *Distal vs proximal*

As exposure to volcanic activity in the Taranaki region is buffered by the National Park surrounding the volcano, the primary hazards of focus in this study are those that have the potential to exceed the Park boundary, namely, ash, lahars, PDCs and debris avalanches. Volcanic ballistic projectiles (hereafter known as ballistics (B)) are thought to travel no further than a 6 km radial distance from the conduit (Alatorre-Ibargüengoitia et al., 2012; Brown et al., 2017; Taddeucci et al., 2017). Lava flow deposits at Taranaki Mounga barely reach the current Park boundary (Zernack et al., 2011), resulting in the exclusion of these two hazards from computational modelling, and therefore from the computational generation of hazard footprints. Instead, ballistic travel distances are estimated using expert judgement and analogue studies, and mapped using a maximum radial travel distance. Lava flows are represented by an approximate travel extent, estimated using empirical studies and the morphology of current hydrological catchments, again limited by the Park boundary (Fig. 5). As Taranaki volcanism is expected to be preceded by at least several days of unrest (Lecointre and Neall, 2005; Torres-Orozco et al., 2018), mapping of proximal hazards within

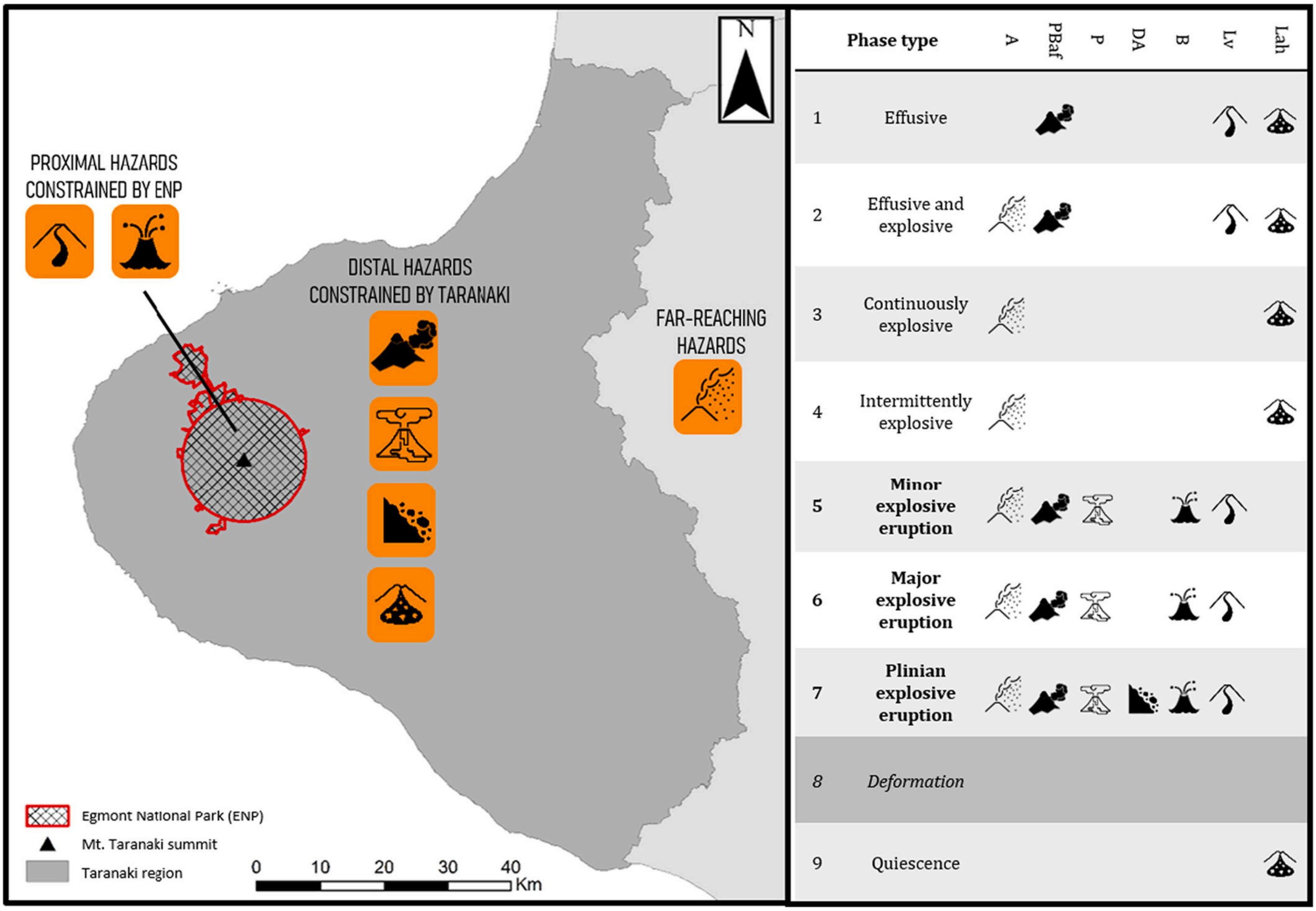

Fig. 5. The spatial extent of volcanic hazards in the Taranaki region. Proximal lava flows and ballistics are constrained to the National Park, distal surface flows are constrained to the Taranaki region, and far-reaching ashfall can extend beyond the regional border. On the right, phase types 1-9 are listed, alongside the possible hazards present given the phase type and duration.

the National Park is deemed unessential, as risk to life is expected to be mitigated through the closure of the Park during the preceding volcanic unrest. Consideration has been given to the potential contribution of proximal hazards (ballistics and lava flows) to lahar generation, and has been determined to be negligible, in light of the considerable contribution from ash and PDC deposits. All scenarios assume no snow or ice cover on the volcano, therefore lava flow contribution to lahar generation is not considered (see Section 4.5 for more on seasonality considerations).

For those hazards that are expected to cross the National Park boundary (Fig. 5) (ash, lahars, debris avalanches and PDCs) we use a hydrological catchment-led methodology. The volume contribution of erupted material is tracked within each hydrological catchment using the National Institute of Water and Atmospheric Research's (NIWA's) 3rd order classification of hydrological catchments, of which there are 40 extending from the Taranaki Mounga volcanic edifice (Fig. 6). The volume of volcanic material deposited within each catchment (within the Park boundary) from ashfall and PDCs is noted, and is considered to contribute towards proceeding lahars (Fig. 6). This is consistent with the calculation of the proximal-hazard zone boundary using LAHARZ (Schilling, 1998), which roughly corresponds to the National Park boundary. Outside of the Park boundary, distal hazards are spatially mapped, using computational modelling methodologies (such as Fall3D, Titan2D and LAHARZ), discussed further in Section 4.6.

4.4.2. *Ashfall*

For ash occurrences during discrete phases (sub-Plinian - Plinian; phase types 5-7), the total erupted volume was selected using published studies on Taranaki Mounga volcanism (Alloway et al., 1995; Green et al., 2016; Platz et al., 2007; Torres-Orozco et al., 2017a, 2017b) and with due consideration to the impact-led nature of the scenario suite. The erupted volume of ash generally increases with increasing scenario magnitude (S1 – L3), whilst staying firmly within the bounds of scientific credibility (Alloway et al., 1995; Green et al., 2016; Turner et al., 2009). The erupted volume of ash varies from 0.002–1 km^3 for discrete phases, and from 0.0001–0.001 km^3 for individual eruptions during prolonged phases. The discrete phases are assumed to follow a sub-Plinian to Plinian style, and the prolonged phases are assumed to follow a Vulcanian style (Bebbington and Jenkins, 2019). The average frequency of explosions during prolonged phases is assumed to be 1/day (Bebbington and Jenkins, 2019; Connor et al., 2003)(see Section 4.6.1).

Meteorological conditions for instances of ashfall hazard were derived from Kidson (2000), which uses cluster analysis of monthly frequencies to classify Aotearoa-New Zealand's weather into 12 synoptic Kidson types. The prevalence of each regime in the Taranaki region and the likelihood of transitioning between these regimes, underpinned the selection of a Kidson type for each instance of ashfall hazard. The need to select prevailing or common weather regimes, whilst also providing a suite of variable ashfall scenarios for end-user purposes was carefully managed.

4.4.3. *PDCs*

Pyroclastic block-and-ash flows (PBafs) occur during scenarios M1-L3. Scenarios M1 and M2 assume a consistent summit morphology, as

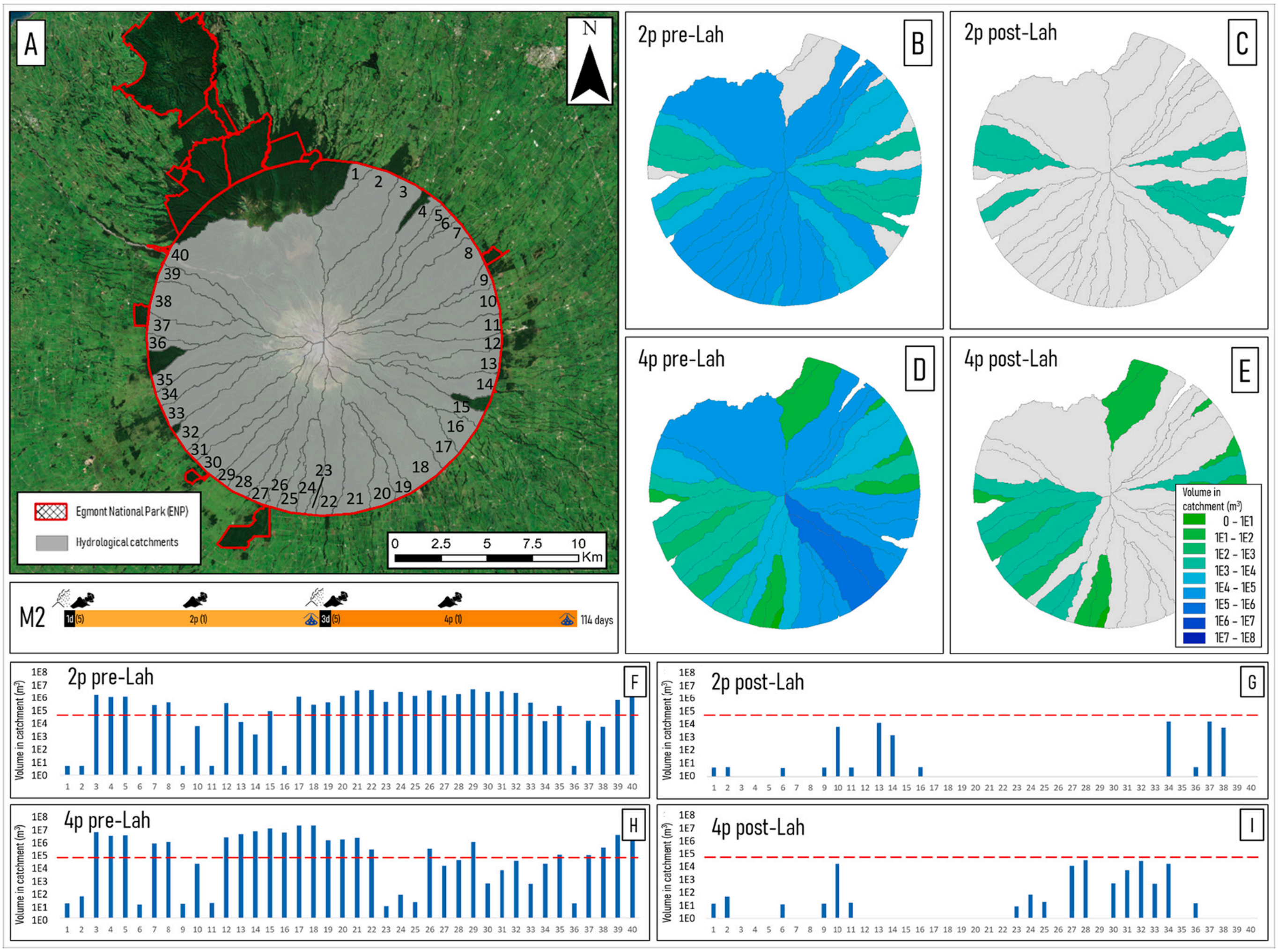

Fig. 6. A) NIWA hydrological catchments (3rd order), constrained by the National Park boundary, labelled 1–40 in a clockwise direction; B) volume of volcanic debris deposited in each catchment pre-lahar at the end of phase 2p; C) volume of volcanic debris remaining in each catchment post-lahar at the end of phase 2p, given a lahar threshold volume of 0.5 × 10^4 m^3; D) volume of volcanic debris deposited in each catchment pre-lahar at the end of phase 4p; C) volume of volcanic debris remaining in each catchment post-lahar at the end of phase 4p using the same threshold; F – I correspond to B – E, with the red line showing the threshold volume (0.5 × 10^4 m^3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is currently observed at the Taranaki Mounga summit. Scenarios M3 – L3 assume a modified morphology after phase 1d, due to the explosive nature of the first phase of activity (further information in Section 4.6.2). As a result, all instances of PBafs under the current summit morphology regime channel material into the NW sector, as is commonly observed during Taranaki Mounga's history (Procter et al., 2010). Where the summit morphology is changed, the orientation of dome collapse events is dictated by end-user requirements.

PBafs occur during discrete and prolonged phases. For the opening discrete phase (1d), the summit dome volume is assumed to be between 1.5 × 10^6 m^3 and 3 × 10^6 m^3, consistent with a range of estimates of the current summit dome volume (Lerner et al., 2019a; Procter et al., 2010). Similarly to other hazard instances, the dome collapse volume in phase 1d increases with scenario magnitude. For prolonged phases, dome growth was simulated using a range of discharge rates for Soufrière Hills volcano, Montserrat, 2005-2008, varying from 1.6 m^3s^{-1} to 5.5 m^3s^{-1}, consistent with Loughlin et al. (2010) and Ryan et al. (2010). Discharge rates generally increase with scenario magnitude, and in some instances (as in scenario M2 for example), the discharge rate increases as the scenario progresses (1.6 m^3s^{-1} in 2p, to 2.6 m^3s^{-1} in 4p). Dome collapse events in prolonged phases are assumed to occur at a rate of approximately 1/week, often followed by a several week period of no collapses, proceeded by a discrete explosive phase that offloads the accumulated volume.

Other PDCs (Ps) occur during phase types 6 and 7 in the 'large' scenario suite (L1 – L3). Their volumes were estimated using empirical studies of previous instances of PDCs at Taranaki Mounga (Torres-Orozco et al., 2017b, 2018), ranging from 0.05 to 1 km^3, with increasing volume with increasing scenario magnitude. Given time and computational constraints and the considerable slope decrease outside of the National Park boundary, we decided to incorporate other-type PDCs by considering their volume contribution to hydrological catchments within the National Park only, not by mapping their extent using numerical modelling methodologies. This is consistent with Torres-Orozco et al. (2018), which observes that other-type PDCs (non-block-and-ash-flow) generally occur during large (≥Volcanic Explosivity Index (VEI) 4 (Newhall and Hoblitt, 2002)) eruptions at Taranaki Mounga, and are largely constrained to the proximal area (Torres-Orozco et al., 2018). Other applications of this framework could use numerical models to map the hazard footprints. We used the vent-facing direction within the scenario, determined through end-user consultation, when choosing the main axis direction of flow for other-type PDCs. For scenario L1, this is to the NE, and to the SE and W for scenarios L2 and L3 respectively. Pyroclastic material was assumed to be deposited in catchments 40–12, 12–31 and 32–40, for scenarios L1, L2 and L3 respectively, and the volume of the flow was distributed across these catchments, relative to the hydrological catchment area. Deposited other PDC material was also considered to contribute towards post-eruptive lahar generation.

4.4.4. Lahars

Primary lahars (i.e. syn-eruptive lahars) are not accounted for in the application of this framework to Taranaki Mounga. The onset of volcanic activity is assumed to occur during a period of no ice or snow cover on the edifice (discussed further in Section 4.5). Secondary (post-eruptive) lahars were assumed to occur if a threshold lahar volume was exceeded. Lahars were also assumed to have occurred by the end of prolonged periods, due to the high-frequency rainfall on Taranaki Mounga. Determining precisely *when* lahars would be initiated and how they would be sequenced far-exceeded the time and computational constraints of this study, but is an important consideration for future work. The threshold volume was calculated by randomly simulating a range of lahar volumes in each catchment using LAHARZ (Schilling, 1998), thereby ascertaining a minimum lahar volume of 10^4 m^3 needed to transport material outside of the National Park.

The term ‘lahar’ describes a range of composition types, varying from debris flows (>60% sediment by volume), to hyperconcentrated flows (20–60% sediment by volume), to stream-flows (<20% sediment by volume) (Doyle et al., 2010; Fagents and Baloga, 2006; Jones et al., 2015; Neall, 2011) and can bulk and de-bulk during transportation (Doyle et al., 2009; Fagents and Baloga, 2006). Taranaki Mounga is prone to rain-triggered hyperconcentrated lahar flows (Neall, 2011; Procter et al., 2009, 2010; Roverato et al., 2015; Zernack et al., 2009) (20–60% sediment by volume). We assume a solid-liquid ratio of 50:50, which is consistent with studies of hyperconcentrated flows (Doyle et al., 2010; Fagents and Baloga, 2006), and also ensures high-impact scenarios for end-user purposes. Assuming a solid-liquid ratio of 50:50 therefore requires a volcanic material volume threshold (V_T) (for any given catchment) of 0.5×10^4 m^3. The calculation of V_T avoided computational modelling of inconsequential lahars. The volume of deposited material in each catchment from ashfall and PDCs is tracked throughout the progression of each scenario. When, for any given catchment, V_T is exceeded, computational modelling of the associated lahar is conducted using LAHARZ (Schilling, 1998) (Section 4.6.3) (Fig. 6).

4.4.5. Debris avalanches

Debris avalanches (DAs) at the Taranaki complex are deemed to be extremely low-probability, high-impact events. There are 16 events observed in Taranaki Mounga's eruption record, with minimum estimated volumes of <1 km^3 - 7.5 km^3 (Alloway et al., 2005; Zernack et al., 2011; Zernack, 2021; Zernack and Procter, 2021). The current volcanic edifice was assessed using three-dimensional limit equilibrium analysis and is thought to be stable, with little variability in stability between sectors (Procter et al., 2019, 2021). The south-east flank is thought to be the least stable, caused by the particularly steep slopes of the volcanic edifice coupled with gravitational forces (Procter et al., 2019, 2021). A trigger is required to initiate sector collapse and associated debris avalanches; this trigger could be hydrological, magmatic or seismic (Roverato et al., 2021). Procter et al. (2019) determined the annual probability of sector-collapse at Taranaki to be 0.00018, increasing to between 0.03 and 0.3 in the event of a large (VEI 4+) eruption.

Debris avalanche events at Taranaki are far-reaching and devastating, resulting in assumed binary impact of all exposed assets through burial and high lateral pressures. From an emergency management perspective, the occurrence of debris avalanches will result in a regime change to the volcano, vastly modifying the current hydrological and morphological state (Procter et al., 2009). The inclusion of debris avalanche events in the primary scenario suite is therefore considered infeasible, as surface hazard modelling cannot be undertaken, and the occurrence of a debris avalanche will necessitate a monumental emergency response, far exceeding regional capacity, or a retreat from the area. In this framework, DA events are addressed in the form of a subsidiary scenario suite (X1 and X2) (Section 6). Debris avalanche events are thought to open or close periods of volcanic activity at Taranaki Mounga (Zernack et al., 2012), and as such, open and close scenarios X1 and X2 respectively (Fig. 7). For scenarios X1 and X2, we chose to collapse the south-east sector, due to the slight decrease in stability observed (Procter et al., 2019, 2021).

4.5. Seasonality

For Kidson types, the relative frequency of each type remains fairly consistent across all seasons (Kidson, 2000), therefore the selection of Kidson types for ashfall hazard is not particularly sensitive to seasonality. Furthermore, analysis of the ERA-Interim global reanalysis dataset (ECMWF, 2009)(8-h sampling between 1979 and 2017) wind speed and direction at Taranaki Mounga's summit only shows reasonable seasonal differentiation above 20 km (exceeded in scenarios L1, L2 and L3).

Taranaki Mounga and the Taranaki region sees peak rainfall during the month of July (NIWA, 2008) and high-intensity weather during the Pacific cyclone season (Nov - Apr). In this scenario framework application, we assumed lahars occurred during prolonged phases (if catchment V_T was exceeded). Climate change scenario modelling by NIWA (2008) shows a general decrease in precipitation in the Taranaki region in the summer months (Dec-Feb), and a general increase in the winter months (Jun-Aug). In general, more frequent extreme rainfall events are expected with the projected changing climate (NIWA, 2008). The implications of seasonality and climate change should be considered in future iterations of this work. Similarly, the effect of snow and ice cover on syn-eruptive lahar generation during snow season on Taranaki Mounga (May – Nov) should be investigated, but is excluded from this framework application.

4.6. Generating hazard footprints

Hazard footprints indicating the hazard intensity for each volcanic product (i.e. ashfall thickness, volume in catchment for PDCs, travel extent for lahars) are produced at the end of each phase, generated from a model of the respective hazard. Footprints at discrete phases are the result of a single input configuration, whereas prolonged phase footprints are the accumulated result of multiple events with input configurations drawn from defined input distributions. The suite presented here consists of deterministic footprints from single draws of input distributions, however the framework could conceivably be extended to present stochastic footprints, provided adequate distributions and computational resources.

4.6.1. Ashfall

The transport and deposition of tephra is simulated using Fall3D version 8.0.1 (Folch et al., 2020), a three-dimensional Eulerian solver for advection-diffusion-sedimentation equations. All ashfall simulations were run on a 0.01° grid with a Gaussian input grainsize distribution ($\mu = 0.2\phi$, $\sigma = 2.4$), truncated at -4ϕ. Mass distribution in the eruption column was assumed to follow the Suzuki distribution (Pfeiffer et al., 2005) with $A = 4.0$, $\lambda = 1.0$ for discrete (phase types 5-7; sub-Plinian-Plinian columns) phases and $A = 5.0$, $\lambda = 10.0$ for prolonged phases to represent vulcanian or single ash explosions (using best fit values from the July 2013 eruption of Tungurahua (Parra et al., 2016)).

Eruption column height for discrete eruptions was estimated using the Mastin et al. (2009) best fit of

$$H = 25.9 + 6.64(V)$$

where H is plume height, and V is eruption volume (in km^3 DRE). Mass flow rates (in kg•s^{-1}) were 10^6 for scenarios S1 - S3, 3×10^6 for M1 - M2, 3×10^7 for M3, and 5×10^7 of L1 - L3. The eruption duration was calculated using the mass flux and phase eruption volume ($\frac{total\ mass}{mass\ flux}$). This resulted in eruption durations of between 0.5 and 12 h.

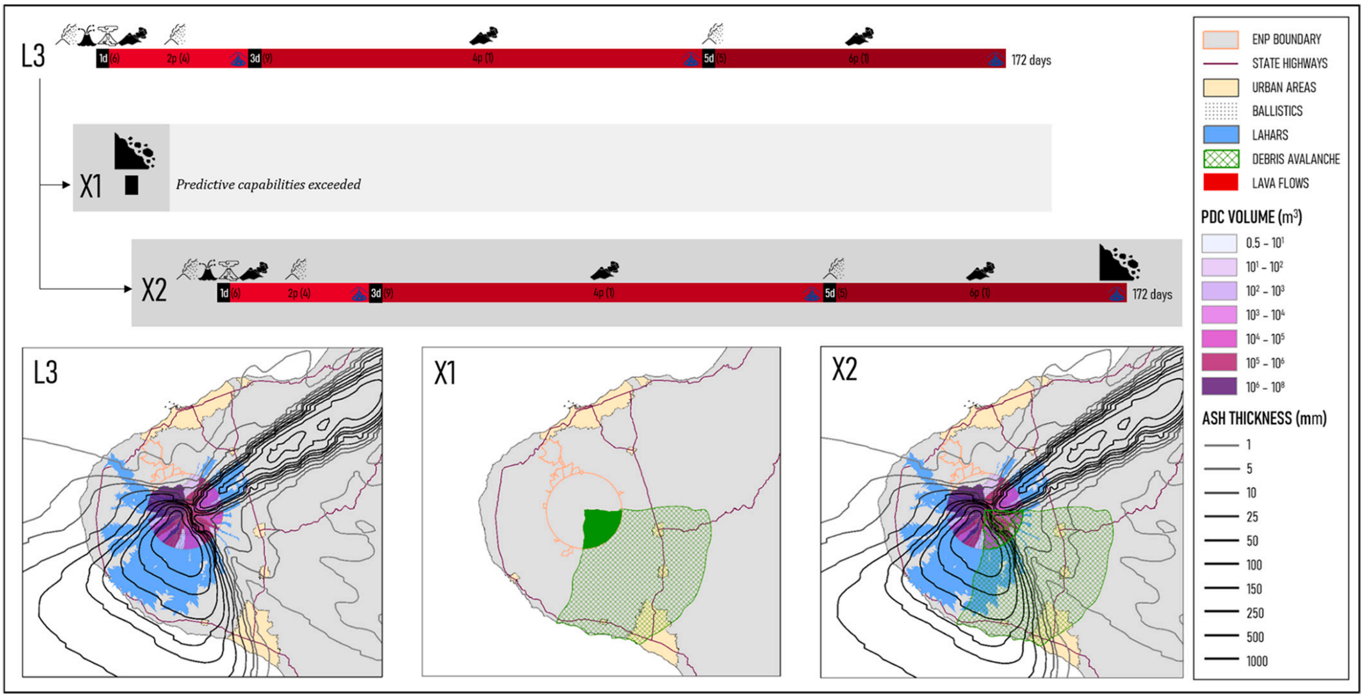

Fig. 7. The 'X' scenario suite, comprised of scenarios X1 (DA event at the beginning of the scenario (1d)) and X2 (DA event at the end of the scenario (6p)). We overlay these DA events on scenario L3 from the initial suite, as DA events are likely to be accompanied by high-intensity explosive activity. Since a DA event will result in a complete morphological and hydrological regime change, we cannot spatially map hazard instances proceeding the DA event. Under this uncertainty, X1 simply consists of the DA event itself.

The continuously and intermittently explosive phase types (prolonged phase types 3 and 4 respectively) were presumed to consist of discrete explosions with small plume heights ($\leq$ 10 km) and mass concentrated at the top of the plume (Parra et al., 2016). Plume heights were sampled from a log-uniform distribution between 2.5 and 5.0 km for medium scenarios and between 5.0 and 10.0 km for large scenarios (following Biass et al. (2016)). The mass flow rate was calculated from plume height as (Folch et al., 2020; Mastin et al., 2009)

$$\dot{V} = 140.8 \bullet H^{4.15}$$

The explosion repose interval was sampled from the log-logistic survivor function (Connor et al., 2003), with $k = 4$ and mean of 20 h, corresponding to approximately 1 explosion/day (also consistent with Bebbington and Jenkins (2019)). Atmospheric properties for each simulation were taken from hourly surface and pressure level ERA5 reanalysis data product (Copernicus Climate Change Service (C3S), 2017) in 8-hourly intervals (00:00, 06:00, 12:00, 18:00 h) between 1979 and 2019. When specified (i.e. for discrete eruptions), the start date and time was randomly selected from dates containing that Kidson type (Kidson, 2000). A random starting time was selected for prolonged phases.

4.6.2. Block-and-ash flow PDCs

The volume of block-and-ash flows in each catchment is controlled by the summit morphology of Taranaki Mounga. Currently, the summit contains remnants of a lava dome (~1.5 × 10^6 m^3) within a 420 m diameter crater breached from the SW to NE (i.e. 'The Chute', towards Hangatahua River (Platz et al., 2007)). This morphology directs most block-and-ash flows towards the NW sector of the National Park; the past ~800 years of block-and-ash flows have almost exclusively impacted this sector (Procter et al., 2010).

Mead et al. (2018) simulated 1024 possible realisations of block-and-ash flows from a Taranaki Mounga summit dome collapse with a Mohr-Coulomb rheology using the Titan2D suite for volcanic mass flows (Patra et al., 2005). The summit dome was assumed to have an ellipsoidal shape with aspect ratios fixed to approximate the current (remnant) dome shape. Simulated dome volumes ranged from 10^5 to 10^7 m^3, dome location ±210 m from the current location, and dome orientation between 0 and π radians. Although many simulations were run, the dimensionality of the input space limits the applicability of these deterministic simulations for generic scenarios. A surrogate model of the simulations is used to alleviate this issue and provide a continuous estimate of volume in each catchment.

Gaussian process (GP) emulation is a commonly applied technique to create surrogate models for volcanic mass flow simulation (Bayarr et al., 2009; Rutarindwa et al., 2019; Spiller et al., 2014). Broadly, GP approximates the simulator by learning the unknown function f that maps the model input space x (i.e. collapse volume, location and orientation) to the output space y (i.e. volume in catchment). An emulator for flow volume in each catchment was constructed from the Mead et al. (2018) simulations using a 'Parallel partial' Gaussian process emulator (PPGaSP (Gu and Berger, 2016)) with Matérn 5/2 kernels. A noise term ('nugget') is added to the PPGaSP as some inputs (basal friction) are masked from the emulator (following Gu and Berger (2016)).

The fitted emulator (optimised using lbfgs algorithm) is then used to sample dome collapse parameters for each phase. All initial discrete phases (1d) use the current dome centroid and orientation (~117.5°), with initial volumes as specified for the scenario. For prolonged phases, individual dome collapse volumes were randomly assigned up to the total volume, with volume in each catchment accumulated for each flow. The current dome location and orientation were used for existing morphology eruptions (M2), and chosen (in location and orientation) for modified morphology eruptions (M3, L2, L3) to introduce variability in impacts for stakeholders (see Table 5).

4.6.3. Lahars

Lahars were simulated using LAHARZ (Schilling, 1998), a Geographical Information System (GIS) program for mapping lahar-inundation hazard zones developed by the United States Geological Survey (USGS) based on a semi-empirical model developed by Iverson

Table 5

Taranaki Mounga summit lava dome location and orientation chosen for each dome collapse event. Scenario M2 use the current dome morphology, and scenarios M3, L2 and L3 used a credible modified morphology, selected to introduce variability in outputs for stakeholders.

Phase	Location (UTM 60S)	Orientation (radians)	Min. volume (10^6 m^3)	Max. volume (10^6 m^3)	Number of flows	Total volume (10^6 m^3)
M2_2p	Current	2.05 (current)	0.1	1.5	4	4.0
M2_4p	Current	2.05 (current)	0.5	2.0	7	11.2
M3_2p	246750, 5646500	2.35	1.5	3.0	12	28.8
L2_4p	246700, 5646100	2.05	2.0	4.0	12	39.6
L3_4p	246550, 5646100	3.14	2.0	4.5	12	48.0

et al. (1998). Lahars were assumed to occur at the end of prolonged phases, and are presented alongside other hazard occurrences during those phases as aggregate maps.

LAHARZ requires a Digital Elevation Model (DEM) input (for Taranaki, we used the 15 m DEM from Koordinates Data Service (Columbus et al., 2011)), a stream threshold value (3000) and a slope approximation (0.44), and then outputs the proximal-hazard zone boundary (PHZB) and surface hydrology. Potential lahar initiation points are the points of intersection between the PHZB and surface hydrology (rivers and streams). Since the PHZB calculated by LAHARZ corresponds well to the National Park boundary, potential initiation points were created for each hydrological catchment (1-40) at, or very

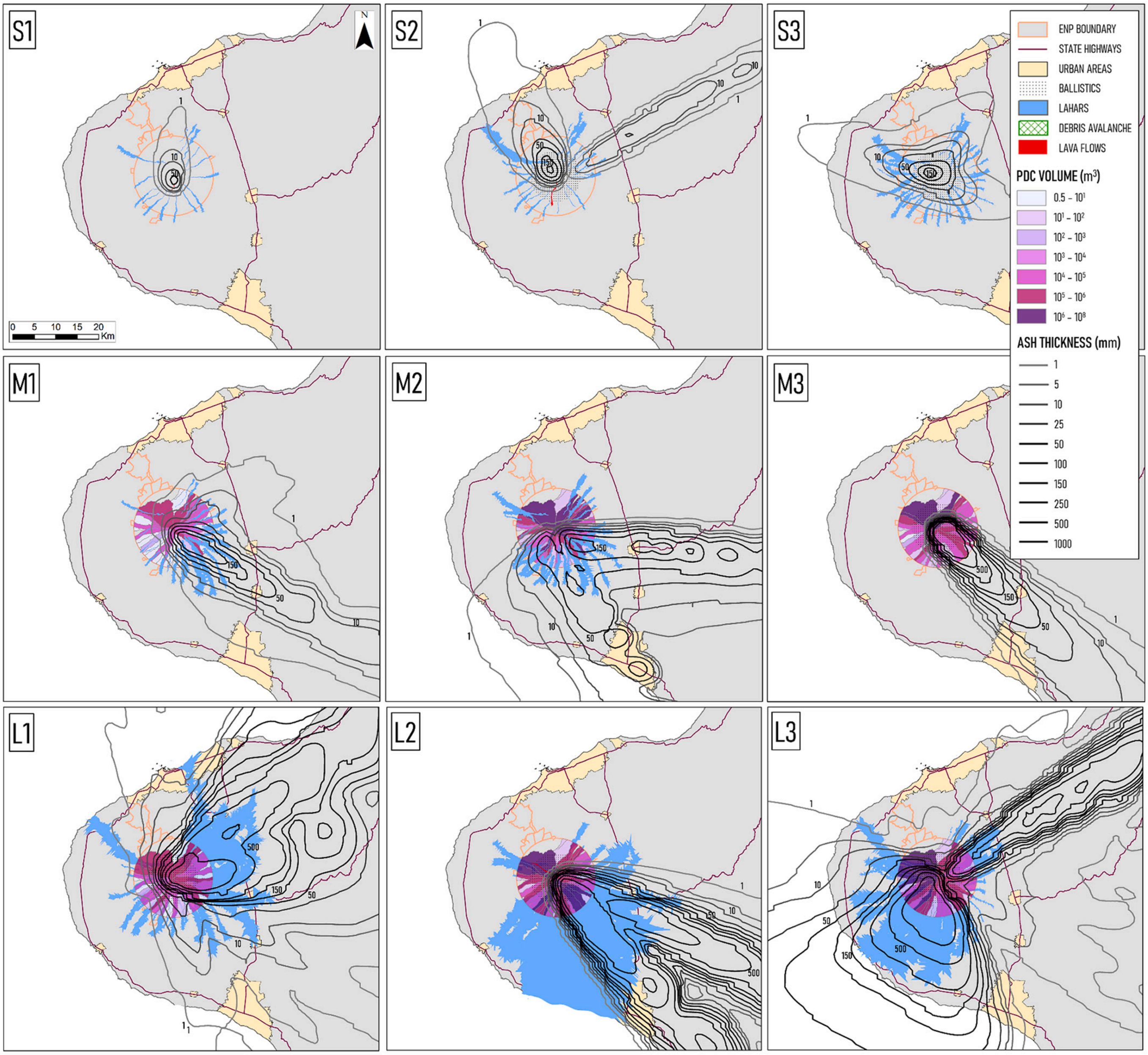

Fig. 8. Aggregated scenario outputs for the main scenario suite (S1 – L3). The small sub-suite is shown on the top row, the medium sub-suite on the middle row, and the large sub-suite on the bottom row. For each scenario, the cumulative deposited material (ashfall, PBaf, other PDCs, lava flows and ballistics) is shown, alongside the resultant secondary lahars (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

near, the National Park boundary. The volume of volcanic debris from PDCs and ashfall in each hydrological catchment was calculated at the end of each phase (1d…6p). When the cumulative volume within any given catchment exceeded V_T (Fig. 6) a lahar of said volume (plus the water contribution) was simulated from the initiation point in the given catchment (Fig. 6).

5. A suite of eruption scenarios for Taranaki Mounga

The aggregated hazard outputs for the nine-scenario suite are displayed in Fig. 8. The methodology for the generation of the scenarios has been outlined in the preceding sections, and the potential applications and limitations of the suite are discussed in proceeding sections. The scenarios are underpinned by data on hazard parameters and have accompanying event narratives. All associated shapefiles for each phase and hazard instance are available for use and circulation. Ashfall outputs are displayed in deposit thicknesses (mm); lahar footprints are available in a binary format (either lahar present or absent); and PBaf and P contribution (m^3) to each hydrological catchment is recorded for each deposition event. Fig. 8 shows outputs from all hazards across all phases of each scenario. Time-sequenced versions of each scenario are available, as shown using the example of scenario M2 in Fig. 9. A summary of the eruption magnitudes (M) of each scenario is shown in Table 6. The volume contribution from ballistics is excluded due to their minimal contribution. Lahars are also excluded from the eruption magnitude calculation as in this application they are post-eruptive (secondary) and are therefore a product of previously emplaced material.

The scenario suite displays a range of eruption intensities and styles. The suite also well-illustrates the complexity of multi-hazard interactions, and the spatial variance of hazard instances, given different meteorological and morphological controls. Lahar instances are co-located with ashfall and PDC hydrological catchment contributions, often observed extending in many directions from the volcanic edifice. The incremental increase of eruption magnitude (and therefore total erupted material) throughout the suite is well-illustrated through the incremental increase of hazard spatial extent, observed in lahars in particular.

The total eruption magnitude for each scenario is calculated following Pyle (2015).

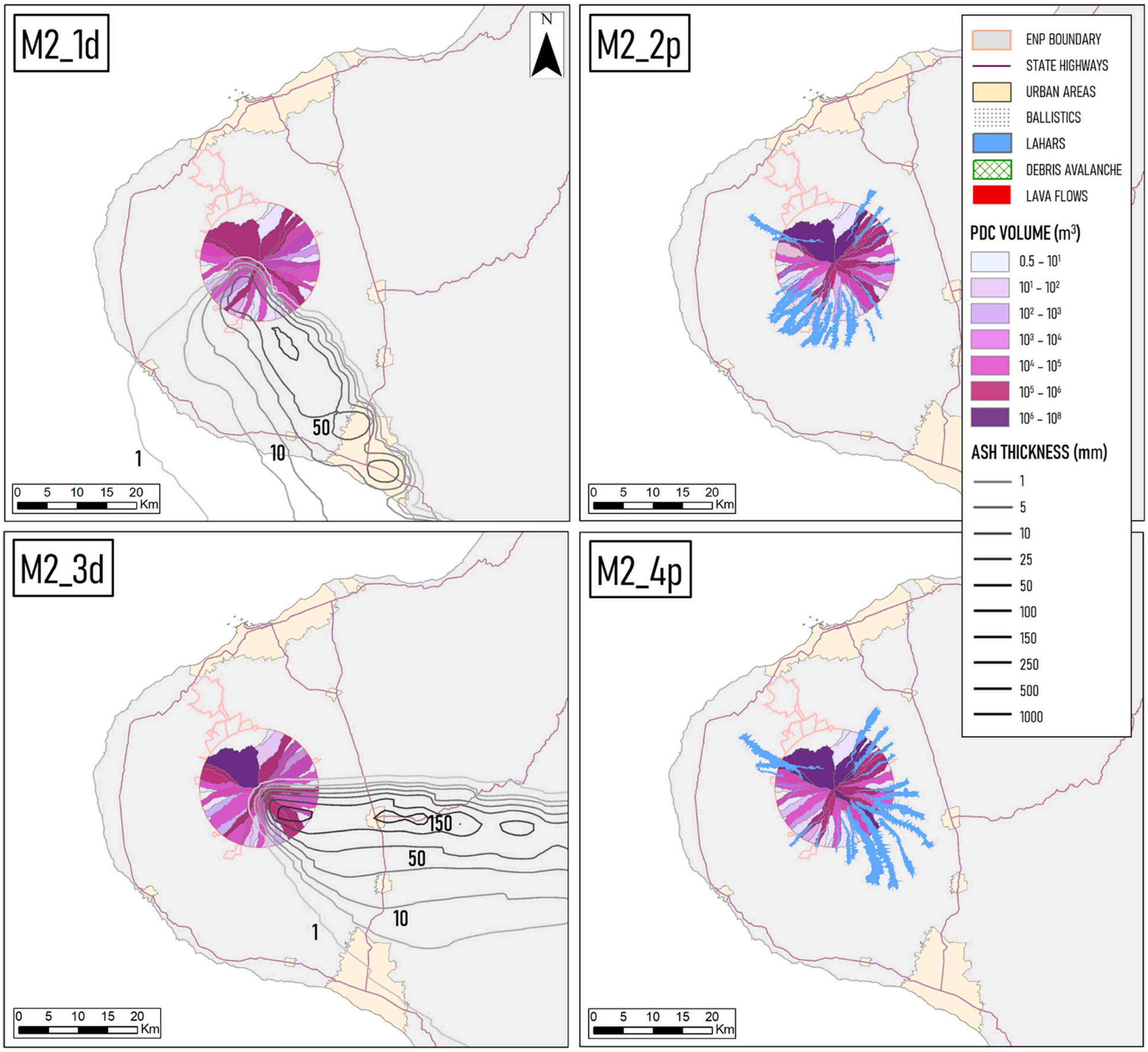

Fig. 9. Outputs for scenario M2, at the end of each phase (1d, 2p, 3d and 4p). Deposited material from ashfall and PBafs is shown alongside the resultant lahars (blue). Time-sequenced scenario outputs are available for all scenarios in both the main and subsidiary 'X' suite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
The eruption location, scenario duration and total volcanic magnitude (M) for each scenario.

Scenario	Eruption location	Scenario duration (days)	Scenario magnitude
S1	Fanthams Peak	29	2.81
S2	Fanthams Peak	87	3.50
S3	Taranaki Mounga summit	86	3.30
M1	Taranaki Mounga summit	86	4.13
M2	Taranaki Mounga summit	114	4.41
M3	Taranaki Mounga summit	85	4.55
L1	Taranaki Mounga summit	143	5.28
L2	Taranaki Mounga summit	114	5.90
L3	Taranaki Mounga summit	172	6.12

$$M = log_{10}[total\ erupted\ mass(kg)] - 7$$

where the *total erupted mass* is the mass contribution from all hazards in each scenario (with the exception of volcanic ballistic projectiles, as this contribution was deemed negligible). The magnitudes calculated (Table 6) were validated against published studies of past and potential future volcanism at Taranaki Mounga (Torres-Orozco et al., 2017a, 2017b, 2018).

6. The ‘X’ scenario suite

Debris avalanches (DA) were excluded from the initial nine-scenario suite, due to their low-probability, and the topographic regime-change they would induce. Though unlikely, DA events are present in Taranaki Mounga's eruptive record (of estimated volumes <1 km^3 - 7.5 km^3) (Alloway et al., 2005; Zernack, 2021; Zernack et al., 2011). We address this in the form of an ‘X’ scenario suite, comprised of scenarios X1 (DA event at the beginning of the scenario (1d)) and X2 (DA event at the end of the scenario (6p)) (Fig. 7). We overlay these DA events on scenario L3 from the initial suite, as DA events are likely to be accompanied by high-intensity explosive activity. Since a DA event will result in a complete morphological and hydrological regime change, we cannot spatially map hazard instances proceeding the DA event. Under this uncertainty, X1 simply consists of the DA event itself. We have included this subsidiary suite in order to address ambiguity around DA events at Taranaki Mounga, and to demonstrate that though possible, DA events are low-probability. Computational and empirical modelling of DA hazard is in its infancy (Procter et al., 2021), and for this reason, coupled with the assumed binary impact of such events, and the vast uncertainty surrounding the potential hazard parameters, we have accounted for their occurrence simply by delineating the sector affected (Fig. 7). The debris avalanche location (SE sector) was selected with due consideration given to plausibility of occurrence (based on published studies of the stratigraphic record (Procter et al., 2019; Zernack et al., 2009, 2012; Zernack, 2021; Zernack and Procter, 2021)). The SE sector collapse was also supported by emergency management end-users, who considered the directionality of the sector collapse most useful for planning purposes.

7. Discussion

7.1. Potential applications of the scenario suite

In this study we present a new modular framework for the development of volcanic eruption scenario suites. The modular framework allows the construction of a diverse suite of multi-hazard, multi-phase volcanic eruption scenarios, varying in magnitude, duration and style. Crucially, the framework allows for stakeholder and end-user input whilst remaining grounded in scientific credibility. The modular aspect of the framework provides end-users with the flexibility that volcanic planning and response necessitates: the scenario suite can be modified before, during and after a volcanic crisis, to produce customised scenarios that incorporate changes in the current state of the volcano (e.g. monitoring information or observed activity style) or changes in end-user requirements. The modular format of the framework empowers decision-makers and end-users to adapt and modify the suite under different operational contexts, and also facilitates an on-going two-way dialogue between scientists and stakeholders. The incorporation of prolonged phase types (2p, 4p and 6p) of a user-determined duration facilitates a greater understanding of the potential complexity of long-duration volcanic events. The application shown in this study is limited to a 6-month duration (1d – 6p) due to time and computational constraints, but the framework has the potential to be applied over multi-year or multi-decadal timescales. We anticipate that this framework can be paired with precursory, syn-event or post-event information, such as monitoring information, evacuation, mitigation and response planning, to develop a more holistic model of volcanic resilience.

The modular framework application to Taranaki Mounga provides an initial nine-scenario suite for potential future volcanic activity. The subsidiary ‘X-suite’ (which considers debris avalanches) further demonstrates the flexibility the modular approach allows. This addresses a gap in volcanic scenario development for Taranaki Mounga volcano, and provides end-users with operationally-useful hazard information for risk reduction planning, response and mitigation purposes. The scenario suite could inform response planning areas, such as evacuations, lifeline utility procedures and business continuity. The complex, long-duration nature of the suite allows decision-makers to evaluate their own tolerable risk throughout prolonged volcanic activity, and identify key tipping points and opportunities for mitigation during a complex eruption sequence. The scenario suite has the potential to facilitate ongoing cross-disciplinary conversation and collaboration around risk reduction, response and recovery activities, and can be modified to suit the purpose of the application, whilst providing a common framework for shared understanding.

The purpose of this study was to address an international research gap in multi-hazard, multi-phase scenario development, but also to address disaster, risk and resilience objectives by producing hazard information that balances the need for credibility, relevance and legitimacy. We believe we have fulfilled this objective by ensuring methodological decisions were impact-led, and driven by end-user needs and requirements, whilst maintaining scientific plausibility.

7.2. Limitations and future research

This paper presents the first iteration of the modular framework development, and the initial application to Taranaki Mounga volcano. Future iterations of this work are anticipated, that further develop the framework, refine the application, and tracks uncertainty. Though the constituents of the scenario framework are subject to change and modification in consideration of the volcanic, social and economic context, the modular framework provides a robust, flexible scenario suite development tool for researchers, decision-makers and emergency managers. A potential future development could be to pair this framework with probabilistic information, quantifying the probability of each scenario and its associated uncertainty (Ang et al., 2020).

In the application of this scenario development framework to Taranaki Mounga, we used the National Park boundary as a methodological delineator. Volcanic hazards that are constrained by this boundary were not spatially mapped, and distal hazards were mapped using empirical or computational modelling methods only once they exceeded the boundary. Within the National Park, a catchment-led methodology was adopted, accumulating the volume of volcanic material deposited in each hydrological catchment during each eruptive phase type until a lahar volume threshold value was reached. This approach is suited to this volcanic context, and was undertaken in close collaboration with local end-users. This approach is not necessarily suited to other risk contexts. Similarly, future land use change within and close to the National Park could vastly change the relevance of this methodology to the Taranaki region. Increasing tourism in the Taranaki region (Venture Taranaki, 2017) could provoke infrastructure investment within and around the National Park, potentially increasing the exposed asset value. Furthermore, changes in surface hydrology and the frequency and intensity of climate extremes could necessitate a different scenario approach. It is important to consider the efficacy of this catchment-led methodology in the context of a changing climate and economy.

Certain volcanic hazards were excluded from the application of this framework to Taranaki Mounga. When relevant, other volcanic hazards (such as volcanic earthquakes, volcanic gas, and volcanic smog) can be incorporated when applied in another context. Deformation-related hazards such as landslides, earthquakes and volcanic gas, may become relevant when using the deformation phase type (phase type 8) or pairing this framework with precursory information. It is also important to consider the potential for non-volcanic triggers (such as seismic earthquakes and hydrothermal alteration) to initiate pyroclastic block-and-ash flows and debris avalanches. Though we adopted a catchment-led approach in this application, empirical or computational models can easily be substituted to simulate the potential spatial extent of surface flows in other applications of this framework. In this application, pyroclastic density currents were categorised into two members; PBafs and Other PDCs. Where appropriate, ‘Other PDCs’ can be subdivided into pyroclastic column collapses, blasts and surges. As new volcanic hazard modelling tools become available, we anticipate they can be easily incorporated into this framework. The empirical model LAHARZ (Schilling, 1998) was used to estimate the inundation footprint of lahars, in full consideration of the purpose of the study and time available. Future iterations of this work will investigate the applicability of other lahar modelling methodologies to this framework, focusing on incorporating hydrological seasonality and models of bulking/debulking (Jones et al., 2017; Manville et al., 2009; Stevens et al., 2003). Future applications of this framework should consider the potential for syn-eruptive lahars, and the sensitivity of lahar initiation and intensity to seasonality.

The nine-member suite developed in the Taranaki application has a maximum duration of 6 months. This was in part due to constraints on the time available to undertake this study. Imminent future work will develop much longer scenario suites (years to decades) and investigate the communication and decision-making challenges that surround prolonged volcanic unrest, quiescence and activity. We also plan to use the scenario suite as a tool to help identify decision-making and policy ‘tipping points’, and investigate how to minimise the ultimate impact associated with complex, long-duration volcanic episodes.

7.3. Considerations for other applications of the framework

We anticipate that this framework can be applied to other volcanos of interest, by applying the framework and modifying the methodology, input parameters and assumptions made. The specifics of the modules used in this framework will vary depending on the volcanic context. The eruption location, phase types (including the initial opening phases), phase durations (particularly for prolonged phases) and hazard occurrences and frequency will need to be determined using available resources for the volcano of interest, and carefully developed in close partnership with the potential end-users of the product. Future iterations of this work will incorporate a formalised engagement structure with stakeholders and end-users, soliciting input throughout the scenario development process to ensure operational applicability and relevance of the end product.

Taranaki Mounga is a well-studied volcano, with a wealth of knowledge surrounding its eruptive history and future eruption potential, but with limited historical records and monitoring information. The lack of historical or instrumental observations led to the inclusion of several analogue studies to determine lava dome extrusion rates during prolonged phases in the Taranaki Mounga application (from Soufrière Hills (Montserrat)). The type and amount of volcanic information will vary between applications, and will often need to be supplemented using historical records, analogue volcanism or other sources of information. Incorporating indigenous knowledge and oral tradition would complement not only the application to Taranaki Mounga, but the application to other volcanoes. This is a potential future development of interest.

8. Conclusions

We have presented an overview of a novel modular framework for volcanic eruption scenario development. We have applied this framework to Taranaki Mounga in Aotearoa-New Zealand, where volcanic hazard scenarios are needed for planning and decision-making purposes. The scenarios cover a credible range of volcanic magnitudes, styles, durations and hazards. We anticipate that this scenario suite will inform volcanic impact assessments, emergency management planning, mitigation planning and provoke further research in this field. The purpose of the application of the modular framework is not to anticipate the next eruption at Taranaki Mounga, but rather to provide a broad, credible suite of scenarios to those that rely on robust accessible hazard information for planning and response purposes, such as emergency managers, infrastructure managers and decision-makers. As such, this study was driven by end-user needs and requirements, and informed and validated by end-users throughout the methodological process. This co-creative approach ensured that the outputs were of equivalent value to end-users and researchers alike. We anticipate that the scenario development framework outlined in this study can be applied to other volcanic contexts globally, and when applied appropriately, it can be used to produce operationally relevant yet scientifically robust volcanic scenario suites.

CRediT authorship contribution statement

Alana M. Weir: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization. **Stuart Mead:** Conceptualization, Methodology, Software, Resources, Data curation, Writing – review & editing. **Mark S. Bebbington:** Conceptualization, Methodology, Writing – review & editing, Project administration, Supervision, Funding acquisition. **Thomas M. Wilson:** Conceptualization, Methodology, Writing – review & editing, Project administration, Supervision, Funding acquisition. **Sarah Beaven:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Teresa Gordon:** Conceptualization, Methodology, Validation. **Craig Campbell-Smart:** Conceptualization, Methodology, Validation.

Declaration of Competing Interest

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

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