Volcanic risk management and insurance in New Zealand

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Introduction

New Zealand volcanologists, emergency managers, and insurers watched the unfolding eruption in La Palma, Canary Islands, this year with interest, well aware such a scenario could happen in this country.

New Zealand hasn't experienced a damage-causing eruption like that seen in La Palma over the last few weeks. Nor has it experienced events like the lava flows from Kilauea, Hawaii, in 2018, the volcanogenic tsunami caused by Anak Krakatoa, Indonesia, in 2018, or the widespread ashfall seen at Taal Volcano, Philippines, in 2020, and Calbuco volcano, Chile, in 2015. But we know it could happen, and we are actively preparing for that eventuality.

In this article we discuss recent experience with volcanic events in New Zealand, the state of volcano science and understanding, and multi-agency preparedness for such events. We cover New Zealand's public-private model of insurance, including insurance coverage of volcanic events; we discuss a recent review of operational policy, seeking to ensure the lessons learned from the Canterbury Earthquake Sequence claims management experience are applied to other hazards. Finally, we look at New Zealand's risk and loss modelling capability, including how we are trying to quantify likely losses from future volcanic events.

The Earthquake Commission is New Zealand's public insurer. As well as providing 'first-loss' insurance cover for natural disasters, we also invest in natural hazard research, including how to reduce the impact of hazards, build resilience, and protect the wellbeing and prosperity of New Zealanders.

While a range of Government agencies and private sector organisations work to reduce volcanic risk and plan and prepare for volcanic activity, New Zealand is fortunate to also have very high insurance coverage for volcanic impacts.

New Zealand has two major public insurance schemes: the Accident Compensation Corporation (ACC) which insures anyone in New Zealand (regardless of residency or citizenship status) with 'no-fault' personal injury cover, and the Earthquake Commission (EQC) which provides cover for residential property (homes and residential land) against natural disaster damage (including volcanic eruption). In addition to the Government-run schemes, vehicle, commercial, and agricultural interests are covered through the private insurance market.

Recent volcanism in New Zealand

While we haven't experienced property damage resulting from a volcanic eruption for many years, New Zealand has not been without its volcanic crises and tragedies. On 9 December 2019, Whakaari/White Island, an offshore volcano in the Bay of Plenty region (Figure 1) erupted, killing 22 tourists. The eruption generated an ash plume and pyroclastic surge (super-hot, fast-moving ash cloud) that affected the entire crater area. Two tour parties were caught in the blast. As well as the fatalities, 25 more suffered serious injuries, and the eruption required a weeks' long response and recovery effort. The tragedy re-started a national conversation on volcanic risk management and communication, and it renewed authorities' planning and preparedness efforts.

In reality, New Zealand is relatively well-served by volcano science, risk assessment, planning, preparedness, and education, having had frequent small-scale reminders of the power of volcanoes over recent decades.

The eruption of Mt Ruapehu in central North Island in 1995-96 was a particular wake-up call. Several explosive eruptions over two years caused ballistics, lahars, tens of kilometres-high ash plumes, and extensive ashfall across several regions. The eruption didn't cause substantial damage, but was enough of a reminder about what could happen, and it initiated a wave of research, planning, and preparedness by a range of agencies.

Since then, there have been several smaller eruptions, as well as some large earthquakes, costly flood and storm damage, wildfires, tsunami, landslides, and drought in New Zealand: natural hazards are well known to the country.

Figure 1. Location of active volcanoes in New Zealand. Source: GNS Science.

New Zealand is situated on the "Ring of Fire", a geographic belt encircling the Pacific Ocean and containing about 90% of the earth's volcanoes. The country has three main types of volcanoes (Figure 1): stratovolcanoes such as Ruapehu, or its cousins Tongariro, Ngauruhoe, Taranaki, and Whakaari, which are all capable of small-to-moderate eruptions, generally from a single location (e.g., Leonard et al., 2021; Cronin et al., 2021; Kilgour et al., 2021); caldera volcanoes, such as Taupō, Okataina, and Rotorua, which have a history of infrequent but moderate-to-large eruptions, including, on rare occasions, super-eruptions (e.g., Barker et al., 2021); and volcanic fields such as Auckland and Bay of Islands in Northland, where small eruptions can occur over a wide geographic area, and generally in a new location every time (e.g., Hopkins et al., 2021). Multiple types of eruptions can occur at each of the volcanoes, and the eruption type can vary minute to minute. Each volcano has its own challenges of risk assessment, monitoring and detection, hazard types, and exposed population and assets.

Volcano science, research, and monitoring in New Zealand

New Zealand's relative advantage when it comes to its natural hazard risk, is our long history of investment in science and research, in particular the geological, marine, and hydro-meteorological sciences. This investment in science means we know a lot about our natural environment, the ground beneath us, and the natural processes that can affect us. It means we have a robust evidence base on which to inform our natural hazard risk management policy and practice. It also means we have an authoritative, evidence-based voice in international markets, in particular, in the international reinsurance market.

At the core of almost all geoscience research is scientific observations of the earth. For the last twenty years, these observations have been provided in real-time by GeoNet, New Zealand's geohazards monitoring system. The GeoNet Programme was established in 2001 by the Earthquake Commission, GNS Science, and Land Information New Zealand (LINZ). It resulted from the recognition that the risk to New Zealand's population and economy from geological hazards is significant, and that a robust evidence base is needed to understand and manage these hazards. GeoNet now comprises a network of more than 700 sensors nationwide, as well as the 24/7 National Geohazards Monitoring

Centre, automated software applications, a data management and storage centre, and skilled technical and scientific staff. The programme detects, interprets, and archives key geophysical data about New Zealand, and provides real-time, open source, public data and information about the hazards around us.

For New Zealand volcanoes this monitoring incorporates several strands of observation and measurement, including:

- **Visual observations –** a network of remotely-operated cameras to supplement in-person observations and observation flights.
- **Seismic monitoring –** provided by the core national seismic network, supplemented by regional networks for specific volcanoes.
- **Chemical analyses –** airborne and ground-based gas monitoring, and groundwater, fumarole, crater lake, and thermal spring water chemistry to detect changes in the behaviour of the volcanoes and their associated geothermal systems.
- **Ground deformation –** geodetic levelling, continuous Global Positioning System (GPS), and Interferometric Synthetic Aperture Radar (INSAR) satellite monitoring to measure changes to the land surface that may be the result of magma, hydrothermal, and/or magmatic fluids in the volcanic system.

In addition to this continuous monitoring capability, a number of volcanic risk management and resilience research platforms are currently in operation across the country (Figure 2). These platforms aim to deliver end-to-end volcanic crisis research; from understanding volcanic processes, assessing hazards, impacts, and risks, readiness and response processes, through to community resilience.

A key feature of the platforms, especially at the regional (volcanic centre) level, is the multi-disciplinary and multi-stakeholder nature of the programme of activity. Even the platforms with a primary science/research purpose tend to include a range of stakeholders, from central and local government, emergency management authorities, risk managers and communicators, representatives from infrastructure, business, and local tangata whenua (indigenous people). The overriding purpose is collaboration and coordination on matters of volcanic risk management, and co-creation of research objectives and knowledge needs. The platforms allow a common understanding of the volcanic hazard and risk, common planning scenarios and frameworks, and coordinated risk communication and education.

At a national level, the New Zealand Volcano Science Advisory Panel is a mechanism for ensuring the provision of authoritative science advice when volcanic activity is affecting New Zealand, through trans-disciplinary and multi-institution collaboration. The Advisory Panel was established in 2008 with representatives of each research institution and hosted by the National Emergency Management Agency. It has played a role in recent volcanic crisis such as Whakaari (2019) and Te Maari (2012) to ensure consistent communication to decision-makers, stakeholders and the public, and coordinate post-event research.

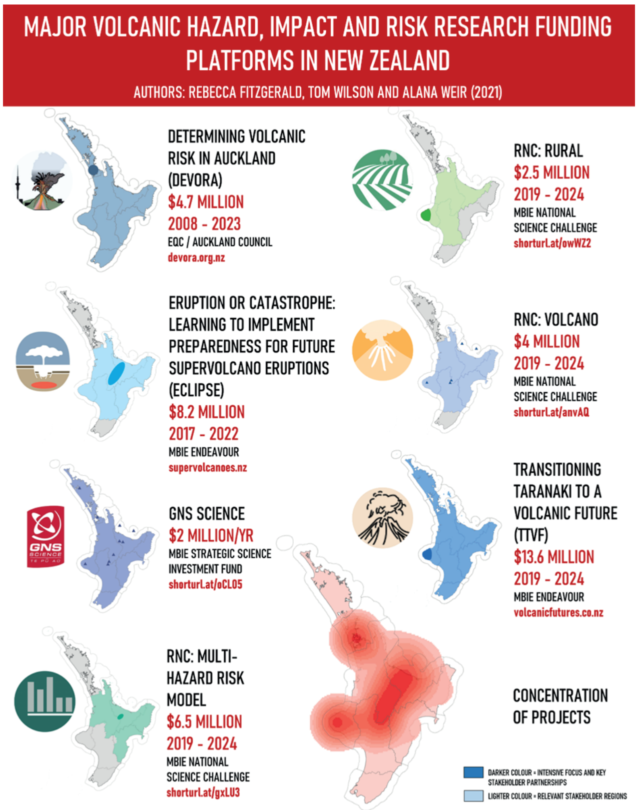

Figure 2. Major volcanic hazard, impact and risk research platforms New Zealand.
Source: Fitzgerald et al., 2021.

Insurance coverage of volcanic impacts in New Zealand

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Coverage of natural disaster damage: About the Earthquake Commission

EQC was initially established as the Earthquake and War Damages Commission in 1944 in response to the economic recovery (or lack thereof) of communities affected by the seismically-active period that occurred in New Zealand between 1929 and 1942. The Earthquake and War Damages Commission provided insurance on an indemnity basis for any property in New Zealand with fire insurance. In 1956 the scope of the legislation was expanded to include landslip and volcanic eruption. Cover for residential land, including structures essential for maintaining access to and utility of the land (e.g. retaining walls, bridges, and culverts) was added in the 1970s.

In 1993 the Earthquake and War Damages Commission Act was re-established as the Earthquake Commission Act 1993 ('EQC Act'), covering damage resulting from earthquake, natural landslip, volcanic eruption, hydrothermal activity, tsunami, and natural disaster fire occurring as a consequence of the above. EQC also covers damage caused by storms or floods to residential land (only).

The maximum amount of insurance available under the EQC scheme is NZD150,000 (1) per residential dwelling (i.e. a single home). EQC covers the first NZD150,000 of damage; if claimants have natural disaster damage that exceeds this amount, their private policy may respond and 'top up' their insurance cover. Damaged residential land is covered for its market value and damaged retaining walls, bridges and culverts are covered for their indemnity value.

What does EQC consider to be 'natural disaster damage'?

For EQC insurance to apply to any particular insured property, the loss or damage to that property must be:

- as a direct result of natural disaster; and
- physical, i.e. has actually occurred; or
- expected to happen in the near future (as considered by EQC) – referred to as 'imminent damage'.

Physical loss or damage as a direct result of natural disaster is a common and well-understood insurance concept. 'Imminent damage' is a unique feature of the EQC scheme and caters to those circumstances where there is an inevitable 'more to come' in terms of natural disaster damage. This component of EQC insurance presents some unique considerations in relation to damage arising from volcanic eruptions, and the type of damage EQC may consider 'imminent' as a direct result of that eruption.

Insurance lessons from other natural hazard events in New Zealand

Prior to 2010, EQC managed around 2000-4000 claims per year, with semi-regular spikes in volume related to natural disaster events. The highest claim numbers received by EQC was around 10,000 claims, in 1968, as a result of the Inangahua Earthquake in New Zealand's South Island.

(1) 1This amount will increase to NZD300,000 from 1 October 2022.

In 2010, a magnitude 7.1 earthquake occurred in Darfield, Canterbury, starting the Canterbury Earthquake Sequence. The sequence included the Christchurch Earthquake of 22 February 2011, which, tragically, resulted in the loss of 185 lives. The Canterbury Earthquake Sequence resulted in widespread property damage across the city of Christchurch, surrounding towns and rural areas: EQC received over 450,000 claims in 16 months. Given the high rate of insurance penetration in New Zealand, the Christchurch Earthquake of February 2011 would become the second largest insurance loss in history, globally, for a seismic event (Source: Munich Re datacentre).

The Canterbury Earthquake Sequence presented a number of complexities for claims management, including:

- multiple damage-causing events, including four 'major' earthquakes, and thousands of smaller aftershocks, making it hard for EQC and insurers to pinpoint exactly when damage occurred to a property;
- damage that went 'undiscovered' for some period of time (for example, subsurface damage to drainage infrastructure);
- damage that only eventuated over longer timeframes (for example, caused by land 'settling' from liquefaction processes);
- a two-tier system of assessment where EQC first quantified the loss, and then the private insurer quantified theirs. At times these assessments did not always align, and gaps in insurance cover were identified between EQC and private insurance cover;
- a system of 'managed repair' where homeowners had limited control and which presented unique liability and operational concerns for EQC;
- several areas of the city where entry was prohibited for a prolonged period of time, resulting in delays to damage identification or making damage assessments difficult;
- the capability and capacity needed for EQC to scale up from ~4,000 claims per year, to 450,000 claims over 16 months; and
- many judicial decisions, resulting in an evolving understanding of EQC's coverage.

Some of the above issues are unique to EQC, being either event-specific, or a result of the public-private model of insurance in New Zealand. However, many of the issues highlight transferable lessons that can be applied to other natural hazards, in New Zealand or overseas. In particular, they highlight the importance of a thorough understanding of the natural hazard in question, and the unique environment in which it may occur – *before* a loss-causing event happens.

This is in large part the rationale for EQC's ongoing investment in natural hazard research. However with the above lessons in mind, EQC recently embarked on a phase of operational policy review, with a view to ensuring the lessons from the Canterbury Earthquake Sequence were properly considered for other natural hazard events – including volcanic eruption.

EQC and coverage of volcanic eruption: previous experience and lessons

EQC's most meaningful interaction with volcanic eruption claims was the 1995-96 eruption of Mt Ruapehu. 203 claims were made to EQC. All were for damage relating to ashfall; almost 90% of the claims related to the claimants' roofs, with 28 related to corrosion of metal roof surfaces.

The EQC Act sets the same baseline cover regardless of the natural hazard faced. This means that EQC can utilise the EQC Act to set out the response process. However, it must undertake careful operational planning to ensure that the features of a particular natural hazard interact with the insurance available under the EQC Act effectively.

EQC worked closely with the New Zealand Volcanic Science Advice Panel to review these settings and add clarity, where needed. The review of the volcanic eruption policy included:

Issues of definition

The EQC Act specifically includes 'volcanic eruption', with no further definition of that term. Further, there were concerns the term 'eruption' was too narrow, and did not adequately consider sub-hazards, for example, ground deformation, steam, gas, or lahars. An early consideration therefore was improving this definition and interpretation.

New Zealand's geohazards monitoring system, GeoNet, makes a distinction between volcanic eruption and volcanic activity. Volcanic eruption is considered to occur when eruption hazards are observed near the vent; volcanic activity can include unrest and volcanic environment hazards, which could include (but are not limited to): steam eruptions, volcanic gases, earthquakes, landslides, uplift, subsidence, changes to hot springs, and/or lahars and mudflows (Figure 3).

In some cases, these hazards are covered by EQC in their own right, as a defined natural disaster under the EQC Act (e.g. earthquake). Where hazards are not distinctly covered in their own right, EQC insurance may not apply. EQC is currently working with the wider insurance industry and the New Zealand Treasury to understand the implications of this.

Issues of timing

EQC claim lodgements are timebound, which means EQC needs to understand at what point a volcanic eruption actually begins (and ends). In New Zealand, we use a system of Volcanic Alert Levels to define the current status of each volcano (Figure 3). The Alert Levels range from 0 to 5, and are intended as a descriptor of what's happening at the volcano, and as a guide for response. EQC considers that a volcanic eruption has occurred when GeoNet has raised the Volcanic Alert level to level 3, 4 or 5. If a wider definition of volcanic activity is eventually agreed, the start and end point would change accordingly.

	VOLCANIC ALERT LEVEL	VOLCANIC ACTIVITY	MOST LIKELY HAZARDS
Eruption >	**5**	**Major volcanic eruption**	Eruption hazards on and beyond volcano*
Eruption >	**4**	**Moderate volcanic eruption**	Eruption hazards on and near volcano*
Eruption >	**3**	**Minor volcanic eruption**	Eruption hazards near vent*
Unrest >	2	Moderate to heightened volcanic unrest	Volcanic unrest hazards, potential for eruption hazards
Unrest >	1	Minor volcanic unrest	Volcanic unrest hazards
>	0	No volcanic unrest	Volcanic environment hazards

An eruption may occur at any level, and levels may not move in sequence as activity can change rapidly.

Eruption hazards depend on the volcano and eruption style, and may include explosions, ballistics (flying rocks), pyroclastic density currents (fast moving hot ash clouds), lava flows, lava domes, landslides, ash, volcanic gases, lightning, lahars (mudflows), tsunami, and/or earthquakes.

Volcanic unrest hazards occur on and near the volcano, and may include steam eruptions, volcanic gases, earthquakes, landslides, uplift, subsidence,changes to hot springs, and/or lahars (mudflows).

Volcanic environment hazards may include hydrothermal activity, earthquakes, landslides, volcanic gases, and/or lahars (mudflows).

Ash, lava flow, and lahar (mudflow) hazards may impact areas distant from the volcano.

Figure 3. New Zealand Volcanic Alert Level Table.
Source: GNS Science.

Issues of scope of coverage

The Canterbury Earthquake Sequence, including various judicial decisions, made it clear that the scope of coverage for any particular hazard needs to be as transparent and specific as possible. With this in mind, EQC reviewed its coverage of volcanic impacts.

EQC now considers that it needs to be prepared to manage claims for damage arising from:

- heat damage from proximity to lava flow;
- impact damage from ballistics;
- degradation of finishes due to prolonged exposure to chemically reactive volcanic ash, aerosol, acid rain or gas;
- roof or gutter deformation or collapse due to ash inundation;
- compromised effluent disposal fields due to ash inundation;
- total loss of the building due to destruction from a volcanic eruption.

Issues related to repeated or ongoing events

A key complexity of the Canterbury Earthquake Sequence was its ongoing nature, including repeated damage-causing aftershocks. A volcanic eruption may be similar: because of the nature of an eruptive episode, an individual property may be damaged by several eruptions or volcanic hazards in any given period. This could mean that insurers may need to respond to multiple events.

Schedule 3 of the EQC Act stipulates that an EQC claim may only be lodged when the property has been damaged by the natural disaster in question. Any subsequent damage that occurs within 48 hours (or in the case of natural disaster fire, seven days) of the initial damage to the property from any natural disaster insured by EQC, is subject to one claim cap (i.e. NZD150,000) and excess. In any given eruptive episode, the EQC cap may reinstate over consecutive or separate 48 hour periods.

When assessing the damage to a property, EQC must also consider whether any further damage is 'imminent' as a result of the natural disaster that has occurred. For volcanic eruption this could include, for example, indicators of ground deformation or a landslide that may cause future damage to land or property. A tricky feature of this type of assessment (in relation to volcanic eruption damage) is how assessors would quantify potential corrosion damage from exposure to corrosive elements over a sustained period of time. EQC continues to work to understand how best to approach this.

Issues of operational process

In addition to considerations around coverage and timing, EQC also reviewed its readiness to manage a volcanic crisis. Key considerations were:

- policy and processes for assessors working in potentially dangerous areas;
- approach to managing claims in exclusion zones;
- technology that could enable smarter assessment;
- approach to, and coverage of clean-up costs, including preventative clean-up;
- coordination and collaboration with partner agencies and key science experts;
- how EQC can better support customers and communities in their response to and recovery from volcanic crises;
- risk communication and public education; and
- EQC's role in reducing risk from volcanic activity.

One of the biggest advances for insurance delivery in New Zealand was on 30 June 2021 with the introduction of the Natural Disaster Response Model (NDRM). Building on the learnings of the Canterbury Earthquake Sequence and other smaller natural disaster claims events, the NDRM is an agreement between EQC and private insurers for the latter to manage and settle all EQC claims up to the relevant cap in conjunction with the private insurance claim.

EQC has worked to develop capability with insurers to enable them to perform this function, including to build a common understanding of natural hazard scenarios, and readiness for different events.

EQC is fortunate to have close relationships with the science and research community in New Zealand, including access to quality science advice for volcanic hazard risk management. The above policy reviews were greatly aided by working in close partnership with the science community to fully understand impacts and develop clear definitions and criteria. Work to better define our operational policies and approach is ongoing and EQC is committed to working with its business partners to share the knowledge it has access to.

A step further: assessing impacts and modelling losses from volcanic events in New Zealand

Like other insurers, EQC utilises deterministic and probabilistic loss modelling to quantify likely losses from hazards. New Zealand has had a mature probabilistic hazard model for earthquakes (National Seismic Hazard Model, NSHM) for many years, with four iterations completed over the last 30 years (Smith and Berryman, 1986; Stirling et al., 1998, 2002, 2012), and a major revision currently in progress (Gerstenberger et al., 2020). However, modelling for other hazards, including volcanic hazard, is not as well advanced.

Development of a national probabilistic volcanic hazard model is a priority for EQC, both for its use in loss modelling (for insurance and reinsurance purposes), and for informing disaster risk reduction and resilience initiatives. A national model would sit alongside other national hazard models – currently in various stages of development – to allow robust comparison between perils and inform national hazard risk management and governance.

Quantifying probabilistic volcanic hazard has been discussed and conceptualised by New Zealand scientists for many years (e.g., Stirling et al., 2017). Single-hazard models have been created, such as the national volcanic ashfall model (Hurst and Smith, 2010) but a nationwide, multi-hazard model (i.e., including other volcanic hazards such as lava flows, lahars, pyroclastic density currents, ballistics, or debris avalanches) has yet to be developed.

There are many challenges associated with the development of a national probabilistic model. These include: characterisation of the eruption magnitude and frequency of all actual and realistic volcanic sources (including probabilistic determination of sources in the case of the Field volcanoes; Bebbington, 2013a) preferably in a time-varying model (Bebbington, 2013b); determination of the statistical dependence between hazards, given many of the volcanic hazards are linked within the volcanic system; the need for uniform definition and metrics for all sources, hazards, and return periods; determining the utility and outputs of such a model, especially for building standards; consideration of communication issues, including the information needs of decision-makers, propagation of model outputs into other decision-making tools, and management and communication of uncertainties; and, the funding required to progress the wide variety of research needed to make the model a reality. However, the consensus of the scientific community in New Zealand is that the time is right to make a determined effort towards this goal, given the rare opportunity presented by the number of volcanic hazard and risk focussed research platforms currently underway (Figure 2).

EQC has been utilising its natural hazard research funding to progress some of the early stages required in this work. This includes, crucially, the steps needed to move from hazard, to risk, to loss.

A three-year deterministic volcanic loss modelling project for eight Auckland Volcanic Field (AVF) eruption scenarios (Figure 4) has recently been completed. The project utilised the most detailed, realistic eruption scenarios ever considered for the AVF (Hayes et al., 2018). The scenarios were co-produced by volcanologists, risk scientists and emergency managers and consider a diverse but credible suite of eruption styles, across eight eruption locations, including multiple volcanic hazards in time and space. This provides a vastly more realistic and accurate estimation of the likely impacts from an AVF eruption.

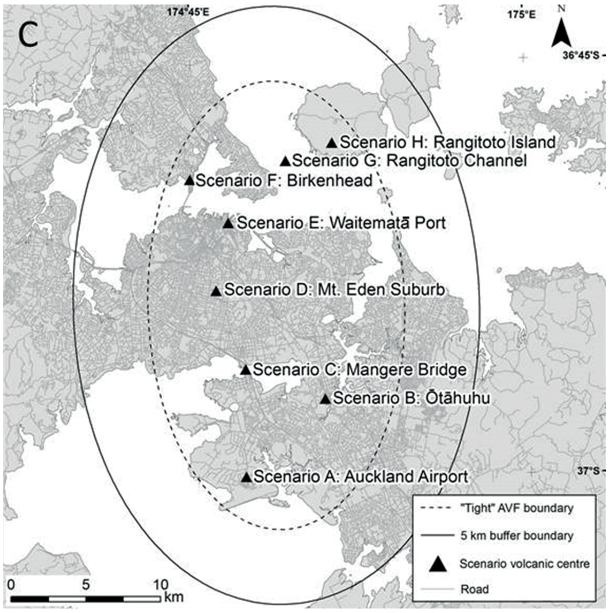

Figure 4. Location of Auckland Volcanic Field eruption scenarios.
Source: Hayes et al., 2018.

The AVF research contained four main phases:

1. development of a preliminary suite of hazard models and associated hazard intensity measures for those volcanic perils expected in Auckland (edifice formation, lava flow, pyroclastic density currents, ballistics, tephra, and gas);
2. amalgamation and curation of digitally-available asset data for Auckland buildings, infrastructure and people (previously this data could best described as ad hoc and key datasets tended to be split across different institutions);
3. development of a suite of Auckland-specific fragility models for assessment of direct impacts to the Auckland built environment (with a focus on buildings) for tephra fall, ballistics, pyroclastic density currents, and lava flows; and
4. testing of tephra fall, ballistics, pyroclastic density currents, and lava flow fragility models for a future AVF eruption scenario through a novel (deterministic) multi-volcanic-hazard impact assessment.

The results from the study showed loss estimates from the eight AVF eruption scenarios for buildings and associated clean-up costs ranged from NZD1.5B (eruption vent location on Rangitoto Island) to NZD63B (eruption vent in dense inner city suburb and heavy tephra fall across 90% of city) (Figure 4, Figure 5; Wilson et al., 2021). Building losses for all scenarios were dominated by pyroclastic density currents near the eruption vent, and tephra fall (when present) more generally. There is considerable variability in losses from the different scenarios, controlled mostly by location of eruption (exposure) and the type and size of particular volcanic hazards (namely pyroclastic density currents). Clean-up costs were shown to be high, which may be something that insurers haven't considered, if this is part of their mandate.

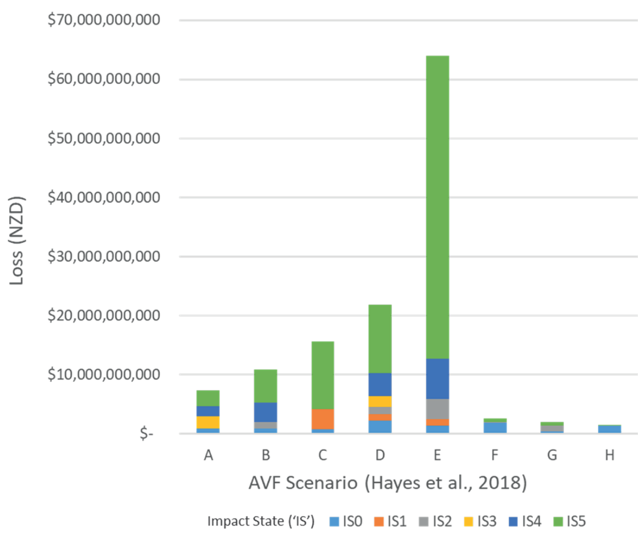

Figure 5. Modelled losses by AVF scenario.
Source: (Wilson et al., 2021.

The Auckland multi-volcanic-hazard loss model represents a considerable advance for the field. It demonstrates the feasibility of a multi-hazard model, and the utility of such a model for volcanic hazard risk management, including in the cost-benefit analysis of mitigation options (for example, the mitigation of tephra fall impacts where roof cleaning and/or bracing may provide damage control). There is clear benefit to considering dynamic multi-hazard impacts, due to the compounding nature of the impact. The model is already of substantial use to local government and emergency management authorities in the Auckland region, where more than a quarter of New Zealand's population lives on a volcanic field.

The next step is to develop this work into a national model. A new three-year phase is now in progress (as of 2021), and is focussed on three main objectives:

1. developing the framework, including methodology, for moving the existing deterministic multi-hazard (AVF) model, to a probabilistic multi-hazard model;
2. scoping the application of probabilistic loss models to Taranaki, Ruapehu, and Tongariro (stratovolcanoes) and Taupō Volcanic Zone (caldera volcanoes); and
3. developing the framework for a New Zealand Volcanic Hazard Risk Model (NZVHRM) and successfully incorporating it into New Zealand's probabilistic loss modelling platform (RiskScape).

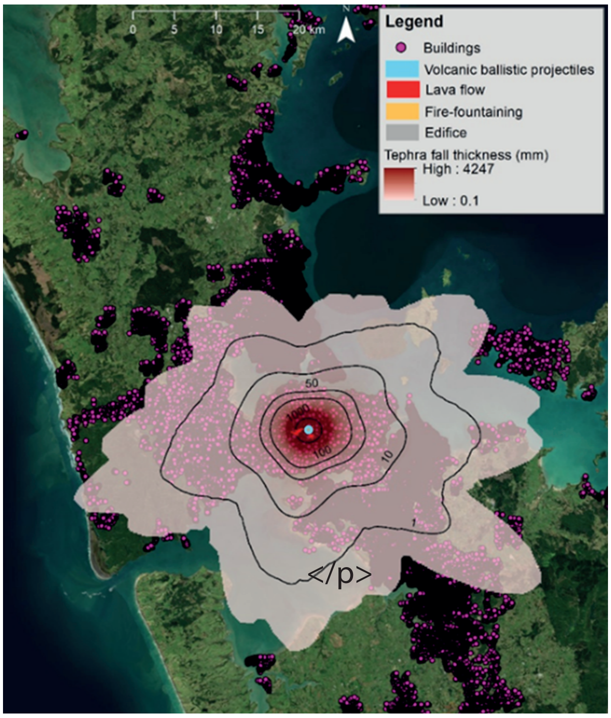

Figure 6. AVF scenario 'D'.
Source: Hayes et al., 2018.

An alternative approach to volcanic risk and impact assessment, potentially bridging the gap between the two dominant approaches (deterministic and probabilistic modelling; Marzocchi and Bebbington, 2012), is also being advanced in a New Zealand context. Ang et al. (2020) developed a hybrid, pseudo-probabilistic hazard model for the AVF, derived from a range of dynamic eruption scenarios. Weir et al. (in press, 2021) present a modular framework for stakeholder co-creation of multi-hazard, multi-phase eruption scenarios that incorporate spatial and temporal dependencies between hazards. The dynamic, hybrid approaches are thought to mitigate some of the limitations of both deterministic approaches (limited in the characterisation of multi-phase, multi-hazard risk, and uncertainty) and probabilistic (complex in development, use, and interpretation). The hybrid approach provides scientifically-credible scenarios that incorporate multi-phase complexity and uncertainty, but still provide a clear, effective knowledge-sharing mechanism for end users, particularly risk and emergency managers (Weir et al., in press, 2021). While potentially too nuanced for use in insurance and reinsurance calculations, these methods hold great potential for better hazard risk management and major event preparedness.

Conclusion

New Zealand's geographic position on the subducting plate boundary between the Australian and Pacific plates means the country is particularly prone to natural hazards such as earthquakes, tsunamis, floods, landslides and volcanoes. The country's volcanoes are mostly well characterised and understood thanks to a long history of volcano science as well as comprehensive indigenous knowledge and oral histories. Despite a history of small-to-moderate eruptions over the last 25 years, some with devastating loss of life, there has not been a large or widespread damage-causing eruption for many decades.

As a nation, we know, however, it is a case of when, not if, the next 'big one' will come. This is reflected in the end-to-end approach to volcanic hazard risk management activity in the country: comprehensive volcano monitoring through GeoNet, New Zealand's geohazards monitoring system, a wealth of investment in volcanology and volcanic risk research programmes, a series of regional and national multi-disciplinary platforms designed for stakeholder collaboration and coordination, an advanced risk and loss modelling capability, and insurance coverage via public and private insurance providers. New Zealand's emergency management authorities are also well-tested through a series of exercises and natural hazard events over the last 10-15 years.

Volcanoes never fail to surprise, though, as the Spanish authorities on La Palma can surely attest. The goal in New Zealand is to understand our risk to the greatest possible extent, and plan and build capability and capacity for adaptive response. Learning from others, as in this volume, is a critical additional step, helping to put us in the best possible position to anticipate and manage any volcanic crises that come our way.

References

Ang, P.S., Bebbington, M.S., Lindsay, J.M., Jenkins, S.F. (2020). From eruption scenarios to probabilistic volcanic hazard analysis: An example of the Auckland Volcanic Field, New Zealand. *J. Volcanol. Geotherm.* Res. 397. doi: 10.1016/j.jvolgeores.2020.106871.

Barker, S.J., Wilson, C.J.N., Illsley-Kemp, F., Leonard, G.S., Mestel, E.R.H., Mauriohooho, K., & Charlier, B.L.A. (2021) Taupō: an overview of New Zealand's youngest supervolcano, *N. Z. J. Geol. and Geophys.,* 64:2-3, 320-346. doi: 10.1080/00288306.2020.1792515.

Bebbington, M. S. (2013a). Assessing spatio-temporal eruption forecasts in a monogenetic volcanic field. *J. Volcanol. Geotherm.* Res. 252, 14–28. doi: 10.1016/j.jvolgeores.2012.11.010.

Bebbington, M. S. (2013b). Models for temporal volcanic hazard. *Stat. Volcanol.* 1, 1–24. doi: 10.5038/2163-338x.1.1.

Cronin, S.J., Zernack, A.V., Ukstins, I.A., Turner, M.B., Torres-Orozco, R., Stewart, R.B., Smith, I.E.M., Procter, J.N., Price, R., Platz, T., Petterson, M., Neall, V.E., McDonald, G.S., Lerner, G.A., Damaschcke, M., & Bebbington, M.S. (2021) The geological history and hazards of a long-lived stratovolcano, Mt. Taranaki, New Zealand, *N. Z. J. Geol. and Geophys.,* 64:2-3, 456-478. doi: 10.1080/00288306.2021.1895231.

Fitzgerald, R., Wilson, T.M., & Weir, A. (2021) Major volcanic hazard, impact and risk research platforms New Zealand.

Gerstenberger, M.C., Van Houtte, C., Abbott, E.R., Van Dissen, R.J., Kaiser, A.E., Bradley, B., Nicol, A., Rhoades, D.A., Stirling, M.W., Thingbaijam, K.K.S. (2020) New Zealand National Seismic Hazard Model framework plan. *GNS Science Report 2020/38.* doi: 10.21420/NB8W-GA79.

Hayes, J.L., Tsang, S.W., Fitzgerald, R.H., Blake, D.M., Deligne, N.I., Doherty, A., Hopkins, J.L., Hurst, A.W., Le Corvec N., Leonard, G.S., Lindsay, J.M., Miller, C.A., Németh, K., Smid, E., White, J.D.L., Wilson, T.M. (2018) The DEVORA scenarios: multi-hazard eruption scenarios for the Auckland Volcanic Field. Lower Hutt, N.Z.: *GNS Science Report* 2018/29. doi: 10.21420/G20652.

Hopkins, J.L., Smid, E.R., Eccles, J.D., Hayes, J.L., Hayward, B.W., McGee, L.E., van Wijk, K., Wilson, T.M., Cronin, S.J., Leonard, G.S., Lindsay, J.M., Németh, K., & Smith, I.E.M. (2021) Auckland Volcanic Field magmatism, volcanism, and hazard: a review, *N. Z. J. Geol. and Geophys.,* 64:2-3, 213-234. doi: 10.1080/00288306.2020.1736102.

Hurst, T., and Smith, W. (2010). Volcanic ashfall in New Zealand – probabilistic hazard modelling for multiple sources. *N. Z. J. Geol. Geophys.* 53, 1–14. doi: 10.1080/00288301003631129.

Kilgour, G.N., Kennedy, B.M., Scott, B., Christenson, B.W., Jolly, A.D., Asher, C., Rosenberg, M., & Saunders, K.E. (2021) Whakaari/White Island: a review of New Zealand's most active volcano, *N. Z. J. Geol. and Geophys.,* 64:2-3, 273-295. doi: 10.1080/00288306.2021.1918186.

Marzocchi, W., Bebbington, M.S. (2012) Probabilistic eruption forecasting at short and long time scales. *Bull. Volcanol.* 74, 1777–1805. doi: 10.1007/s00445-012-0633-x.

Leonard, G.S., Cole, R.P., Christenson, B.W., Conway, C.E., Cronin, S.J., Gamble, J.A., Hurst, T., Kennedy, B.M., Miller, C.A., Procter, J.N., Pure, L.R., Townsend, D.B., White, J.D.L., & Wilson, C.J.N. (2021) Ruapehu and Tongariro stratovolcanoes: a review of current understanding, *N. Z. J. Geol. and Geophys.,* 64:2-3, 389-420. doil: 10.1080/00288306.2021.1909080.

Smith, W. D., and Berryman, K. R. (1986). Earthquake hazard in New Zealand: inferences from seismology and geology, in *Recent Crustal Movements of the Pacific Region, Vol. 24,* eds W. I. Reilly and B. E. *Harford Wellington: Bulletin Royal Society,* 223–243.

Stirling, M. W., Wesnousky, S. G., and Berryman, K. R. (1998). Probabilistic seismic hazard analysis of New Zealand. *N. Z. J. Geol. Geophys.* 41, 355–375. doi: 10.1080/00288306.1998.9514816.

Stirling, M. W., McVerry, G. H., and Berryman, K. R. (2002). A new seismic hazard model for New Zealand. *Bull. Seismol. Soc. Am.* 92, 1878–1903. doi: 10.1785/0120010156.

Stirling, M. W., McVerry, G. H., Gerstenberger, M. C., Litchfield, N. J., Van Dissen, R. J., Berryman, K. R., et al. (2012). National seismic hazard model for New Zealand: 2010 update. *Bull. Seismol. Soc. Am.* 102, 1514–1542. doi: 10.1785/0120110170.

Stirling, M.W., Bebbington, M.S., Brenna, M., Cronin, S.J., Christophersen, A., Deligne, N.I., Hurst, T., Jolly, A.D., Jolly, G., Kennedy, B.M., Kereszturi, G., Lindsay, J.M., Neall, V.E., Procter, J., Rhoades, D.A., Scott, B.J., Shane, P., Smith, I.E., Smith, R., Wang, T., White, J., Wilson, C.J., & Wilson, T. (2017). Conceptual Development of a National Volcanic Hazard Model for New Zealand. *Frontiers in Earth Science,* 5, 51. doi: 10.3389/feart.2017.00051.

Wilson, T.M., Fitzgerald, R, Allen, N, Hayes, J.L. & Deligne, N.I. (2021) Overview of the National Volcanic Hazard and Risk Model. *Presentation to DEVORA Annual Forum.*