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# The communication of volcano information in New Zealand – a narrative review

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**ABSTRACT**

Communication of volcano information is critical for effective volcanic risk management. A variety of information is communicated to inform decisions and guide actions for planning, preparedness, and response. Such information needs to be reliable, and fit-for-purpose across different stages of volcanic activity (quiescence, unrest, short or long-term eruptive stages, and the post-eruptive stage). However, an understanding of communication across these different stages of volcanic activity remains limited. We undertook a narrative review of New Zealand literature to explore what information is communicated about volcanoes, across which stages of activity and by whom. Results highlight that NZ literature only documents certain aspects of volcano information and communication, specifically regarding certain locations, stages of volcanic activity (i.e. quiescence or unrest), or hazards. Literature gaps exist regarding volcano communication during unrest and post-eruptive stages, as well as how volcano information evolves between these phases, and how decision-makers use such information. Additional work would be useful to document existing examples of volcano information for different stages of activity. Further research could help in understanding the information needs of decision-makers during each of these stages to improve information and communication.

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## Introduction

The North Island of New Zealand (NZ; known as Aotearoa in te ao Māori) is home to multiple active volcanic centres (Figure 1), which are closely monitored for activity (Miller and Jolly 2014). Over the past decades, eruptions have occurred at different volcanoes generating explosions, lahars, landslides, ballistic ejecta, pyroclastic density currents, and ashfall (Table 1). These events have caused casualties, economic losses, and damage to infrastructure and the environment, and have affected public health (Hickling et al. 1999; Johnston et al. 2000; Becker et al. 2001; Newnham et al. 2010). The 2019 Whakaari (White Island) eruption was the most recent significant event, marked by violent blasts that resulted in 22 fatalities and caused serious burn injuries to several survivors (Zanini and Bennett 2024).

To manage volcanic risks, a variety of approaches are adopted, with communication playing a crucial role. During pre-eruptive stages, communication improves understanding of hazards, educates on preventive actions, and supports planning and inter-agency relationships. During and after eruptions, communication guides decision-making and addresses short- and long-term needs of affected parties. Organisations like GNS Science, National Emergency Management Agency (NEMA), Civil Defence Emergency Management (CDEM) groups, councils, Department of Conservation (DOC), science advisory panels, indigenous Māori groups (iwi, hapū), environmental agencies, infrastructure agencies, health authorities, the aviation industry, research agencies, and other stakeholders are integral in this communication process – generating, receiving, reworking, and sharing volcano information to cater to diverse audiences with varying information needs.

Information about volcanic activity is communicated using multiple channels including meetings, presentations, publications, public lectures, radio, television broadcasts, and websites. Emails, fax, phone calls, emergency mobile alerts, and short text messages (SMS) are also used to quickly disseminate scientific information to different stakeholders and registered

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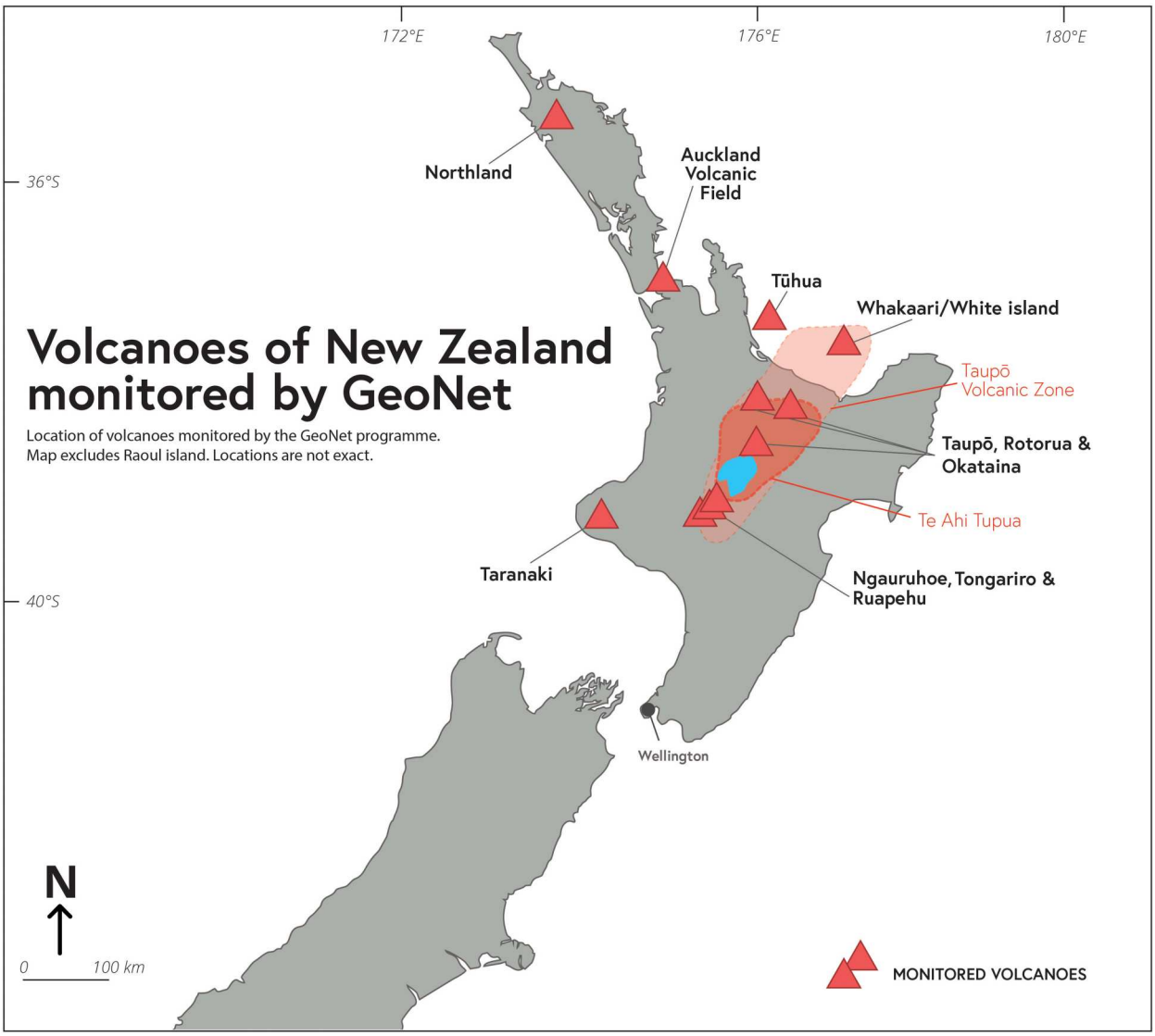



**Figure 1.** Location of New Zealand's active volcanoes and volcanic centres or fields – Bay of Islands – Kaikohe Volcanic Field, Whangarei Volcanic Field, Auckland Volcanic Field, Tūhua Mayor Island, Whakaari White Island, Okataina Volcanic Centre, Rotorua Caldera, Maroa Volcanic Centre, Taupō Volcanic Centre, Tongariro Volcanic Centre, Taranaki Mt Egmont, Kermadec Group – Raoul Island, Macauley Island-Brimstone Island, and the 'Rumble' submarine volcanoes (map excludes Raoul Island, Macauley Island-Brimstone Island, and the 'Rumble' submarine volcanoes, which are considered as part of the 14 active volcano areas).

end-users (Potter et al. 2014). Social media represents an emerging eruption communication avenue; however, little is documented about it in NZ-specific literature (Kotlarsky et al. 2022).

Ensuring consistent, reliable, and fit-for-purpose communication among the different agencies across different stages of volcanic activity is essential to minimise risks and reduce disruptions (García and Mendez-Fajury 2018; Andreastuti et al. 2023). Yet, there is limited understanding of what communication is happening by whom and to whom in specific stages and how it affects decision-making and actions.

This paper synthesises existing literature in a narrative literature review to explore these questions. The insights gained from this study will help to improve hazard and risk communication and decision-making, enhance emergency communications and early warnings, and ensure that information provided is accessible and purposeful. It will contribute towards enhancing disaster preparedness for response, which is one of the goals of the Sendai Framework for Disaster Risk Reduction (SFDRR), to which NZ is a signatory (UNDRR 2015).

## *Organisations involved in volcano communication: An overview*

GNS Science is responsible for providing scientific and technical information about volcanoes' status (Department of the Prime Minister and Cabinet 2015). Through the GeoNet project, New Zealand's geological hazards are continually monitored across all stages (Potter et al. 2018). GeoNet is a collaboration between multiple organisations including the Natural Hazards Commission Toka Tū Ake (previously Toka Tū Ake EQC), GNS Science, and Land Information New

**Table 1.** Summary of major eruptions, incidents, and impacts in New Zealand recorded over the last two hundred years. In addition to the above, multiple unrest and eruptive events have been recorded, like Ruapehu eruptions in 2007, unrest in Taupō volcanic zone from 1983 onwards, eruptions at Whakaari/White Island from 1960s onwards, Tongariro eruption in 1975, Ngauruhoe eruptions in 1974/75 and a small event in 1977, Ruapehu eruption in 1969, Mt. Ngauruhoe eruptions in 1954–55, and Tongariro eruptions in 1896–97. These have not caused widespread impacts; however, they highlight the extent of volcanic activity in New Zealand (Barker et al. 2021; Kilgour et al. 2021; GNS Science 2024a).

| Volcanic activity/incident | Event type and impacts |
|---|---|
| Whakaari/White Island eruption, 2019 | Explosive eruption, claimed 22 lives, impact on tourism, economic costs to organise rescue operations and compensation claims (Baker et al. 2022). |
| Te Maari Craters eruptions, Tongariro Volcanic Centre, 2012 | Series of eruptions. Ash emissions. Small lahar near eruption site. Damaged sections of the Tongariro Alpine Crossing, affected vegetation. No fatalities reported (Department of Conservation 2012). |
| Ruapehu eruptions, 1995–1996 | Major eruptions causing ashfalls, lahar, and pyroclastic fall deposits, damaged infrastructure like roads, disrupted local economy, tourism, agriculture, and electricity supply affected. No reported casualties. Economic costs of ~130 million NZD (Johnston et al. 2000). |
| Tangiwai disaster, caused by lahar, 1953 | A lahar triggered by Ruapehu crater lake wall collapse destroyed a railway bridge and caused a passenger train to derail. 151 persons were killed (Johnston et al. 2000). |
| Ruapehu eruptions, 1945 | Eruption and ashfall, lasted months, impact on agriculture, water, and electricity supply, no casualties reported (Johnston et al. 2000). |
| Whakaari/White Island eruption, 1914 | Explosive eruption and lahar, claimed 10 lives (Kilgour et al. 2021). |
| Tarawera eruption, 1886 | Massive eruption near Rotorua, estimated to kill about 120 people and caused significant economic losses (Rowe et al. 2021). |

Zealand (LINZ), and is responsible for volcanic eruption monitoring (Potter et al. 2014). GeoNet communicates the status of current activity for each volcano (Gentle et al. 2016; Potter et al. 2018). Volcanic alert levels (VAL) are assigned based on interpretation of observations (Potter et al. 2014). VALs range from 0 to 5 and provide information on volcanic activity and most likely hazards in each level.[1] This living information is available on a website and application but is only actively written about and broadcast when changes occur (i.e. when unrest begins, communicated by a change to VAL 1) or to provide an update, via Volcanic Activity Bulletins (VABs), news stories, or YouTube videos, which often go out via social media. In addition to volcanic status, GNS Science, through its website (www.gns.cri.nz) provides a wide range of other information about volcanoes in NZ, like historical details, the hazards they pose, and preparedness and mitigation actions (including links to international information).

NEMA and local CDEM groups are the lead government agencies at the national level and regional level, respectively, mandated through legislation to manage an emergency caused by natural hazards, including volcanic eruption (Ministry of Civil Defence and Emergency Management 2002; Department of the Prime Minister and Cabinet 2015). In the quiescence stage the agencies are involved in raising hazard awareness (e.g. through public education websites like GetReady (National Emergency Management Agency 2024)), and improving preparedness (e.g. through developing contingency plans), while during and post eruption they have active response roles and are involved in public information management (PIM) and co-ordination between different agencies through crisis incident management (CIM) (Auckland Emergency Management, March 2015).

DOC is responsible for managing volcanic risks within conservation areas, like Tongariro National Park where active volcanoes Mounts Ruapehu, Tongariro, and Ngauruhoe are located. DOC provides visitor safety information and up-to-date advice based on VAL and VABs, and works in close co-ordination with different agencies like GNS Science, iwi and hapū, emergency management agencies, science advisory panels, and other stakeholders to reduce volcanic risks within its jurisdiction (Department of Conservation 2023).

Agencies, including the Civil Aviation Authority (ensures safe aircraft operations near volcanic ash, establishes volcanic hazard zones, publishes information and other relevant materials), MetService (provides volcanic ash advisories and graphics (VAA and VAG, respectively), significant meteorological information (SIGMET) and other information for aviation industry), Airways NZ (issues notices to airmen (NOTAMs), collects and disseminates Volcanic Activity Reports (VARs), and ensures updated volcanic ash SIGMETs are passed to stakeholders), GNS Science (adjusts VAL and Aviation colour code (ACC) and issues VAB and Volcano Observatory Notices for Aviation (VONA)), and aircraft operators (provide VARs) have defined roles in monitoring, reporting, and managing volcanic ash hazards for aviation.[2]

Māori iwi and hapū are important partners in the volcano risk management process who work closely with governmental agencies to reduce risks for the local community (Murray et al. 2015; Gabrielsen et al. 2017). Regional and local councils, emergency service agencies (e.g. police, fire and emergency services, ambulance service), sector specific agencies (e.g. health, critical infrastructure) provide support to emergency management functions to minimise impact on life and property. Universities and research institutes (like the National Institute of Water & Atmospheric Research, NIWA) play a consultation

role providing knowledge advice and scientific inputs. The media is another key stakeholder that relays information to the public.

To support agencies to work together in discussing and planning for volcanic activity, formally coordinated volcanic advisory panels or groups exist. The panels and groups typically comprise science agencies, universities, emergency managers, emergency responders, infrastructure agencies, Maōri iwi and hapū, MetService, central government representatives like DOC, health agencies, and agriculture agencies (Smith 2009; Doyle et al. 2015). Such forums improve capacity and communication, as seen before, during, and after the 2007 Ruapehu Crater Lake breakout lahar (Becker et al. 2017). At present there are five main advisory panels or groups in NZ: New Zealand Volcanic Science Advisory Panel (NZVSAP), Central Plateau Volcanic Advisory Group (CPVAG), Caldera Advisory Group (CAG), Taranaki Seismic and Volcano Advisory Group (TSVAG), and DEVORA (Determining Volcanic Risk in Auckland). NZVSAP is the national level advisory group formed to improve communication between scientists and responding agencies (Leonard et al. 2014; Doyle et al. 2015). NZVSAP fosters relationships between scientists and different agencies; develops and maintains plans, guidelines, and standard operating procedures (SoPs) to support multi-agency cross-disciplinary collaboration; and ensures timely and consistent science advice is provided during volcanic activity in order to inform government responses and public messaging (National Emergency Management Agency 2023). The regional scientific advisory groups (e.g. CAG, CPVAG) bring different agencies together for information sharing, response planning, informing science and research needs, and maintaining ongoing communication among the key stakeholders (Central Plateau Volcanic Advisory Group 2018). A core goal of these groups is to improve communication coordination and identify response processes in advance of an event, to prevent duplication or conflicting messages between organisations (Doyle and Paton 2017).

## Method

Information about volcanoes range from overviews of volcanoes (e.g. geographic profile, maps, hazard information) to impact and consequence information. Communication encompasses all communication happening before, during, and after a volcanic crisis, including exchanges between scientists, government agencies, various stakeholders, media, and the public (Pallister et al. 2019). Searches were conducted on Scopus and Web of Science databases using a combination of keywords related to volcano (volcano, caldera, lava, ashfall, tephra, pyroclastic, lahar), communication (communication, warning, messages, forecast, model, scenario, decision, alerts, information), and New Zealand (New Zealand, Ruapehu, Tongariro, Te Maari, Ngauruhoe, Taupo, Whakaari/White Island, Rotorua, Tarawera, Okataina, Taranaki, Auckland, Northland, Raoul Island, Tūhua/Mayor Island, Maroa, Macauley Island, Brimstone Island, and the Rumble). The search was limited to English language articles. No other limits were applied.

2775 articles identified from both databases were exported to a spreadsheet. After removing duplicates, we reviewed the information provided in the title and abstracts to exclude articles unrelated to communication. This left us with 64 articles on which a full-text review was conducted and based on the exclusion criteria (articles that were not focused on New Zealand volcanoes, those that were solely about communication technology, and those that were conceptual, experimental, or theory-based without reflecting current practice) were removed. 41 articles were selected for analysis. Reference lists of these articles were screened, and 13 additional articles selected for review.

During this stage we identified that academic literature found in formal databases were inadequate to provide a comprehensive understanding of volcano communication. Hence, we draw on 'grey' literature.[3] The websites of key agencies[4] and online search engines (e.g. Google, Bing) were searched with the above-mentioned keywords for research and technical reports, theses and dissertations, presentations and posters, policy, standards, and guideline documents. Thirty-five documents were identified as relevant and included in the review (this, however, does not imply an exhaustive review of grey literature). In total, 89 documents were reviewed. The process used to identify the relevant articles for the narrative review is described by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart (Figure 2). The articles were searched for themes (Gregory and Denniss 2018). Full text of the articles were read, the information relevant to the research questions were coded inductively,[5] following which the codes were condensed into candidate themes before developing the final themes. The findings report on a range of topics related to information and communication and focus on two aspects: (1) different types of information related to volcanoes (e.g. products, tools, plans, scenarios); and (2) communication processes (e.g. which stakeholders are involved, how messages are exchanged).

We organised the data obtained from the review into five different stages of volcanic activity from quiescence through to post-eruption. Volcanic activity can be categorised in five stages, (1) quiescence (period of inactivity when the volcano does not show signs of eruption); (2) unrest (increased seismic activity, deformation, indicating possible eruptions), (3) eruptive phase (duration of eruption, including lava flows, ashfall, lahars, and

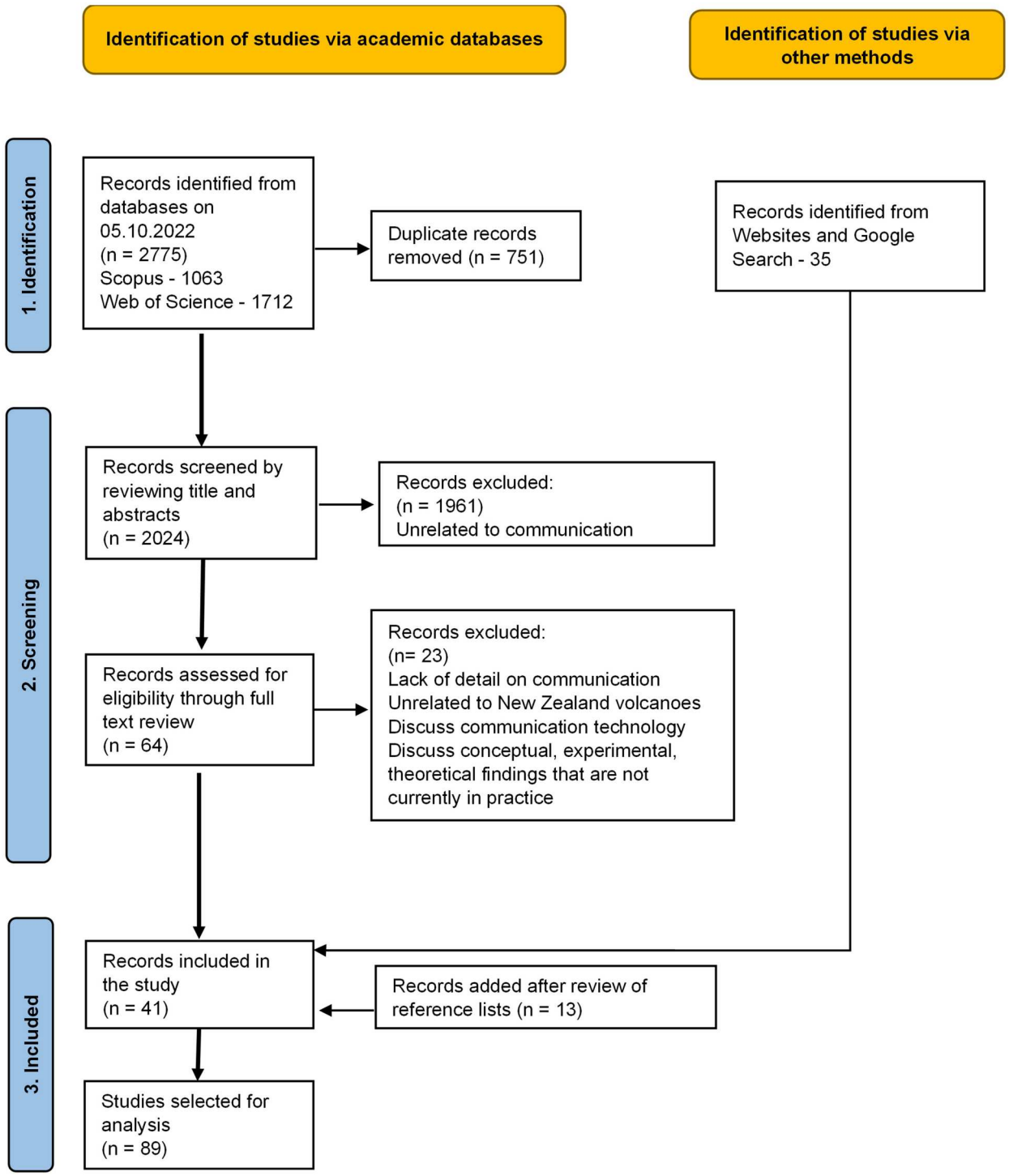



**Figure 2.** Preferred reporting items for systematic reviews and meta-analysis (PRISMA) flow chart for how the literature review was conducted.

secondary hazards like landslides), (4) post-eruptive stage (immediate aftermath of eruption, which can include impact assessment and emergency response activities) and (5) longer term recovery (stage that involved restoration of assets and activities affected by the eruption) (Figure 3). As illustrated in Figure 3, the character of volcanic episodes varies considerably, ranging from brief, sporadic eruptions to prolonged, continuous activity spanning months or years, e.g. the Pu'u'ō'ō eruptions with lava flows in Kīlauea, Hawaii, continued for over 35 years (Garcia et al. 2021). Volcanoes may go from quiescence or minor unrest to heightened unrest and back to minor unrest or quiescence without an eruption, e.g. Mt. Ruapehu in 2020–2021, where the VAL was raised from level 1 to level 2 and then returned back to level 1 without an eruption (Department of Conservation 2021). Consequently, the communication approaches differ depending on the volcano type, its behaviour, and transition of stages in the volcanic episode.

Our focus is on understanding the common communication aspects observed during the different stages,

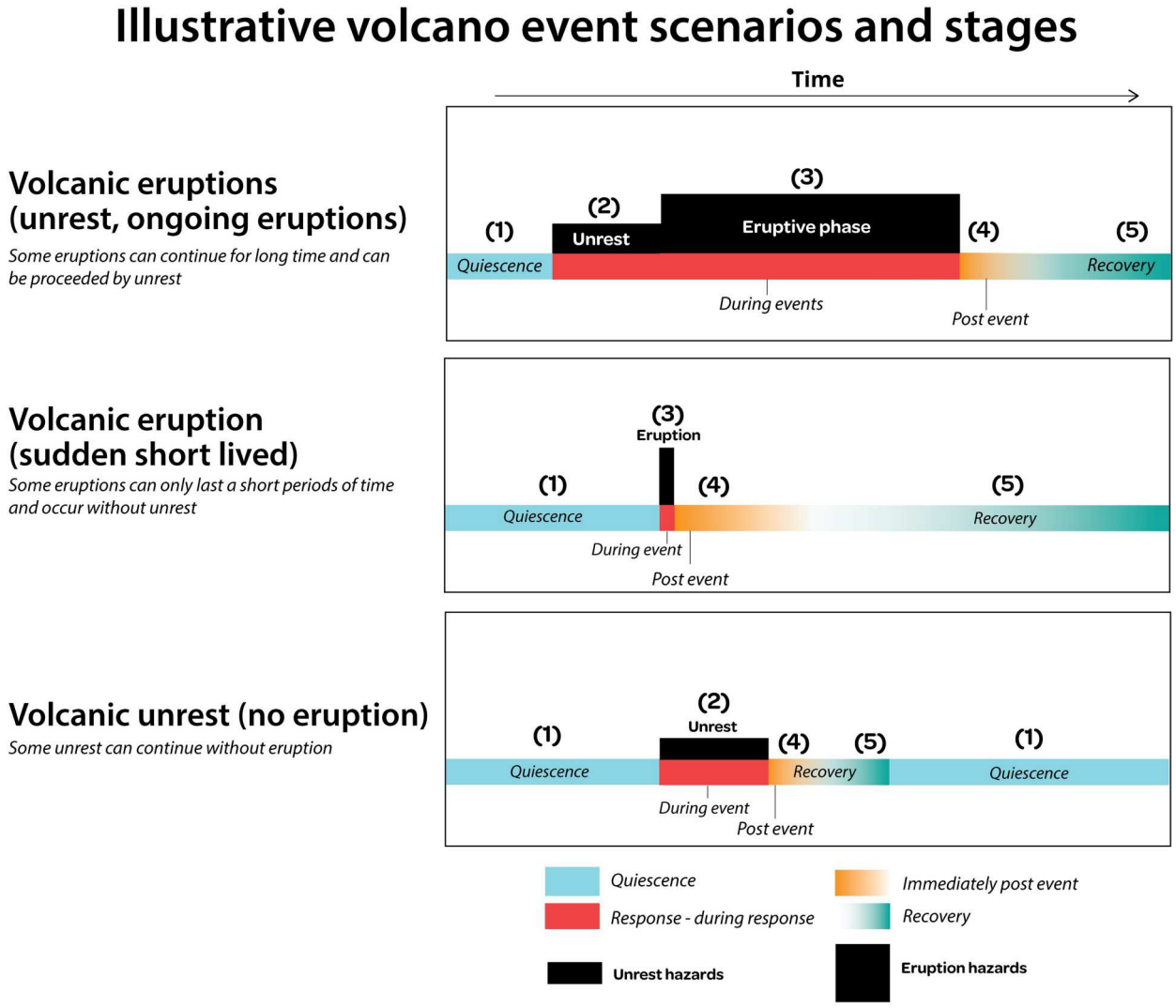



**Figure 3.** The figure presents three illustrative volcanic activity scenarios through time. The five stages of volcanic activity when the communication is happening are (1) quiescence, (2) unrest, (3) eruptive phase, (4) post-eruptive stage (directly after), and (5) longer term recovery. The first scenario shows a volcanic episode where the volcano shows unrest, followed by eruptions over a long time before entering the post eruption stage. The second scenario shows a short eruption stage without any unrest. The third scenario shows volcanic unrest without any eruption. We present three illustrative cases; there are many other variations in the progression of volcanic activity.

like quiescence or eruption, across these volcanic episodes. The findings are presented in five groups, each corresponding to the stages of volcanic activity. Due to the scant literature on post-eruptive stage (4) and recovery (5), these two stages are discussed together.

## Results

### *Information and communication during quiescence*

The quiescence stage is marked by inactivity. A volcano can remain quiescent for thousands of years (Siebert et al. 2015). During this stage, the purpose of communication is to advance understanding of volcanic hazards and risks, preparedness, mitigation, capacity building, and planning.

Public education is one of the key activities during quiescence. To advance public understanding of volcanic hazards and associated risks, maps, infographics, models, videos, fact sheets, and assessment reports are produced and disseminated by different agencies during this stage (Dohaney et al. 2015; Stewart et al. 2018; Saha et al. 2022), e.g. volcanic hazard maps created to visually communicate information about locations that could be affected by future volcanic eruptions (Civil Defence Taranaki Emergency Management 2022). Additionally, museums, observatories, and visitor centres provide information about the volcanic systems for different audiences. Volcanic centres like Tongariro National Park (TNP) and Taranaki attract national and international tourists (Erfurt-Cooper and Cooper 2010). In places like TNP, targeted information on possible hazards and mitigative actions are communicated through DOC signposts in exposed areas (Dhellemmes et al. 2016).

Research to improve existing volcano communication practices is an important aspect of this stage. Such studies include reviews of existing emergency communication and collaboration mechanisms (Becker et al. 2017; Doyle and Paton 2017), development and evaluation of warning arrangements (e.g. NZ's volcanic alert level system (Potter et al. 2014), the eruption detection or lahar warning system (Leonard et al. 2008)), and trials of innovative approaches towards public education like role-play simulation (Dohaney et al. 2015) or virtual field-trips (Saha et al. 2022). Pre-emptive development of public education and communication products based on scientific findings that might be required closer to volcanic eruption are also undertaken during this stage, e.g. guidance materials for public on actions to adopt before, during, and after eruptions (Ministry for Primary Industry 2012). Although an upward trend is observed where scientists are communicating science to media and the public, most often the target audience of the publications are decision-makers, officials, or fellow academics and scientists. The findings from academic publications are used by government agencies like NEMA or CDEM groups to produce simpler content like illustrative CDEM book series, infographic materials targeted at raising awareness of the public, or consistent messaging about volcanoes (National Emergency Management Agency 2023).

Capacity development initiatives for emergency preparedness enhance coordination capability of multiagency teams and improve their communication processes, knowledge and skills (Doyle et al. 2015). Regular planning meetings (National Emergency Management Agency 2023) and multi-agency exercises are often driven by emergency management authorities and first responders, such activities being common within emergency service training. For example, Exercise Ruaumoko was conducted between 2007 and 2008 and simulated the unrest through the eruption stage of an event in the Auckland Volcanic Field to practice co-ordinated inter-agency responses to an eruption, including the provision of coordinated science advice (Ministry of Civil Defence and Emergency Management 2008; Brunsdon and Park 2009). The outcomes of the exercise helped the stakeholders achieve a common operating picture, understand the coordination roles and processes, and identify areas for improvement (Doyle et al. 2015). Warning exercises, such as the lahar exercises conducted with staff and public regularly on Whakapapa ski field on Mt. Ruapehu, constitute opportunities for communicating risk, practicing, and building the capacity to respond (Leonard et al. 2008). Capacity development may be aligned with the aforementioned scenario planning, collaborative exercises, storyboarding, and simulations (Doyle and Paton 2017).

The quiescence stage is suitable for developing policies, plans, and guidelines for volcano preparedness and response. These can cover a range of topics, like SoPs, response and contingency plans, and establishing emergency operation centre (EOC) functions and procedures (Auckland Emergency Management, March 2015; Central Plateau Volcanic Advisory Group 2018; Department of Conservation 2023). Land use plans are used by authorities to reduce exposure to hazards. Taranaki provides an example of a place where land-use planning has attempted to address the lahar risk (Becker et al. 2010).

Information delivered via scenarios showing likelihoods of unrest, eruptions, hazards, and impacts posed may be used to help guide policy and planning. Scenarios can encompass exercises and simulations of a mock event to enhance response capability; be a rationalisation tool to support decision-making, planning or storyboarding to identify alternative futures; or be used as a form of communication product to convey potential futures (Doyle et al. 2015). Scenarios may be short or long term (from a short-lived eruption stage through recovery) and cover aspects such as the likelihood of a future scenario occurring, the hazards and risk that may occur, the geographic extent (e.g. through representation on a map), and impacts. Recent initiatives include the development of a suite of eruption scenarios for Auckland (Doyle et al. 2015; Deligne et al. 2017; Hayes et al. 2020; Cardwell et al. 2021; Wild et al. 2021), Taranaki (Weir et al. 2022), and scenario planning for calderas like Taupō Volcanic Centre (Calderon et al. 2020). These are used during quiescence to help with planning and exercising for an eruption response and pre-planning for recovery (Doyle et al. 2015; Deligne et al. 2017; Hayes et al. 2020; Cardwell et al. 2021; Wild et al. 2021).

Indigenous knowledge, or Mātauranga Māori, plays a key role in information, communication, and decision-making regarding volcanic risks. A case study from Ngāti Rangi, whose rohe (tribal area) includes Mt. Ruapehu, highlights the contribution Mātauranga Māori has on culturally relevant monitoring, information collection, and communication (Gabrielsen et al. 2017). Such contributions are relevant during times of quiescence, through involvement in unrest, response, and recovery. Perspectives on what could be communicated and how (e.g. via pūrākau, waiata, karakia / stories, songs, and prayer) differ from western perspectives, due to the intrinsic relationship that exist between Māori and the natural world such as their maunga and whenua (mountain and land), and constitute a unique communication consideration (Pardo et al. 2015). Thus, activities during quiescence include research on how indigenous knowledge and practices can inform volcanic risk management, co-creation of knowledge and resources, and formulation of partnerships to enable

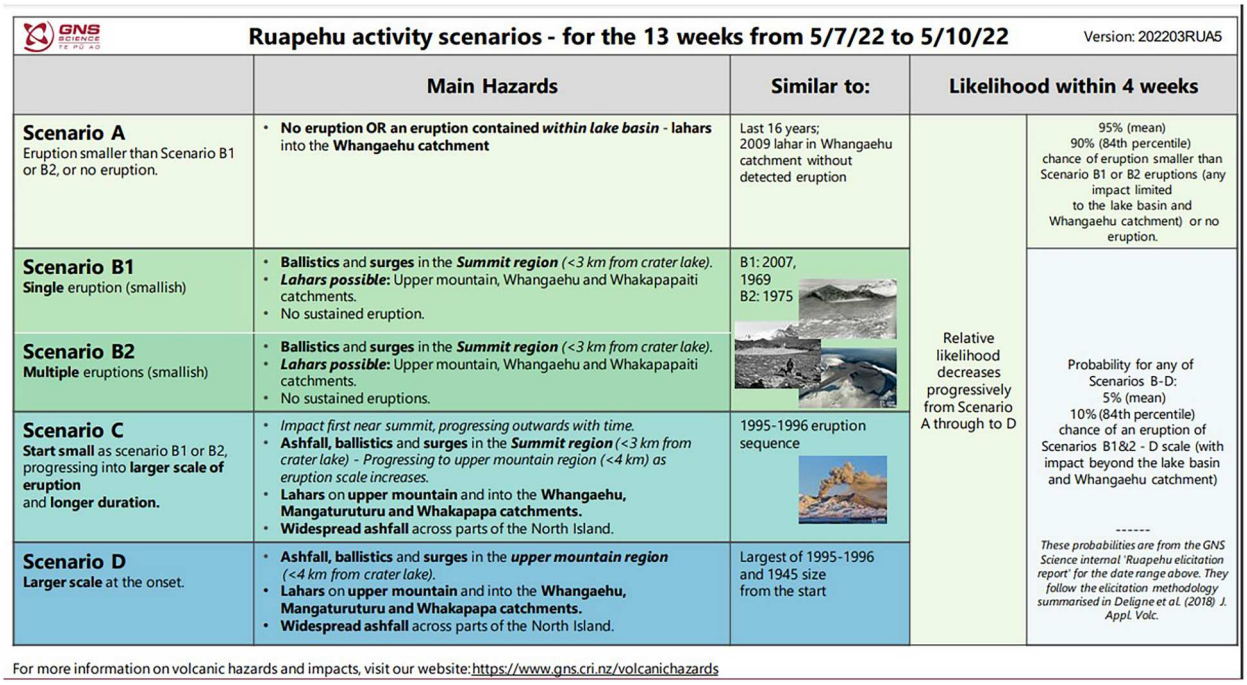
agencies work collaboratively during eruptive events (Jolly et al. 2014; Mayall-Nahi et al. 2021).

### *Information and communication during unrest*

Volcanic unrest is the interaction of magma or its associated fluids with rocks, groundwater, or hydrothermal fluids to produce noticeable signs such as seismicity, gas emissions, and surface deformation (Newhall et al. 2017). Unrest can be short or long-lived[6] and may or may not culminate in an eruption (Phillipson et al. 2013; Illsley-Kemp et al. 2021; Machacca et al. 2023).

Information about volcanic phenomena and risks are featured more often in media and public discussions during unrest stages. For example, Potter et al. (2015) analysed media articles to determine periods of historical unrest for Taupo Volcanic Centre and found that these articles communicated descriptions of felt earthquakes, subsidence, and other phenomena such as increases in gas emissions or hydrothermal eruptions. These communications mainly focussed on physical changes in the environment but do mention impacts on society (Johnston et al. 2002). Aside from such instances of communication, no other substantial communication about unrest periods has been documented in the NZ peer-reviewed literature. International unrest examples from volcanic centres such as Long Valley caldera, California, USA, (Peers et al. 2021) or Mt. St Helens, Washington, USA, (Driedger et al. 2004) could help guide thinking within NZ on this issue.

The 2022 Ruapehu and Taupō Volcano unrest periods have provided new opportunities to explore communication during this stage. During the ongoing 2022–2023 Taupo unrest episode, the need for communication focused on earthquakes and other unrest hazards, including possible ground movement, lake waves, landslides, and hydrothermal system responses, was recognised (GNS Science 2024a). Scientists have developed a series of scenario communication products for unrest events to share a range of alternative futures to assist agencies with their decision-making (Figure 4). For each explicit scenario (e.g. from a decrease in unrest, to a major eruption occurring) an example of a previous event is provided as an analogy, alongside potential hazards and the likelihood of that particular scenario occurring. Supporting information is given for context (e.g. maps, photographs, data, results from event trees). Particular hazards may be of greater interest to some agencies (e.g. ash for the aviation or agricultural industries), and scenarios and information for these may be communicated in advance (Guffanti et al. 2009; Stewart et al. 2018). At present, detailed scenarios are primarily conveyed to agencies (e.g. emergency management, critical infrastructure providers), rather than directly to the public. However, the public do receive condensed information about these scenarios through avenues such as the GeoNet VABs, news media, emergency management agencies, or the DOC. The information in these messages is tailored to the needs and interests of diverse audience groups, improving the understanding of the scenarios. Event-specific hazard maps (Central Plateau Volcanic Advisory Group 2012) are created during unrest, once a likely vent and the potential eruption size becomes more certain (Potter et al. 2014). Unrest scenarios can inform exercising



**Ruapehu activity scenarios - for the 13 weeks from 5/7/22 to 5/10/22** Version: 202203RUA5

| | Main Hazards | Similar to: | Likelihood within 4 weeks | |
|---|---|---|---|---|
| **Scenario A** Eruption smaller than Scenario B1 or B2, or no eruption. | • **No eruption OR an eruption contained *within lake basin*** - **lahars** into the **Whangaehu catchment** | Last 16 years; 2009 lahar in Whangaehu catchment without detected eruption | Relative likelihood decreases progressively from Scenario A through to D | 95% (mean) 90% (84th percentile) chance of eruption smaller than Scenario B1 or B2 eruptions (any impact limited to the lake basin and Whangaehu catchment) or no eruption. |
| **Scenario B1** **Single** eruption (smallish) | • **Ballistics** and **surges** in the ***Summit region*** *(<3 km from crater lake).* • ***Lahars possible*:** Upper mountain, Whangaehu and Whakapapaiti catchments. • No sustained eruption. | B1: 2007, 1969 B2: 1975 | | Probability for any of Scenarios B-D: 5% (mean) 10% (84th percentile) chance of an eruption of Scenarios B1&2 - D scale (with impact beyond the lake basin and Whangaehu catchment) |
| **Scenario B2** **Multiple** eruptions (smallish) | • **Ballistics** and **surges** in the ***Summit region*** *(<3 km from crater lake).* • ***Lahars possible*:** Upper mountain, Whangaehu and Whakapapaiti catchments. • No sustained eruptions. | | | |
| **Scenario C** **Start small** as scenario B1 or B2, progressing into **larger scale of eruption** and **longer duration.** | • *Impact first near summit, progressing outwards with time.* • **Ashfall, ballistics** and **surges** in the ***Summit region*** *(<3 km from crater lake) - Progressing to upper mountain region (<4 km) as eruption scale increases.* • **Lahars** on **upper mountain** and into the **Whangaehu, Mangatururu and Whakapapa catchments.** • **Widespread ashfall** across parts of the North Island. | 1995-1996 eruption sequence | | ------ *These probabilities are from the GNS Science internal 'Ruapehu elicitation report' for the date range above. They follow the elicitation methodology summarised in Deligne et al. (2018) J. Appl. Volc.* |
| **Scenario D** **Larger scale** at the onset. | • **Ashfall, ballistics** and **surges** in the ***upper mountain region*** *(<4 km from crater lake).* • **Lahars** on **upper mountain** and into the **Whangaehu, Mangatururu and Whakapapa catchments.** • **Widespread ashfall** across parts of the North Island. | Largest of 1995-1996 and 1945 size from the start | | |

For more information on volcanic hazards and impacts, visit our website: https://www.gns.cri.nz/volcanichazards

**Figure 4.** Ruapehu volcanic activity scenarios valid from 05/07/2022 to 05/10/2022 developed by GNS Science (2022).

needs, as observed during the 2022 Ruapehu unrest period, when an informal 'walkthrough' exercise was conducted, or for exercise Ruaumoko in Auckland where unrest was injected as part of the exercise (Lindsay et al. 2010).

### Information and communication during eruptive phases

Eruptions vary in style, size, extent, and duration even at the same volcano (Mastin et al. 2009; Kereszturi et al. 2014). Eruption hazards include ballistic projectiles, ash, pyroclastic surges and flows, gases, lahars, lava flows, landslides, and even seiches or tsunami where a large body of water is involved (Siebert et al. 2015).

External communication during eruptive stages has two specific foci: (i) dissemination of eruption details, and (ii) sharing of information necessary for response actions. Scientific information about the eruption and its details are communicated by GNS Science, which includes changes to VAL and Aviation Colour Code, issuance of VAB, and other relevant information (Potter 2014; Department of the Prime Minister and Cabinet 2015). Response advice is provided by CDEM groups, DOC, and other emergency service agencies (Auckland Emergency Management, March 2015; Civil Defence Taranaki Emergency Management 2022; Department of Conservation 2023). Depending on the extent of disruption, emergency management agencies (CDEM groups and NEMA) can declare a state of local or national emergency (Ministry of Civil Defence and Emergency Management 2002). Additional information, such as hazard maps, situation reports (sitreps), incident reports, live updates, information on things to do, and more, is disseminated by relevant agencies (Becker et al. 2001; Potter et al. 2014; Erfurt 2022). In the eruption phase the desire and need for science and response information by agencies increases, as does the public appetite. Messages targeted at the public are generated by key agencies, and these messages are then repeated by other communicators, like the media.

Additionally, information is shared within and between the different stakeholders responding to a crisis. For example, during the Ruapehu 1995–96 eruptions, DOC, GNS Science, ski field operators, police, local and national CDEM, and Regional/District Councils were some of the stakeholders communicating with each other (Johnston et al. 2000). In communication between these organisations, the information provided by the principal responding agency was used to generate further messages guiding decisions and actions. For example, this informed the DOC's update of visitor safety related information (e.g. track and hut closure information and maps). Since then, the arrangement of such agencies into panels and advisory groups has provided a mechanism for coordinating this communication, which was utilised for the 2012 Tongariro eruptions (Jolly et al. 2014).

In addition to these wider panels/groups, often sector specific organisations cluster together and closely interact with each other. For example, the Civil Aviation Authority (CAA) and the Meteorological Service closely coordinate to make aviation-related decisions based on volcanic activity information provided by GNS Science through the New Zealand Volcanic Ash Advisory System (Scott and Travers 2009; Stewart et al. 2018).[7] A substantial proportion of these interactions between the different stakeholders happen through telephone calls, emails, and face-to-face interactions (Stewart et al. 2018).

Warnings are a specific form of information and communication during eruptive phases. Mt. Ruapehu has an Eruption Detection System (EDS) in combination with two public facing warning systems at both the Whakapapa Ski Field and Whakapapa Village. These are designed primarily to address and alert the public of potential lahar through the ski field and downstream village. The Eastern Ruapehu Lahar Alert and Warning System (ERLAWS) was designed to address the 2007 Ruapehu Crater Lake breakout lahar, and while recently decommissioned, the system was used collectively by agencies in response to the 18 March 2007 lahar that flowed down the Whangaehu catchment (Keys 2007; Massey et al. 2010). The public received notification via mobile phone text message (Becker et al. 2017), albeit somewhat delayed due to network issues. A key to these effective responses, however, is ensuring communication and public education take place during quiescence, to build people's understanding and capacity to respond correctly when the warning is issued (Leonard et al. 2008).

Hazard or eruption phenomena maps and visualisations are key tools for supporting communication about potential danger and distribution of eruption products during different stages – work is ongoing to understand the value of these maps as a communication tool (Leonard et al. 2014; Thompson et al. 2015; Thompson et al. 2017a; Clive et al. 2021). Additionally, future-focussed scenarios have not been widely used as an information and communication tool during eruptive stages. An eruption scenario was trialled during the 2019 Whakaari eruption, several days after the main eruption had occurred on 9 December, where the likelihood of one future scenario occurring was communicated to stakeholders and the public via GeoNet and risk maps were developed for stakeholders to help responders with decision-making (Becker et al. 2023). However, we could not find any specific examples in the existing NZ literature.

NZ literature on information and communication during the eruption phase is focused on TNP volcanoes, due to the impact of their recent eruptions. Little or no differentiation is made for communication related to sudden short-lived eruptions versus ongoing eruptions, which may be due to only one longer duration eruptive episode occurring at TNP in the past 50 years (Ruapehu 1995–96). It is noteworthy that an eruption does not necessarily mean a crisis (e.g. GNS Science 2006). In such cases, communication is used to maintain a close watch on the situation and inform about preparedness actions to be taken if there is escalation. Communication happening throughout the eruption stage has direct implications on how response and recovery unfold (Ronan et al. 2000).

### *Information and communication during post-eruptive stages*

Compared to other stages, provision of information and communication in the post-eruptive stages is the least researched. The studies that do exist indicate that discrete streams of information and communication appear during this stage catering to emerging needs. These streams are often local in scale, centred around providing contextualised information for affected response agencies and communities. For example, after the 2012 Tongariro eruption, DOC held meetings in collaboration with GNS Science, civil defence teams, iwi, and other responding agencies (e.g. police, fire service, utility infrastructure providers, NZ Transport Agency) to coordinate the ongoing response and provide information (Jolly et al. 2014). Health agencies, welfare agencies, insurance and compensation agencies, and other stakeholders assist in the preparation of post-eruption messages and advice specific to their responsibilities (Gisborne CDEM Group 2012).

Cascading or longer duration hazards in the post-eruption phase have required particular attention. One example includes the Ruapehu Crater Lake where different scenarios were modelled to determine the hazard and risk of a break-out lahar following the 1995–96 eruptions (Hancox et al. 1997; Hancox et al. 1998; Keys and Green 2008), and a lahar warning system was planned (Galley et al. 2004) and developed (Becker et al. 2017). Information and communication may be required for certain sectors such as agriculture, which may experience ongoing and potentially cascading effects from ashfall (Thompson et al. 2017). Demand for information on ashfall clean-up (e.g. guidance on appropriate clean up methods, safe disposal of ash) is a big component of this phase (Hayes et al. 2015; Stewart et al. 2018).

Post-eruption agency debriefs, and enquiries comprise a component of information and communication during this stage, with a view to improving response and communication processes in the future. Debriefs regarding actual volcanic activity (e.g. Ruapehu 1995–96 in Keys and Williams (1996)) are used after exercises to understand how response, including information provision and communication might be improved in future (e.g. for the 1992 Exercise Nga Puia, Okataina (Martin 1992); or the 2007–08 Exercise Ruaumoko in Auckland (Ministry of Civil Defence and Emergency Management 2008)).

Similar to the immediate post-event eruptive stage, there is a research gap on volcano communication in the recovery stage in NZ. NEMA and CDEM groups host information on their websites about short-term recovery actions after an eruption (National Emergency Management Agency 2022), which could be referred to for information and consistent messaging. Occasionally in the quiescence stage, scenarios have been used to inform recovery planning processes (Cardwell et al. 2020, 2021; Hayes et al. 2020). However, in the post-eruption and recovery stages scenarios have been less utilised, and if they have been used, it has been only in an ad-hoc way.

Given the limited research in NZ on volcano information and communication in the recovery stage, issues and lessons identified in international literature can be useful to inform recovery communication practice in the country, e.g. how communication can address feelings of uncertainty (Sword-Daniels et al. 2016), or considerations to ensure community participation in recovery processes (Stewart et al. 2018).

## Discussion

Figure 5 and Table 2 summarise the results of our review of volcano literature.

The review highlights the evolving nature of information and communication in different stages of volcanic activity, in terms of topics, frequency, level of tailoring, and purpose. Although scientific information about the current physical status of a volcano is always available (e.g. via the VAL, VABs, and news items on GeoNet), the need for more frequent and detailed information increases throughout unrest, eruption, and post-eruption stages (Leonard et al. 2014). During quiescence, communication focuses on public education and science communication, planning for volcanic events, building response capacity across agencies and the public, and improving emergency communication and warning systems. During unrest, communication focuses on information regarding physical science, what might happen in future (e.g. via scenarios), and response planning. In the eruptive phase, communication provides updates on the volcano's physical status, potential hazards, warnings, emergency declarations, situation

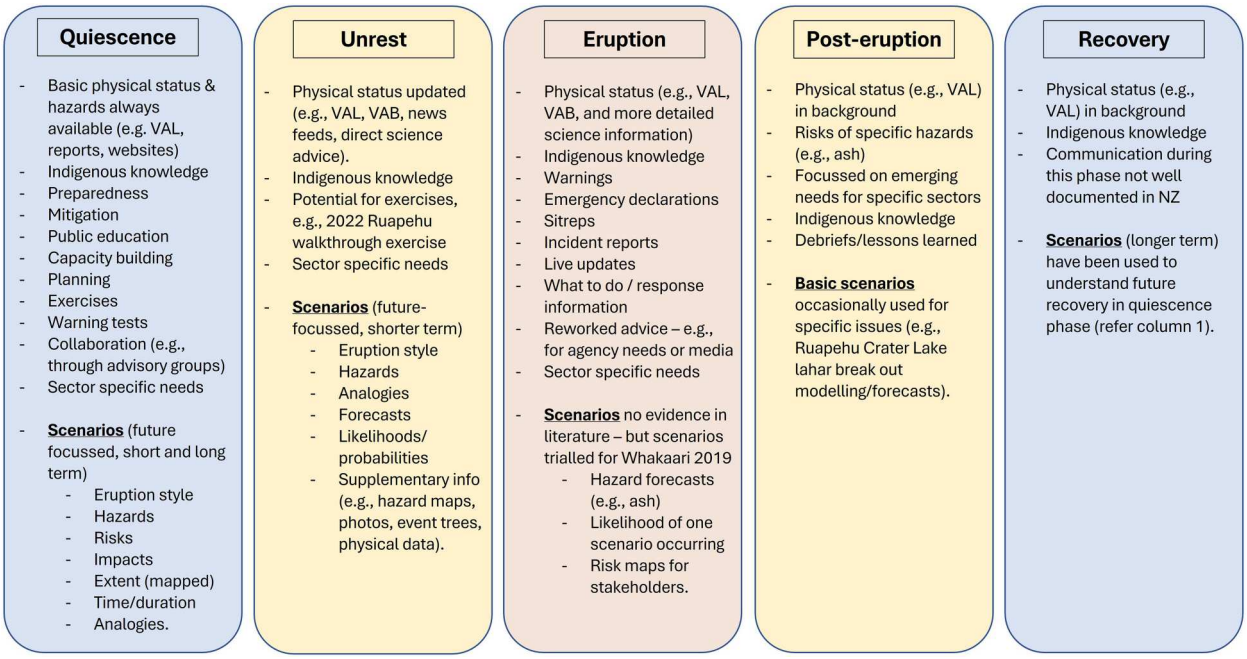



**Figure 5.** Information and communication activities across different stages of volcanic activity – Summary of findings from review of New Zealand-specific literature and supplementary grey literature (VAL = Volcanic Alert Level; VAB = Volcano Alert Bulletin).

and incident reports, and advice for emergency management decisions. In the post-eruption and recovery stages, communication is more tailored to the emerging needs of specific sectors. We note that scenarios in relation to volcano communication can refer to a range of initiatives across the emergency management sector (e.g. scenario planning, storyboarding and identifying futures, exercising and training timeline scenarios, decision aids, and communication products; e.g. Doyle et al. 2015) and outline their usage in the different stages.

Despite the diversity of material, our findings highlight some gaps worthy of future consideration. Firstly, most studies and documents report on information and communication during quiescence and eruption, focused on central north island volcanoes, probably because of their recent eruptive events. Scant literature exists on volcano information and communication during unrest, post-eruptive, and recovery stages. This gap is problematic because without relevant examples of how volcano communication unfolds during these stages, it is not possible to identify the emerging communication needs, concerns and challenges and undertake necessary improvements. Given that information about communication during unrest does exist in supporting documents (e.g. VABs, reports, and grey literature), these documents could be collated and published as case studies. Additionally, looking at international examples through analogue volcanoes and global crises and drawing strategies from global best practices would help in informing communication during these stages (Doyle and Becker 2022).

Secondly, a related issue is the transition and evolution of information and communication between the different stages. Transition of information between volcanic stages has not been explored in the NZ literature, particularly as volcanic activity escalates or de-escalates. For example, questions still exist around how we communicate changes in likelihoods or potential hazards as stages of activity change, and what this means for decision-making and inter-agency communication networks. These transitional aspects would benefit from future research.

Thirdly, further research would be beneficial to understand the decisions made across different stages and the corresponding information needs. For example, during the 2022 Taupō Volcano unrest, questions arose from decision-makers regarding how deformation might impact infrastructure and how this could be communicated and acted upon, but the NZ and international literature gives no guidance on this. It is possible that impact-based forecasts might be useful in the volcano context to help decision-makers understand what the issues might be, and to guide their responses, as has been explored in a severe weather context (Potter et al. 2021). The Taupo 2022 unrest, therefore, is but one example where emerging needs from decision-makers have provided an opportunity to think about what additional information and communication might be required. This example highlights that more social science research about what is useful from a decision-maker's perspective would be beneficial in filling in gaps about information and communication practices across different stages of activity.

Currently, evaluative research examining the effectiveness of existing communication practices in volcano risk management and prevention is limited.

**Table 2.** Communication roles and responsibilities of different agencies across stages of volcanic activity.

| Information and communication across stages of volcanic activity | | | | | | |
|---|---|---|---|---|---|---|
| | | | Key communication products/ communicative actions related to volcano communication (varies depending on location) | | | |
| Key stakeholders | Subgroups/projects | Roles and responsibility in volcano communication | Quiescence (Business as Usual) | Unrest | Eruption | Post-eruption | Recovery* |
| GNS Science | GeoNet and other research programmes | Monitor volcanic activity and provide science advice regarding volcanic activity | VAL, VAB, ACC, VONA | | | | |
| Volcanic advisory groups | CAG, CPVAG, TSVAG and DEVORA | Discussion and information sharing, relationship building among agencies and stakeholders, response planning | Form collaborative networks, provide information, develop preparedness and response plans, guide research directions, maintain ongoing communication | Typically no role (except possibly for Taranaki)* | | | |
| NZ Volcano Science Advisory Panel | Infrastructure, Health & Primary Industries subgroups | Event science advice and coordination among stakeholders. | Plan response including maintenance of documents like SoPs and contingency plans, conduct regular meetings, ensure interagency relationships are maintained, undertake relevant research | Provides scientific advice to response agencies, co-ordinate science decisions and actions, support consistent public messaging, international scientific liaison | | | |
| Dept. of Conservation | Eruption Detection System, Lahar Warning System. (both Ruapehu) | Volcanic risk management in DOC area (Tongariro NP, Taranaki NP) | Provide visitor safety information and advice, install and maintain risk signs in DOC area, maintain contact, plan response by developing guidelines and SoPs, engage in multi-agency drills and exercises, form collaborative networks | Public information management (for DOC area) and initial response until (if) CDEM/a volcanic advisory group takes over | | | |
| Emergency management agencies | NEMA, CDEM groups | Emergency management across 4Rs, reduction, readiness, response and recovery | Provide public education; build relationships and form collaborative networks; plan response by sharing information and developing contingency plans, guidelines, SoPs; develop capacity building activities like undertaking drills, multi-agency exercises | Public information management and response co-ordination role<br>Provide warning, alert, update, advice<br>Emergency declaration (if required)<br>Sitreps | | | |
| MetService, CAA & aviation industry | Wellington VAAC, Air Traffic Control. | Ash advisory to aviation industry (International Civil Aviation Organization obligations) and airspace management. | Monitor ash from volcanic events, provide public education, develop response and capacity building activities | VAA, VAG, Notam, Sigmet, expert advice and information for aviation industry | | | |
| Local Government | Regional council<br>District/city council | Support and assists in response<br>Regional council are responsible to provide hydrological data and flood warning | Support actions by other agencies | Relay information shared by other agencies, adds location specific information | | | |
| Sector specific agencies | Primary industry, health, infrastructure etc. | Support function based on sectoral requirements, e.g. provide information on status of networks to EOC/ ECC, taking appropriate response action etc. | Support actions by other agencies | Relay information shared by other agencies, adds sector specific information. Interact with NZVSAP subgroup. Interact with CDEM. | | | |
| Emergency service agencies | Police, FENZ, St. Johns | During and post event support and assistance to minimise impact on life and property | Support actions by other agencies | Relay information shared by other agencies, adds location specific information to minimise impact on life and property. | | | |
| Iwi | Hapū | Partners in volcano risk management | Integrate traditional knowledge (Mātauranga Māori) with scientific approaches, improve collaboration between community and agencies | Hazard communication to iwi and local community, extend support to different agencies | | | |
| Universities & research institutes | Different universities, NIWA etc. | Consultation role, members of scientific communities | Provide knowledge, advice, and scientific inputs | | | | |
| Media | Different media outlets | Disseminating news, information, and opinions to inform the public | Relay information shared by agencies; report on ground conditions, impacts, and issues; are typically more active during volcanic crisis | | | | |

Note: VAL: Volcanic Alert Level; VAB: Volcano Alert Bulletin; ACC: Aviation Colour Code; VONA: Volcano Observatory Notices for Aviation; CAG: Caldera Advisory Group; CPVAG: Central Plateau Volcanic Advisory Group; TSVAG: Taranaki Seismic and Volcanic Advisory Group; DEVORA: DeTermining Volcanic Risk in Auckland; SoPs: Standard Operating Procedures; CDEM: Civil Defence Emergency Management; NP: National Park; DOC: Department of Conservation; VAAC: Volcanic Ash Advisory Cenre; VAA: Volcanic Ash Advisory; NEMA: National Emergency Management Agency; CAA: Civil Aviation Authority; EOC: Emergency Operation Centre; ECC: Emergency Coordination Centre; Notam: Notices to airmen; Sigmet: Significant meteorological information; NZVSAP: New Zealand Volcanic Science Advisory Panel; FENZ: Fire and Emergency New Zealand.

*Communication activities in recovery may include other agencies/aspects depending on the specific eruptive event.

The studies that exist are mostly focused on emergency communication, warning, and response (e.g. Leonard et al. 2008; Doyle et al. 2015; Becker et al. 2017). Future research could adopt a wider lens, comprehensively examining how current communication practices correspond to the principles of different stages of emergency management – reduction, readiness, response, and recovery (Gabrielsen et al. 2017). Additionally, studies could also investigate the suitability of existing approaches in communicating to diverse stakeholders utilising clear evaluation parameters (e.g. speed, accuracy, ease of use). These would help in identifying areas where enhancements are necessary. Given scenarios are a well-utilised form of information provision and communication, future research would also be beneficial to consider what elements of scenarios could be consistent across the stages of volcanic activity (e.g. a consistent use of likelihood/probability), what might need to be adapted across stages and/or type of volcano, and whether scenarios could be more usefully applied in a post-eruption context.

The infrequent nature of damaging volcanic events coupled with the complexity and variability of volcanic hazards create unique challenges for volcano risk communication (Fearnley et al. 2018; Campbell 2020). For example, perceptions and expectations of people about volcanic hazards, and emergency communication and warnings shaped by experiences of other hazards like floods, might be irrelevant or misleading in the case of volcanoes. Volcanic hazards can also affect areas farther away from the volcanic centre (as opposed to some other hazards), there are high levels of uncertainty in volcano communication, and alerts for other hazards like floods might be received beforehand while a volcanic eruption can occur at any Volcanic Alert Level. Future research would be beneficial to unpack these unique challenges in volcano risk communication and ways to address them.

Additionally, understanding what acceptable risk and risk tolerance levels are for people regarding volcanic risks, and ensuring communication is adequate to meet people's expectations, is important. While different agencies acknowledge that there will always be some residual risks (Department of Conservation 2023) and individuals are responsible for managing their own risks in NZ (Ministry of Civil Defence and Emergency Management 2002), studies examining how residual risk and people's responsibility is conveyed to the public, how it is interpreted and understood, whether a shared understanding is achieved, and what gaps and concerns exist, warrants being undertaken. Particularly, in-depth qualitative studies with diverse groups of people (e.g. long term residents, tourists, culturally and linguistically diverse groups) would help in tailoring communication in ways that improves understanding and enables people to make informed decisions. This relates to the fundamental question of the role of risk communication in volcanic risk management in NZ – whether communication only provides science-based facts on hazards and advice on recommended actions, or whether it might aim to influence behaviour and actions to reduce hazard risks (Wardman 2008). A critical evaluation of existing communication practices exploring questions like what common consensus exists related to the communication role of different agencies, how it contributes to reducing volcanic risks beyond improving response capacity, and what the ethical obligations of different agencies are under the current emergency management regime in NZ (Dahlstrom and Ho 2012), would be beneficial to substantially enhance communication efforts for reducing volcanic risks. This would contribute to improving anticipatory actions to achieve effective disaster risk reduction (UNDRR 2023). Research rooted in risk perception and communication literature would be valuable to answer these deeper questions and inform current practice.

## Conclusion

A narrative review of academic and grey literature on volcano communication in New Zealand was undertaken to investigate information provision and communication across different stages of volcanic activity. Most of the literature focused on information and communication in the quiescence stage where preparedness and planning were prevalent, and the eruption stage where information is generally tailored to support agency response decisions. Gaps exist in the literature about volcano information and communication during unrest and post-eruptive stages (including recovery), indicating that more effort could be undertaken in these areas. The review highlighted that information and communication tend to evolve over time, with increasing demand for information as stages of volcanic activity move from quiescence into unrest, and then into response. While some literature reported on information and how it linked to decision making, this was mostly for the eruptive stage, and consequently more work could be undertaken to better understand the needs of decision-makers across a range of stages so that such information needs are met ahead of a crisis. Additionally, the types of information available tended to differ across stages (e.g. numerical likelihoods are less used in quiescence, but well utilised in unrest) and it is possible that information developed in one particular stage of activity could be applied across to another stage of activity (e.g. perhaps by using common tools such as scenarios). Given the gaps highlighted by this review, ongoing research could focus on identifying what is lacking and exploring potential improvements

to ensure future responses to volcanic crises are well-prepared.

## Notes

1. No volcanic unrest, volcanic environment hazards; 1: Minor volcanic unrest, volcanic unrest hazards; 2: Moderate to heightened volcanic unrest, volcanic unrest hazards, potential for eruption 3: Minor volcanic eruption, eruption hazards near vent; hazards; 4: Moderate volcanic eruption, eruption hazards on and near volcano; and 5: Major volcanic eruption, eruption hazards on and beyond volcano. Eruption hazards 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 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.' GNS Science (2024b).
2. Refer to Lechner (2022). https://www.aviation.govt.nz/assets/licensing-and-certification/meteorology/living-with-volcanic-ash.pdf for further details.
3. Documents produced by governmental departments, academia, science agencies, and industry that are not published through academic publishers and are not indexed in academic databases.
4. GNS Science, National Emergency Management Agency (NEMA), Civil Defence Emergency Management Groups, council websites, universities and science agencies, Department of Conservation, sectoral agencies (e.g., Ministry of Primary Industries, Ministry of Health), MetService, Civil Aviation Authority.
5. Data driven coding to capture patterns present in the data. It does not use pre-determined structure and codes for analysis.
6. A short-lived eruption is a volcanic event that lasts from minutes to days, whereas a long-lived eruption can persist for months to years.
7. Refer to Lechner (2022). https://www.aviation.govt.nz/assets/licensing-and-certification/meteorology/living-with-volcanic-ash.pdf for details.

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## Data availability statement

All data utilised for the nararative literature review can be found in the publications in the reference list. No additional data was collected for this paper.

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