Revised Threat Assessment of New Zealand's Volcanoes

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ABSTRACT

We present a revised version of the New Zealand Volcano Early Warning System (NZVEWS) volcano threat assessment, updating the 2012 assessment.

The purpose of this assessment is to guide future investment in volcano monitoring instrumentation for New Zealand's active volcanoes. This report ranks New Zealand's volcanoes by an internationally recognised threat assessment method, which we modify for New Zealand conditions. The underlying assumption is that higher-threat volcanoes warrant higher levels of instrumentation.

In this revised assessment, we include new exposure factors (gross domestic product [GDP] exposure and short-term visitors), as well as introduce a new vulnerability metric based on the 2018 New Zealand Deprivation Index. We group the threat ranking and vulnerability-modified threat rankings of volcanoes into 'high', 'medium' and 'low' groups based on 33% quantile distribution of threat scores. Where discrepancies between threat ranking and vulnerability-modified threat ranking exist, we take the higher value for final group assignment.

Ōkataina Volcanic Centre, Auckland Volcanic Field, Taranaki, Ruapehu, Taupō and Tongariro/ Ngauruhoe are the highest-threat volcanoes in New Zealand and warrant prioritisation for future network upgrades pending the outcome of the second stage of this work, which investigates instrumentation requirements for each threat-level group.

KEYWORDS

Volcano, threat, exposure, vulnerability, New Zealand, monitoring

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1.0 INTRODUCTION

The last widescale upgrade of Aotearoa New Zealand's volcano monitoring instrument network was completed in 2012. That upgrade fully digitised the network and more than doubled the number of monitoring stations keeping track of volcanic activity in New Zealand. A benchmarking study of the built network was presented by Miller and Jolly (2014).

Ten years on, it is appropriate to re-visit the capability of the networks to ensure that they remain fit for purpose for the next decade, to guide investment in ongoing maintenance and upgrades and to horizon-scan what future technologies may come onstream.

Since 2012, eruptions at Whakaari (2012, 2013, 2016, 2019) (Kilgour et al. 2021) and Tongariro (2012) (Jolly et al. 2014) and unrest episodes, e.g. Taupō 2017, 2019 (Muirhead et al. 2022) and Ruapehu 2022, have occurred. In response to these events, instrumentation network and software changes have occurred. For example, after the 2012 Tongariro eruptions, the network around Tongariro was expanded initially with portable stations, which became permanent several years later. In 2012, the SeisComP3 software was adopted as the national earthquake detection and location system, which had unintended consequences for volcano seismic monitoring through an increase in the minimum number of stations required for earthquake detection. This particularly impacted the networks around Taranaki and Auckland Volcanic Field, potentially reducing their ability to detect small earthquakes.

The appraisal of New Zealand's volcano monitoring instrumentation requirements is undertaken in two parts. This report applies a modified version of the US Geological Survey (USGS) National Volcano Early Warning System (NVEWS) method (Ewert et al. 2005, 2018), which we call 'NZVEWS', to update the 2012 report by Miller and Jolly (2014). Here, we outline the calculation of hazard and exposure factors that go into a volcanic 'threat' ranking and the subsequent grouping into 'High', 'Medium' or 'Low' threat categories.

Volcanic threat is defined by Ewert (2007) as the combination of 24 factors describing a volcano's hazard potential and exposure of people and property to those hazards, independent of any mitigation efforts or actions (Ewert et al. 2018).

A follow-up report will detail the instrumentation recommendations for each volcano as derived from USGS guidelines (Moran et al. 2008), comparisons with international best practises and a workshop held in December 2021 with the New Zealand volcano science community.

The aim of this report is to provide partial justification for the allocation of funding for monitoring instrumentation at New Zealand's volcanoes based on the 'threat' that they pose to New Zealand. The guiding assumption is that higher-threat volcanoes deserve a higher level of instrumentation compared to lower-threat volcanoes. Despite the similarities between our approach and those of a quantitative volcanic risk assessment, this report is not intended as such and is produced solely for the purpose of justifying instrumentation levels based on a nationally consistent threat assessment method.

The USGS method has been applied (with some adjustments) to several countries and regions, including Chile (Lara et al. 2006), Central America (Palma et al. 2008), Mexico (Espinasa-Perena et al. 2015), Peru (Macedo Sanchez et al. 2016), Argentina (Elissondo et al. 2016) and Ecuador (Santamaria and Bernard 2018). Other methods have been developed to rank exposure to explosive volcanic hazards, e.g. Jenkins et al. (2022).

The USGS method does not include vulnerability scores for volcanoes, instead calculating threat as the product of hazard and exposure alone. Palma et al. (2008) included an exploration of how vulnerability could be incorporated into the threat scoring and found an enormous variability in the depth and extent of available information and in the relative importance of the differing social factors that influence vulnerability.

In this report, we apply the 2018 New Zealand Deprivation Index (NZDEP; Atkinson et al. 2019a) as a vulnerability term in order to reflect the social impact of volcanic hazards and extend our definition of 'threat' to 'hazard × exposure × vulnerability'. We use the NZDEP as it is a nationally consistent measure of deprivation, which is somewhat, although not completely, aligned with the concept of vulnerability.

The volcanoes considered by the 2022 review are the same as those of the 2012 review, namely: Whangārei Volcanic Field, Kaikohe / Bay of Islands Volcanic Field, Auckland Volcanic Field, Tūhua / Mayor Island, Taranaki / Egmont, Whakaari / White Island, Ōkataina Volcanic Centre, Taupō, Rotorua, Reporoa, Maroa caldera, Tongariro (including Ngauruhoe), Ruapehu, Raoul Island and Macauley Island (Figure 1.1).

These are volcanoes that are classified in the Smithsonian database as active during the Holocene. The Smithsonian database is likely erroneous as showing Maroa, Reporoa, Rotorua and Macauley being active during Holocene; however, these volcanoes were active during the Pleistocene and are included here for completeness. Additionally, all four have active hydrothermal systems and hence pose some degree of volcanic or hydrothermal explosion hazard. Therefore, we retain them in our assessment.

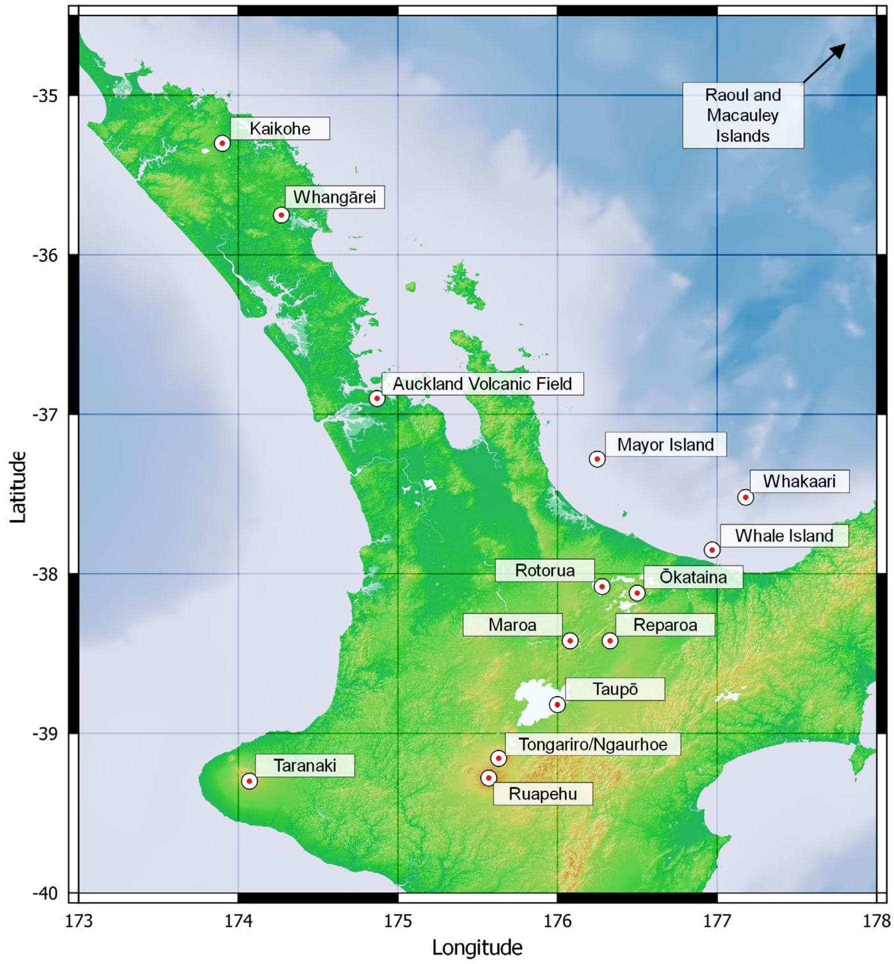

Figure 1.1 New Zealand volcanoes assessed in this report.

2.0 2012 REVIEW SUMMARY AND UPDATES

The USGS instrumentation recommendations describe four levels of minimum instrumentation requirements that are directly linked to volcanic threat rankings. For example, USGS level 4 networks (containing the highest number and quality of instrumentation) would be deployed at the highest-threat-group volcanoes, while level 1 networks, comprised of only a few sensors, would be deployed at the lowest-threat-group volcanoes.

The 2012 review of the network Miller and Jolly (2014) found that Auckland and Taranaki volcano monitoring networks were two levels below the USGS NVEWS instrumentation recommendation standards (Moran et al. 2008) for their equivalent threat groups, mostly due to poor coverage of GNSS (Global Navigation Satellite System) stations.

Since that time, InSAR technology has matured such that repeat pass interferometry is available on a 6- to 12-day cycle, providing wide spatial coverage even if at relatively low time resolution. In the 2012 report, additional broadband stations were recommended for the Auckland and Taranaki volcano seismic networks to fill azimuth gaps, which at the time of writing remain unfilled. For monitoring improvements, the next-priority volcanoes were found to be Tongariro/Ngauruhoe, Ruapehu, Taupō, Ōkataina and Whakaari, all requiring additional seismic and geodetic instrumentation.

Since the 2012 review, Tongariro/Ngauruhoe volcano monitoring has been boosted by an additional five seismic/acoustic stations and three GNSS stations, installed post the 2012 Te Maari eruptions. Whakaari received an additional seismic and GNSS station; however, the infrastructure there was badly damaged in the 2019 eruption and requires wholesale replacement at the time of writing.

In 2012, geochemical monitoring using fixed, automatic instruments was limited to Whakaari, and there was an overall requirement to move toward more continuous and automated gas flux and geochemical monitoring across all volcanoes. Addition of continuous SO_2 (Differential Optical Absorption Spectrometer [DOAS] method) stations on Tongariro, and most recently on Ruapehu, and installation of 'low-rate' data loggers at various springs and fumarole features in Tongariro National Park have contributed toward this requirement. Additionally, the adoption of new satellite monitoring technology (TropOMI) has allowed remote sensing of volcanic plumes from Ruapehu and Whakaari (Burton et al. 2021) under optimal conditions.

3.0 2022 THREAT ASSESSMENT METHOD AND INPUT DATA

For the 2022 review, we calculate 'threat' in two ways; as:

$$Threat\ Score\ = \sum hazard\ factors\ x\ \sum exposure\ factors$$ Equation 3.1

and also as:

$$Vulnerability - Modified\ Threat\ Score\ = \sum hazard\ factors\ x\ \sum exposure\ factors\ x\ \sum vulnerability\ factors$$ Equation 3.2

The Threat Score is defined following the USGS definitions (Ewert et al. 2005, 2018) and is a unitless, relative score intended to rank volcanoes solely for instrumentation assessment purposes. The underlying assumption is that higher-threat volcanoes justify a higher level of instrumentation.

Hazard and exposure factors sum internally and then multiply to produce the Threat Score. Below, we outline the factors that make up the Hazard and Exposure scores. New exposure factors introduced since the 2012 review include the number of short-term visitors to active volcanoes and an adjustment to the calculation of the per capita percentage of national Gross Domestic Product (GDP) exposed.

No normalisation of either score range is performed prior to Threat Score calculation, as we are only interested in a relative ranking and normalisation by the maximum value would not alter the order.

The Vulnerability-Modified Threat Score is our approach to incorporating vulnerability into a threat score. A more detailed vulnerability method that included resilience metrics has recently been applied in Mexico, e.g. Nieto-Torres et al. (2021). However, it is difficult to apply vulnerability and resilience measures developed for one country to another. There is also no strict quantitative definition of vulnerability that can be globally applied.

This review is explicitly not a quantitative volcanic risk assessment. The inclusion of vulnerability goes some way toward a risk assessment, but a full risk assessment is beyond the scope of this report. This report should not be used to assess the likelihood of occurrence or loss resulting from a volcano.

3.1 Hazard Factors

Hazard factors account for volcano type (large cones and caldera score 1 and cones / basaltic fields 0), maximum volcano explosivity index, explosive activity and eruption recurrence, and whether the volcano has produced a range of hazards in the Holocene, including lava flow, pyroclastic flow, lahar, tsunami and sector collapse. Finally, historic unrest indicators are included, such as observed seismic unrest, ground deformation or magmatic degassing. Table 3.1 shows the scoring chart for hazard factors. Information is taken from the Global Volcanism Programme database version 4.10.[1]

The scoring is largely a binary yes/no (1/0) depending on whether the hazard factor exists. The main change from the 2012 assessment is to use a 0.5 score instead of 0 when lack of data for the observed seismic, deformation or degassing activity prohibit a reliable score,

1 https://doi.org/10.5479/si.GVP.VOTW4-2013

as per Ewert et al. (2018). As these monitoring data may only be available at some volcanoes for 10–20 years, it is conceivable that frequently active volcanoes could have previously had activity that is not recorded by modern monitoring. This provides a precautionary approach where information is sparse. For the other factors, we assign the higher value if a hazard is credible at a volcano, even if not yet documented.

Full scores for each factor per volcano are provided in Appendix 1.

Table 3.1 Scoring ranges of hazard factors.

Hazard Factors	**Scoring Ranges**
Volcano type	0 or 1
Maximum volcanic explosivity index (VEI)	0 to 3*
Eruptive activity in past 500 years	0 or 1
Major explosive activity in past 5000 years	0 or 1
Eruption recurrence	0 to 4**
Holocene pyroclastic flows?	0 or 1
Holocene lahars?	0 or 1
Holocene lava flows?	0 or 1
Hydrothermal explosion potential?	0 or 1
Holocene tsunami?	0 or 1
Sector collapse potential?	0 or 1
Primary lahar source?	0 or 1
Observed seismic activity since the last eruption	0 or 1
Observed ground deformation since the last eruption	0 or 1
Observed fumarolic or magmatic degassing since the last eruption	0 or 1
Sum of Hazard Factors	**0 to 20**

* Note that, for maximum volcanic explosivity index, VEI ≤2 scores 0, VEI = 3 or 4 scores 1, VEI = 5 or 6 scores 2 and VEI ≥7 scores 3. See Ewert et al. (2018) for full details.

** Eruption recurrence scores as 0 for no known Holocene eruption; 1 if eruption interval is 5000–10,000 years or for a restless large volume silicic system that has erupted in the last 100,000 years; 2 if eruption interval is 1000–5000 years, 3 if eruption interval is 100–1000 years; and 4 if eruption interval is 1–99 years.

3.2 Exposure Factors

Exposure factors account for population, built infrastructure, aviation and economy exposed to volcanic hazards. It incorporates population within a 30 km radius of the volcano, evidence of historical fatalities or evacuations determined from historical archives, proximity to airports, proximity to various infrastructure and proximity to culturally or environmentally sensitive areas such as national parks. We modify the USGS Exposure Score to include two additional factors, percentage of New Zealand's GDP land area exposed within a 50 km radius of the volcano, as well as a metric based on short-term visitor numbers (day-trippers) who venture near the volcano, which can result in a temporary but substantial increase in at-risk population. We included GDP in the 2012 report, but we modify the calculation metric to make it proportional to population size. Fifty kilometres is chosen for GDP exposure to be consistent with the distance used in the aviation metrics for exposure to ashfall, recognising that economic impacts from ashfall can occur further from the volcano than ground-based hazards.

The main exposure change from the 2012 review is better quantification of population statistics through geospatial analysis of the New Zealand Statistical Area 2 (SA2) database[2] (Figure 3.1). SA2-level data from the 2018 Census, Population and Migration statistics were extracted from the database.

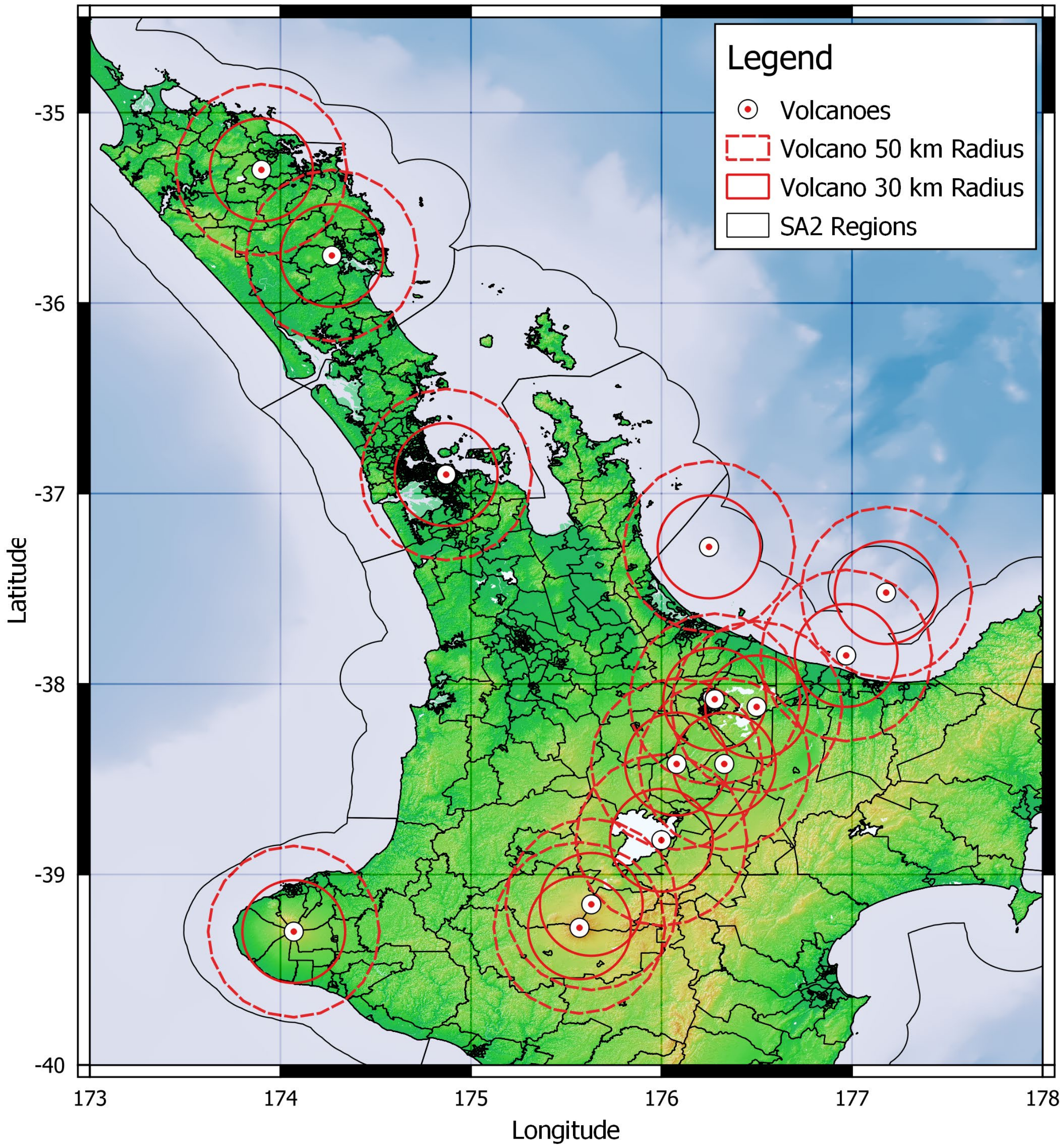

Figure 3.1 New Zealand's monitored volcanoes (small red and white circles). The bold red circle is a 30 km radius around the volcano and the dashed red circle is a 50 km radius. Thin black lines indicate SA2 areas.

SA2s in city council areas generally have a population of 2000–4000 residents, while SA2s in district council areas generally have a population of 1000–3000 residents. In rural areas, many SA2s have fewer than 1000 residents because they contain sparse populations that cover a large area. SA1 areas are smaller areas created by joining meshblocks and typically contain 100–200 residents, with a maximum population of 500.

2 https://nzdotstat.stats.govt.nz/wbos/index.aspx?_ga=2.240310401.363741482.1659994930-1895010313.1659994930

Table 3.2 Scoring ranges of exposure factors.

Exposure Factors	Score
Population exposed to regional hazard (log_{10} of population within 30 km)	0 to 6.1
Population exposed to flow hazard (log_{10} of approximate population downstream or downslope)	0 to 4
Percentage of national Gross Domestic Product within 50 km	0 to 24.3
Historical fatalities?	0 or 1
Historical evacuations?	0 or 1
Local aviation exposure	0 to 2
Regional aviation exposure (log_{10} passenger numbers for airports within 50 km)	0 to 4.7
Power infrastructure?	0 or 1
Transportation infrastructure?	0 or 1
Major development or sensitive area?	0 or 1
Volcano is a significant part of a populated island?	0 or 1
Short-term visitors exposed to local hazard (log_{10} estimated daily visitor count)	0 to 4
Sum of Exposure Factors	**0 to 51.1**

To calculate the population within 30 km from each volcano, the SA2 dataset was queried and the calculation performed as:

$$Population_v = \sum_i^N Population_i * \frac{A_{i,30}}{A_i} \quad \text{Equation 3.3}$$

where A_i is the total area of the SA2 block, $A_{i,30}$ is the area of the SA2 block within 30 km of the volcano (Figure 3.1) and *Population* is the population within the SA2 block. This equates to scaling the population within the SA2 block by the proportion of the block within 30 km of the volcano. These scaled SA2 populations were then added together to get an estimate of the total population within 30 km of each volcano. Figure 3.2 shows the log_{10} of the population within 30 km of the volcano.

An assumption in the use of these population regions is that the population is evenly distributed within that area. This may be the case in suburban areas but, in larger rural areas, population within an SA2 may be highly clustered in towns, with large areas of the SA2 region being uninhabited. This may result in an over-estimation of exposed population if most of the population is outside the $A_{i,30}$ area but divided equally into the $A_{i,30}$ area. Future revisions of the assessment could use the newly developed RiskScape database (https://riskscape.org.nz/) that has resolution at the household level, reducing the over- or under-estimation of population exposed. Island volcanoes such as Raoul Island and Whakaari have no permanent population but can have small numbers (10) of temporary residents or day visitors.

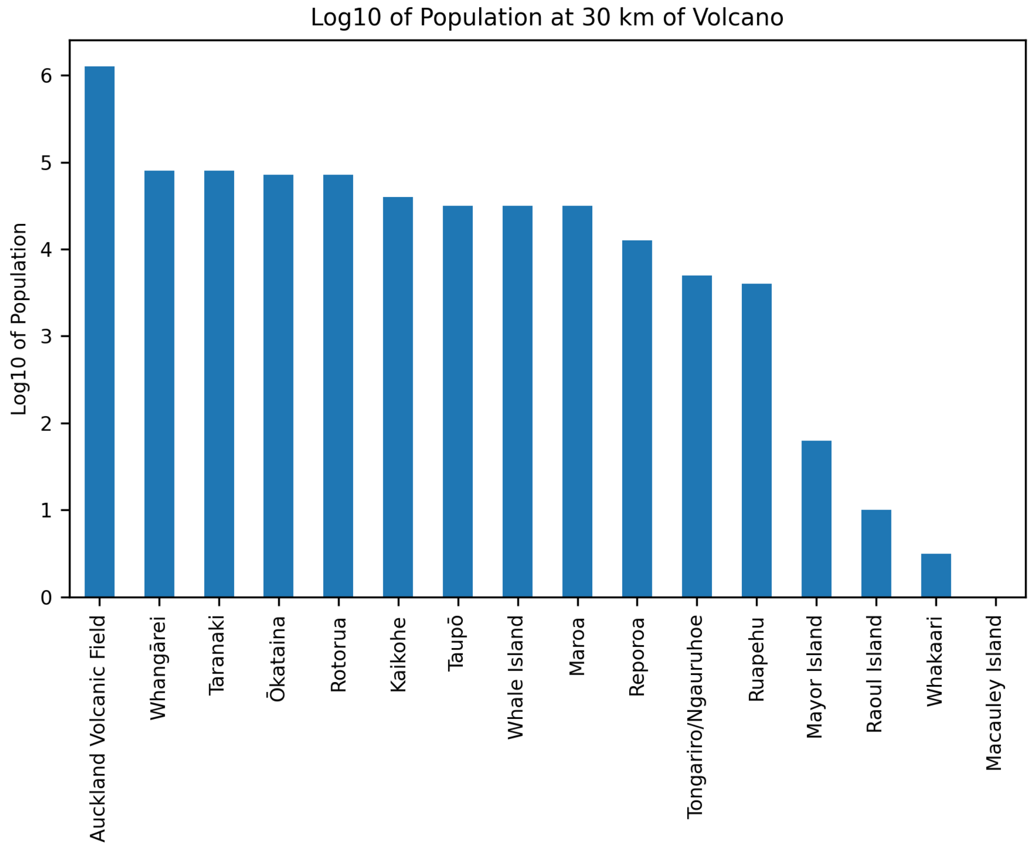

Figure 3.2 Log$_{10}$ of population within 30 km of volcano.

Population exposed to a flow hazard is determined by the proportion of population within an SA2 area that is within a catchment known to generate flow hazards such as lahar. Flow hazards such as lahars primarily exist at the cone volcanoes Ruapehu and Taranaki, i.e. those volcanoes with crater lakes or significant seasonal snow cover. Flow hazards such as lava flows are important in the Auckland Volcanic Field, while flow hazards such as pyroclastic density currents can occur from cones and caldera volcanoes.

It is beyond the scope of this study to undertake a comprehensive digital elevation model (DEM)-based flow simulation for each volcano, so we rely on published data.

Lahar activity at Taranaki in the past 1000 years has been primarily confined to the Stony River catchment in the northwest and Maketawa Stream in the east (Cronin et al. 2021; Procter et al. 2021). We calculate populations in these catchments, as well as for the Pātea River that passes through the town of Stratford.

For Ruapehu, the majority of lahars pass down the Whangaehu Valley or tributaries that feed into that valley, with only minor flows into sparsely populated areas to the west. For these Taranaki and Ruapehu catchments, we place a 1 km buffer around the catchment and extract the population in that buffer within 30 km of the volcano.

For the Auckland Volcanic Field, there is both uncertainty around the location of the next eruption site and which catchments might be impacted (Hopkins et al. 2021). For lava flows at the Auckland Volcanic Field, we estimated the at-risk population by using a 2.5 km buffer, equivalent to the length of a typical lava flow in Auckland (Kereszturi et al. 2012) and applied that to low ‘Zone 1 depressions’ identified in Kereszturi et al. (2012). We then took the average of the exposed population in these depressions, given that an eruption is only likely to impact one of them.

For pyroclastic flows from large caldera volcanoes Taupō, Ōkataina and Rotorua, we take the $\log_{10}$ of the population within 30 km of the volcano. No specific catchments were estimated, and this is simply a first-order estimate of population that may be directly impacted by a large silicic eruption.

For all flow hazard population estimates, as we take the $\log_{10}$ of the population for inclusion in the exposure score, the impacts of over- or under-counting the exposed population are reduced when reflected in the final exposure score. Refer to Table A1.2 for flow hazard exposure scores.

Regional aviation exposure concerns exposure to ashfall and is calculated as the $\log_{10}$ of the number of visitors per year to airports within 50 km of a volcano, unless there are no airports within 50 km of a volcano, in which case the exposure is defined as zero (Figure 3.3). Visitor statistics were from 2016 and are sourced from figure.nz.[3] For some small airports, the available data are rounded to the nearest 1000 or 10,000, so are clearly estimates, but an alternative, comprehensive estimate of visitor numbers was not available. Note that our aviation exposure to ashfall does not consider dominant wind directions that may increase or decrease the ashfall exposure of certain airports depending on their location up- or downwind of a volcano (e.g. Jenkins et al. 2022).

The original USGS NVEWS report uses 300 km for determining aviation exposure; however, in a small country such as New Zealand, this large distance results in no sensitivity between individual volcanoes. In other words, all volcanoes are within 300 km of each other and would all score the same value if 300 km distance was used. The use of 50 km is to be consistent with GDP exposure; however, we recognise that, in larger eruptions, impacts may be felt further than 50 km.

The regional aviation exposure factor highlights the many small airports that exist in New Zealand to serve domestic travel needs. Note that Ruapehu and Tongariro/Ngauruhoe score 0 (Figure 3.3), as they are more than 50 km from a regional airport. The nearest airport is Taupō, which is 75 km from Ruapehu and 60 km from Tongariro Volcano. Whakaari is within 50 km of Whakatāne airport. Auckland has by far the highest aviation exposure score, reflecting its importance as New Zealand's main international gateway. An alternative approach would be to consider aircraft flight paths and the number of passengers carried on each flight; however, those data are not readily available for New Zealand. Flight paths are also readily adapted to avoid volcanic ash clouds, so we only consider potential direct impacts on the airports themselves.

3 https://figure.nz/table/IXqyhyrlAebINmwC and https://figure.nz/table/dhHz8ypnPW4dkfC5.

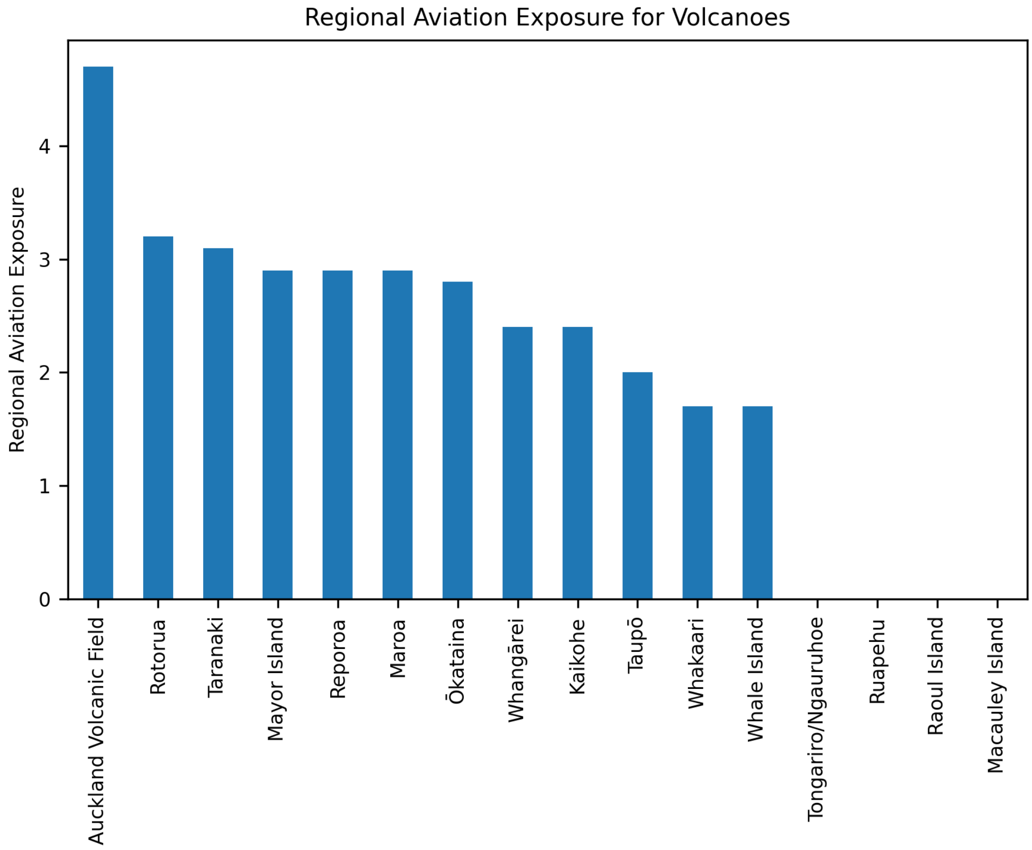

Figure 3.3 Regional aviation exposure. Tongariro and Ruapehu score zero, as there is no regional airport within 50 km of these volcanoes.

For fatalities, we only consider those caused directly by eruptions, not fatalities due to exposure to passive geothermal hazards, such as asphyxiation by H_2S (Bassindale and Hosking 2010) or drowning in hot pools (Brown et al. 2017). All fatalities due to these geothermal hazards have occurred in Rotorua.

3.2.1 Significant Short-Term Visitors with Local Hazard Exposure

New Zealand's cone and island volcanoes, Ruapehu, Tongariro/Ngauruhoe, Taranaki, Whakaari, Tuhua, Whale Island and Raoul Island, are or have been tourist sites, attracting varying numbers of daily visitors. Often these tourists are within very close range of potential volcanic hazards (e.g. Whakaari, Ngauruhoe), even if the total time spent is small. To account for these short-term, high-consequence visits, we calculate an additional exposure factor based on the $\log_{10}$ of the short-term (daily) population visiting volcanoes within national parks or as specific tourist attractions without resident populations (Appendix A2.2). We exclude volcanoes such as Rotorua, Taupō and the Auckland Volcanic Field from this, as they host large resident populations and it is not possible to determine the number of visitors that come to visit for volcano-based tourism. In Auckland, the next eruption site is unknown, so it is not possible to calculate visitor numbers to an unknown location. In Taupō and Rotorua, potential vent sites are also under lakes, which inherently limits access to possible eruption locations. We also exclude geothermal attractions outside of the volcanoes studied, for example, the geothermal fields between Taupō and Rotorua.

Examples include up to 10,000 skiers per day (maximum values, score = 4) at Ruapehu (Ruapehu Alpine Lifts 2021); 140,000 visitors annually completing the Tongariro Alpine Crossing between Tongariro and Ngauruhoe, where peak daily values can be more than 1000 (score = 3); and 100 visitors per day to Whakaari (score = 2) prior to the 2019 eruption.

It is unknown if such visitor numbers will return to Whakaari after the 2019 eruption; however, we include this factor for completeness. Visitor numbers in Tongariro and Taranaki national parks are from Department of Conservation reports.[4]

3.2.2 New Zealand Gross Domestic Product Exposure

As for the 2012 study, we include an additional exposure factor based on the percentage of New Zealand GDP potentially exposed within a 50 km radius around each volcano (Figure 3.1). In this study, we modify the calculation process as follows to make the score GDP per capita rather than GDP per area as in the 2012 study.

As GDP data[5] is available only at a regional scale, we use New Zealand Regions rather than SA2 area in our spatial calculations. Additionally, we extend the radius of our calculation buffer around each volcano to 50 km (rather than the 30 km) to accommodate the region-based scale of GDP values.

We calculate the GDP within 50 km of each volcano as:

$$GDP_v = \sum_i^N \frac{GDP_i}{Population_i} * \left(Population_i * \frac{A_{i,50}}{A_i}\right) \quad \text{Equation 3.4}$$

which simplifies to:

$$GDP_v = \sum_i^N GDP_i * \frac{A_{i,50}}{A_i} \quad \text{Equation 3.5}$$

where A_i is the total area of each region and $A_{i,50}$ is the area of each region within 50 km of the volcano (Figure 3.1). GDP_i is the GDP of each region and $Population_i$ is the population of each region.

Essentially, this equates to calculating the GDP in the region within 50 km of the volcano by scaling each region's per-capita GDP by the population of the region within 50 km of the volcano and then summing these values. Importantly, we assume that regional GDP is proportional to regional population and that each region's population is evenly spread over its area.

To convert GDP values into our GDP exposure factor (percentage of New Zealand GDP), we scale them by the total New Zealand GDP. Figure 3.4 shows the GDP exposure factor values for each volcano. The GDP factor highlights that many of New Zealand's volcanoes are close to population and industry areas, disruption of which could significantly impact New Zealand's overall economy (Figure 3.4).

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4 https://www.doc.govt.nz/globalassets/documents/about-doc/role/visitor-research/visitor-sites-data-2018-2019.pdf and https://www.doc.govt.nz/globalassets/documents/about-doc/role/visitor-research/twt-visitor-trends-report.pdf

5 https://www.stats.govt.nz/information-releases/regional-gross-domestic-product-year-ended-march-2020/

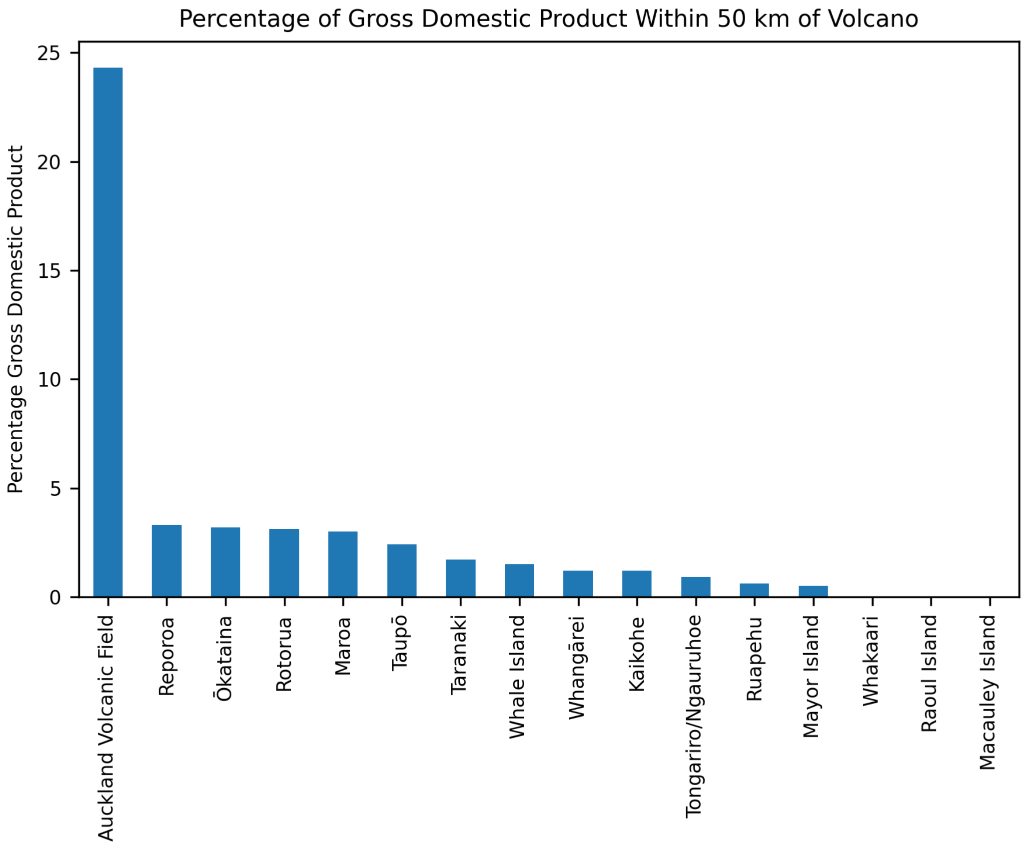

Figure 3.4 Percentage of total New Zealand gross domestic product within 50 km of volcano.

Auckland has by far the largest economic exposure, reflecting the importance that Auckland has to the vitality of the national economy. As a small country, the New Zealand national economy is vulnerable to local hazards in key centres such as Auckland. For example, many national food distribution warehouses are in Auckland, and an eruption in the Auckland Volcanic Field that destroyed such a warehouse would have impacts felt around the country. Conversely, ashfall from a distal eruption could stop aviation traffic into and out of Auckland International Airport, New Zealand's main international port, disrupting economically important export businesses across all of New Zealand.

3.3 New Zealand Deprivation Index as a Vulnerability Measure

Natural hazard vulnerability indices typically cover: Exposure to a hazard; Susceptibility of the population, including children, older adults and those with physical or mental health needs; and Resilience, such as having enough money to cope with crises or having the knowledge or skills and awareness to face hazards, as well as sufficient housing, food and water to cope with shortages (Mason et al. 2019).

Our NVZEWS review covers Exposure to hazards, and we propose the use of the NZDEP as a measure of Susceptibility and Resilience, which we broadly term 'vulnerability'. In the 2022 review, we include a vulnerability index, based on the NZDEP, to calculate a Vulnerability-Modified Threat Score. The NZDEP[6] is an area-based measure that reflects the relative level of socio-economic deprivation in an area (Atkinson et al. 2019a). Higher levels of socio-economic deprivation are associated with worse health and higher environmental risk. In general, people who live in areas with higher deprivation indices are more susceptible

6 https://www.ehinz.ac.nz/indicators/population-vulnerability/socioeconomic-deprivation-profile/

to environmental risks, have fewer resources to protect themselves from environmental hazards and are less likely to have the means for coping with the impacts of environmental risks (Atkinson et al. 2019a).

The Deprivation Index is a decile-based integer derived from deprivation scores, with higher values of the index indicating a greater relative degree of deprivation. An index value of 1 indicates that a given geographic area is in the lowest 10% of deprivation scores nationally (i.e. least deprived), while an index value of 10 indicates that a given region is in the highest 10% (i.e. most deprived) of deprivation scores nationally.

Deprivation scores result from a principal component analysis of nine census values that together reflect eight dimensions of material and social deprivation. Atkinson et al. (2019a) state that "these dimensions reflect lacks of income, employment, communication, support, qualifications, owned home, living space and dry living conditions".

We calculate deprivation scores in a radius of 30 km around each volcano, following the method of Atkinson et al. (2019b) for defining deprivation scores over customised areas. These scores use populations in the smaller SA1 region, required by the method of Atkinson et al. (2019b).

$$Deprivation_v = \frac{\left(\sum^N\left[Deprivation_i * Population_i * \frac{A_{i,30}}{Ai}\right]\right)}{\left(\sum^N\left[Population_i * \frac{A_{i,30}}{Ai}\right]\right)} \quad \text{Equation 3.6}$$

where $Deprivation_i$, is the deprivation score for the SA1 region, $A_{i,30}$ is the area of the SA1 region within 30 km of the volcano, A_i is the area of the entire SA1 region and $Population_i$ is the population of the SA1 region.

In effect, we scale SA1 deprivation scores by the proportion of each SA1 region within 30 km of a given volcano and by the population of that SA1 region. Scaled deprivation scores are then summed across all SA1 regions within 30 km of the volcano, and this sum is divided by the total population included in the scaling of the deprivation scores (that of all the SA1 regions within 30 km of the volcano). Only those SA1 regions with land area (i.e. not those ocean areas around islands) and where the deprivation score is defined were included in our deprivation-score re-calculations.

To convert deprivation scores into Deprivation Index values, each volcano's deprivation score was placed into the distribution of scores of Atkinson et al. (2019a) and the relevant Deprivation Index value was extracted.

To avoid multiplication by zero errors when the vulnerability-modified threat score is calculated, we add 1 to the Deprivation Index. This applies to island volcanoes with no population within 30 km. These Deprivation Index values are our vulnerability scores for each volcano.

4.0 RESULTS

Here we summarise the hazard, exposure and vulnerability scores for each volcano.

4.1 Hazard Scores

Table 4.1 shows the hazard, exposure, vulnerability and threat scores, and Figures 4.1–4.3 show the distribution of these scores for each volcano.

Table 4.1 Summary of hazard, exposure and threat scores ranked from high- to low-threat volcanoes.

Volcano	Total Hazard Factors	Total Exposure Factors	Vulnerability Score
Ōkataina	17	19.4	9
Auckland	7	43.9	7
Taranaki	14.5	20.7	6
Ruapehu	17	16.7	7
Taupō	15	17.4	6
Tongariro/Ngauruhoe	18	12.6	9
Rotorua	8.5	20.2	8
Whakaari	18.5	7.2	1
Maroa	8.5	15.4	8
Reporoa	7.5	15.3	6
Raoul Island	17	5.5	1
Mayor Island	11.5	7.7	6
Whale Island	6.5	10.7	8
Kaikohe / Bay of Islands	4	13.2	9
Whangārei	1	13.5	8
Macauley Island	11	0	1

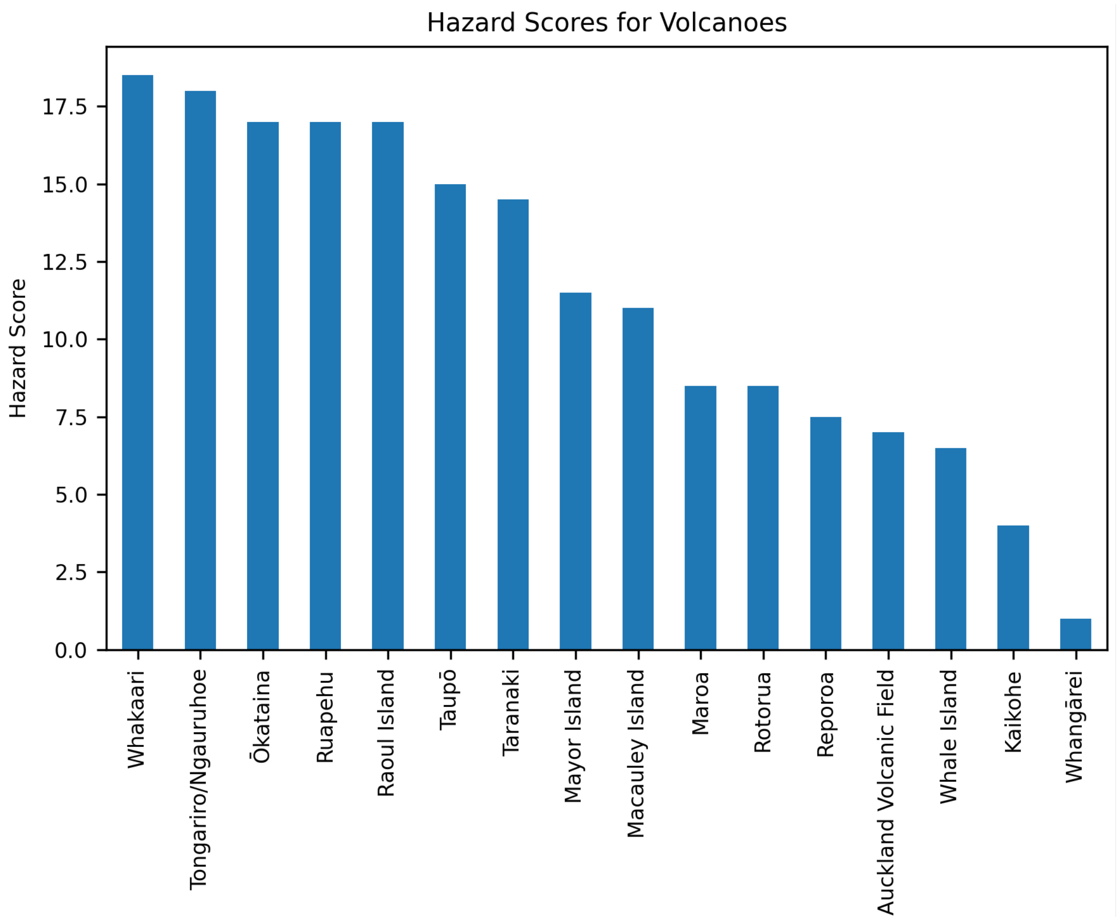

Figure 4.1 Hazard scores for New Zealand volcanoes.

The five volcanoes with the highest hazard scores have all erupted within the most recent 150 years and have generated a range of volcanic hazards that have resulted in fatalities. For example, pyroclastic flows (Whakaari 2019) (Ardid et al. 2022), hydrothermal explosions (Raoul Island 2006) (Christenson et al. 2007), ashfall (Ōkataina / Mt Tarawera 1886) (Rowe et al. 2021) and lahars (Ruapehu 1953) (Leonard et al. 2021). In addition, these volcanoes have present-day signs of unrest. Whakaari has continuous seismic activity, high heat flow into a hot crater lake, magmatic degassing and localised ground deformation (Caudron et al. 2021). Ōkataina, Ruapehu and Tongariro/Ngauruhoe all have seismic activity and active geothermal systems.

A small step down in hazard score to Taupō volcano is the result of no eruptive activity in the last 500 years and a longer eruption recurrence interval compared to Ruapehu and Tongariro volcanoes. Sector collapse is also not a likely hazard at Taupō caldera compared to the stratovolcanoes. Taranaki scores similar to Taupō, but this is on account of there being no current unrest observations at Taranaki compared to the volcanoes with higher hazard scores.

Scores below 10 reflect volcanoes with no unrest indicators, low volcano explosivity indices for previous eruptions and no major explosive activity in the last 500 or 5000 years. For example, the Auckland Volcanic Field ranks low on the hazard scale due to the relatively small previous eruption size (maximum volcanic explosivity index [VEI] of 2 or 3, scoring 0 or 1; see Table 3.1) compared to maximum VEI of 5 or 6 for Ruapehu, which scores 2 in this regard. Similarly, the Auckland Volcanic Field's limited potential to produce hazards such as lahars, hydrothermal explosions, tsunami or sector collapse, along with no documented evidence of volcanic unrest (score of 0.5, as records only extend back to the mid-20th century) also keeps its hazard score down, despite an eruption occurring ~500 years ago at Rangitoto.

4.2 Exposure Scores

Auckland Volcanic Field, situated within Auckland City, has the largest exposure score (Figure 4.2). This is due to the large population exposed, the high percentage of GDP generated in Auckland and the proximity of an international airport with high daily visitor numbers. Auckland also has the highest exposure to flow hazards, specifically lava flows.

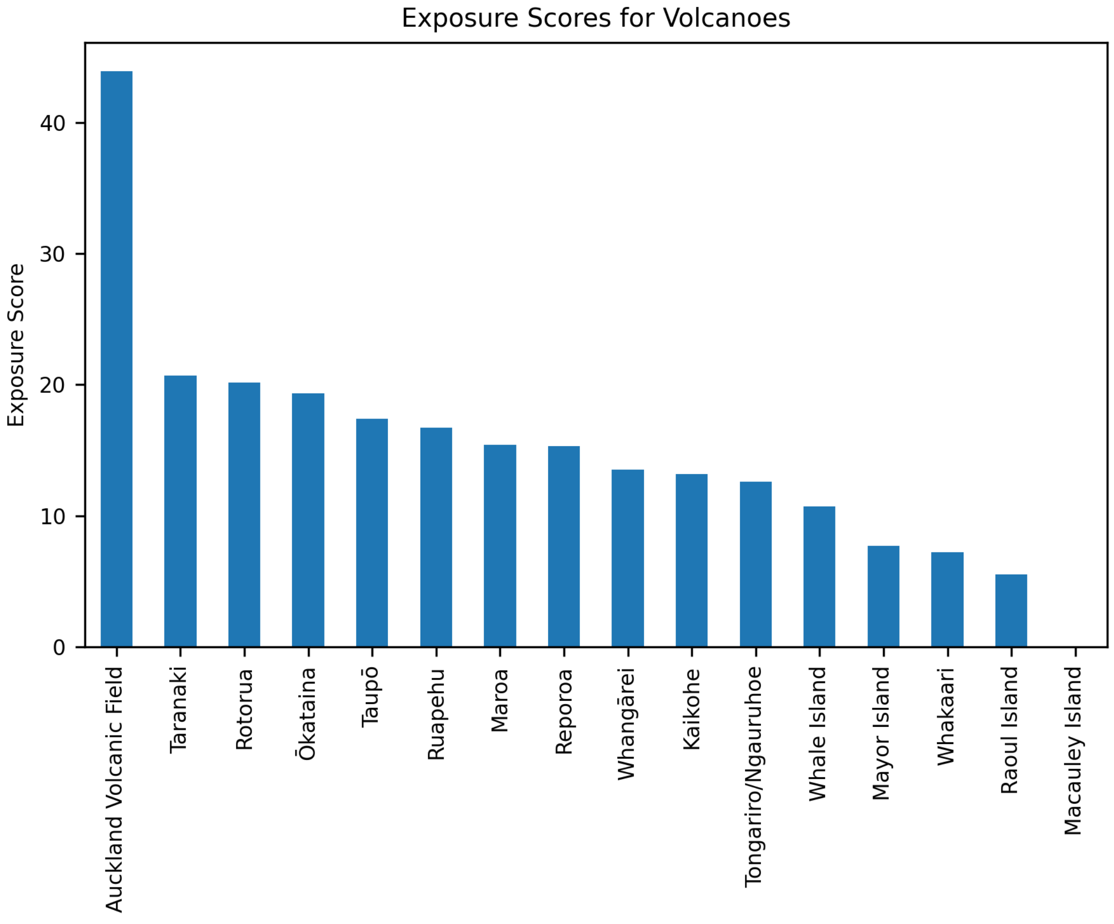

Figure 4.2 Exposure scores for New Zealand volcanoes.

The remainder of the volcanoes have substantially lower exposure scores than the Auckland Volcanic Field, which steadily decrease across the remainder of the volcanoes, with notable steps down to offshore island volcanoes due to their distance from populations and infrastructure. Converse to its hazard score, Whakaari has the third-lowest exposure score, reflecting its offshore position – 50 km from the nearest population centre – and only the small airport with low daily visitor numbers at Whakatāne within range for aviation score calculations.

Taranaki volcano has the second-highest exposure score due to a combination of the population around the volcano, the abundance of people within potential flow zones (largely potential lahar paths), the relatively high GDP (due to the oil and gas industry and dairy farming) and the proximity of airports.

4.3 Vulnerability Scores

The distribution of vulnerability scores is shown in Figure 4.3.

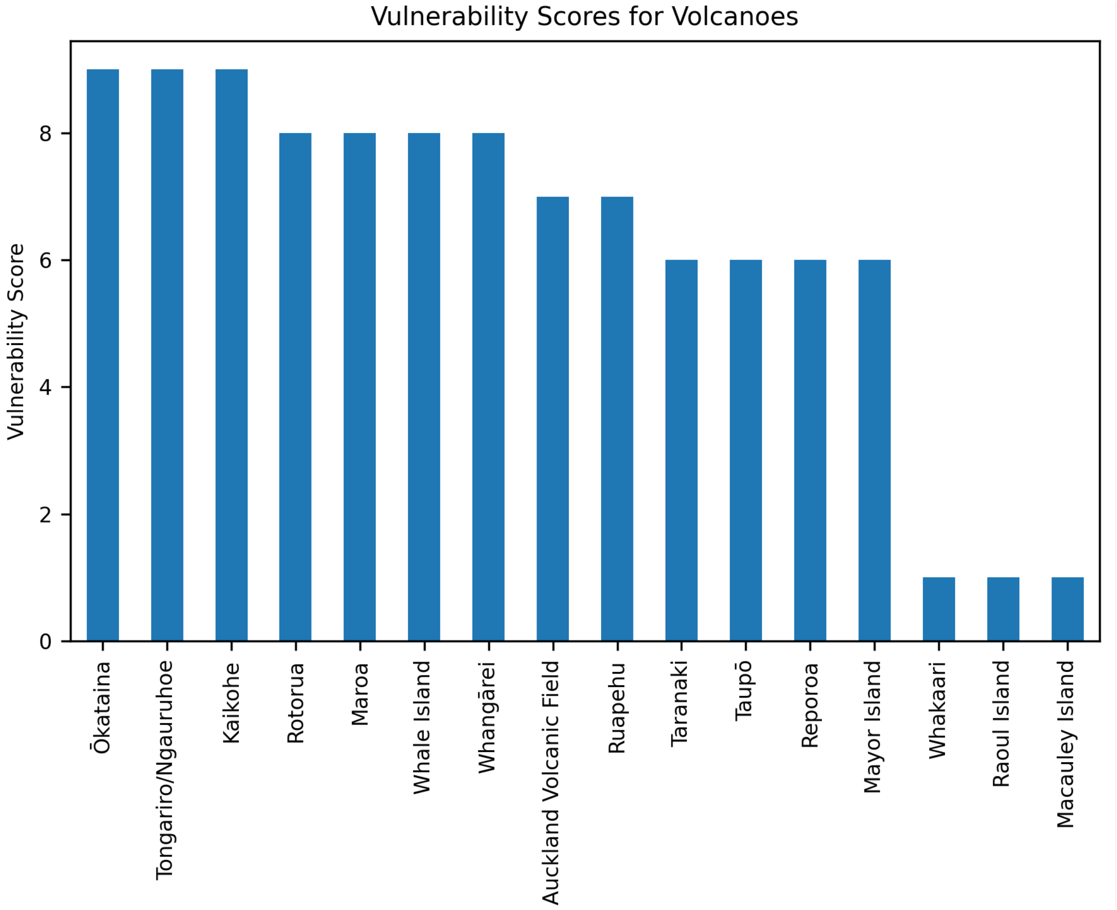

Figure 4.3 Vulnerability scores for New Zealand volcanoes.

The island volcanoes – Whakaari, Raoul Island and Macauley Island – have no population within a 30 km radius and as such would have a vulnerability score of 0 with our calculation method. The remainder of the volcanoes have vulnerability scores 6 or higher, indicating that people who live close to volcanoes are generally in the higher vulnerability part of the population. Ōkataina, Tongariro/Ngauruhoe and the Kaikohe / Bay of Islands field have the highest vulnerability index scores of 9, nearly the maximum score of 10. Overall, most volcanoes occur in areas that have higher levels of vulnerability compared to the mid-decile ranking (5).

4.4 Threat Scores

Hazard and exposure scores multiply to create a Threat Score (Equation 3.1), tabulated in Table 4.2. The Ōkataina Volcanic Centre has the highest threat score (Figure 4.4) because of its high hazard and exposure scores. Although the Auckland Volcanic Field has a very high exposure score, its small hazard score means that its threat score falls just behind the Ōkataina Volcanic Centre in the overall threat ranking. Close behind the Auckland Volcanic Field is Taranaki Volcano.

Table 4.2 Threat and vulnerability scores and ranking for each volcano.

Volcano	Threat Score	Threat Ranking	Vulnerability Threat Score	Vulnerability-Modified Threat Ranking
Ōkataina	329	1	2961	1
Auckland	307	2	2151	2
Taranaki	300	3	1800	5
Ruapehu	284	4	1987	4
Taupō	261	5	1566	6
Tongariro/Ngauruhoe	227	6	2041	3
Rotorua	171	7	1370	7
Whakaari	133	8	133	13
Maroa	131	9	1047	8
Reporoa	114.8	10	688	9
Raoul Island	93.5	11	93.5	15
Mayor Island	88.6	12	531	11
Whale Island	69.6	13	556	10
Kaikohe-Bay of Islands	52.8	14	475	12
Whangārei	13.5	15	108	14
Macauley Island	0	16	0	16

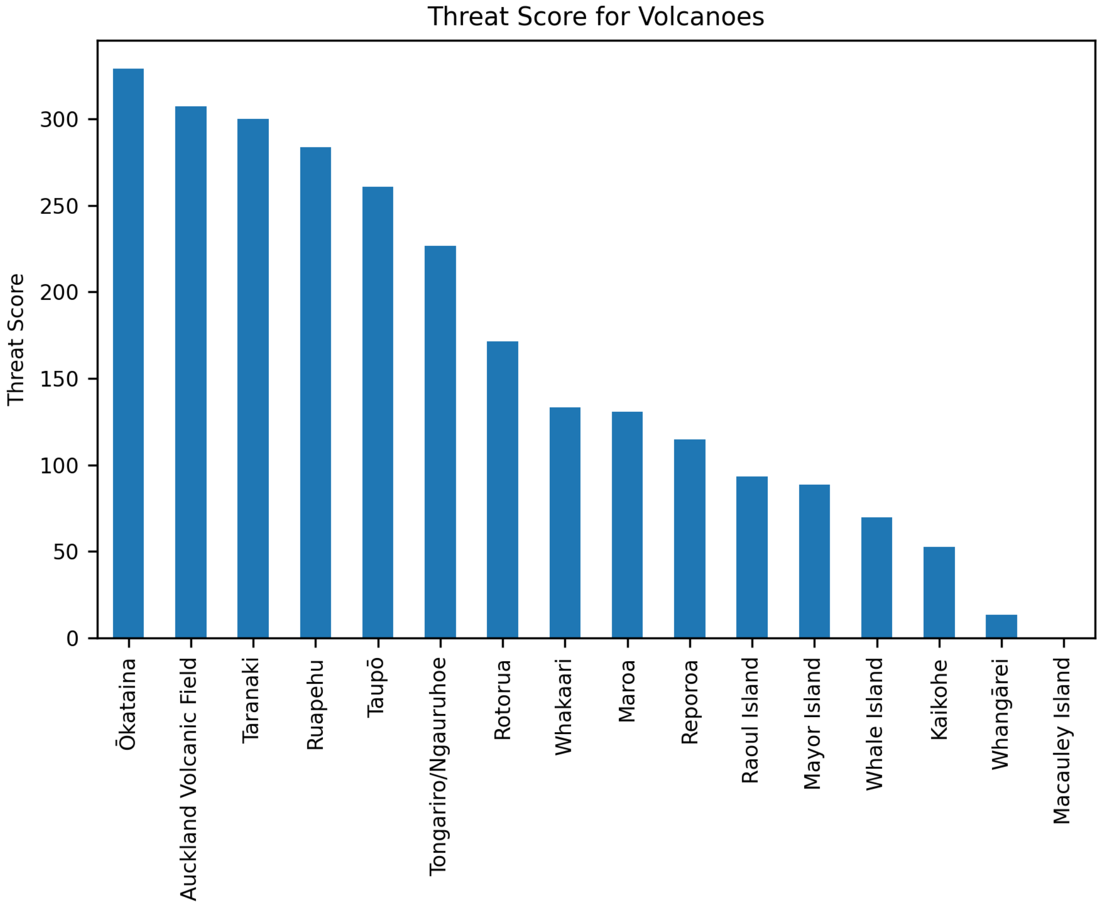

Figure 4.4 Distribution of threat scores for New Zealand volcanoes.

When the vulnerability score is included in the threat score (Equation 3.2), there are some changes in the ranking (Table 4.2; Figure 4.5). Ōkataina Volcanic Centre remains the highest threat volcano in this case, but there is a larger step to the remaining volcanoes. Auckland Volcanic Field remains in second-highest threat position, but Taranaki falls to fifth place below Tongariro/Ngauruhoe and Ruapehu. Whakaari drops significantly in the threat ranking, reflecting its low vulnerability score.

Ruapehu and Tongariro/Ngauruhoe score slightly differently, reflecting slight differences in the Deprivation Index between the populations north of Tongariro/Ngauruhoe and south of Ruapehu. As noted in the vulnerability methods section, our use of the Deprivation Index may not be a full measure of vulnerability, especially for those local communities with long experience at living close to volcanoes.

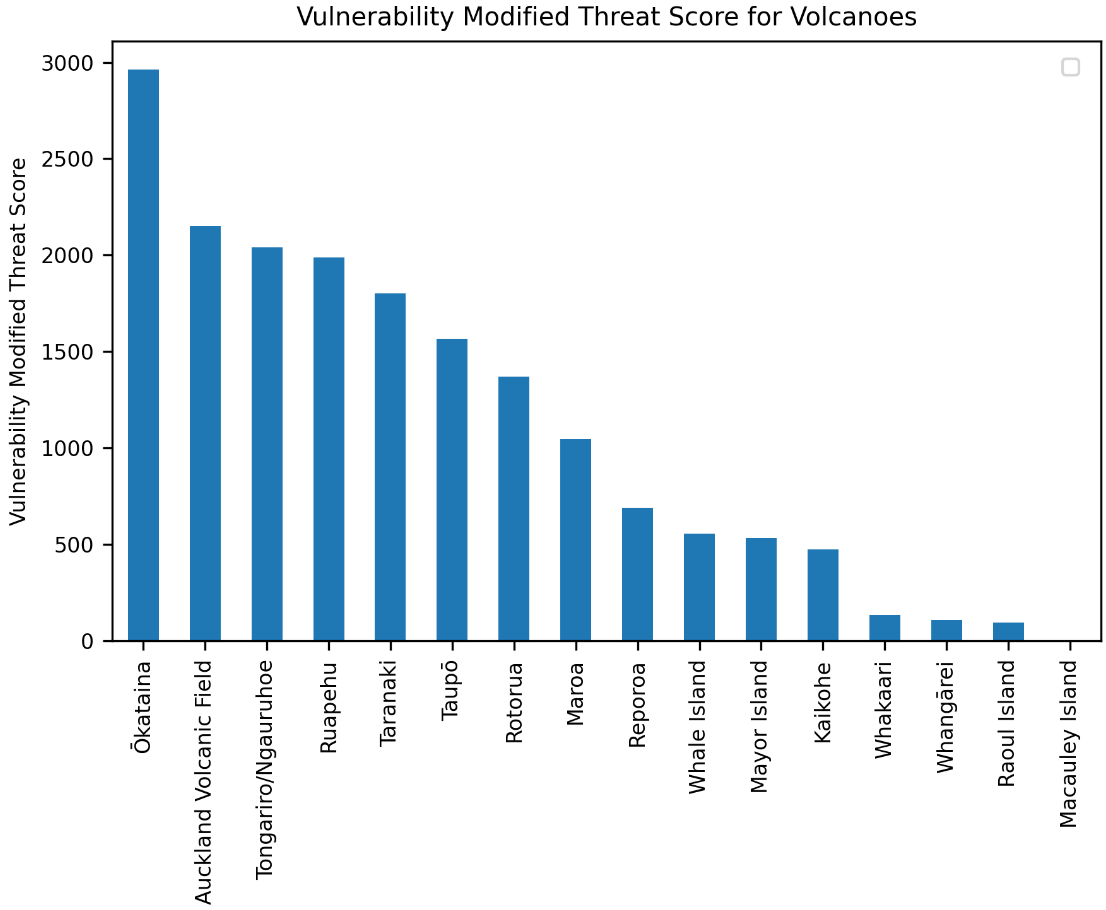

Figure 4.5 Vulnerability-modified threat scores for New Zealand volcanoes.

4.5 Threat Ranking and Grouping

We divide the two ranked threat score distributions into high, medium and low groups, based on the 33% quantiles of each score's distribution (Figures 4.6 and 4.7).

The main impact of the two threat scoring methods is that, without vulnerability, Taupō is placed in the high group, while Tongariro/Ngauruhoe is in the medium group. However, when vulnerability is included, Taupō falls to the medium group and Tongariro/Ngauruhoe rises to the high group. Whakaari also moves from the medium group to the low group when the vulnerability score is included in the threat calculation.

Regardless of scoring method, the highest-threat group covers the most recently active caldera (Ōkataina), the two largest stratovolcanoes (Taranaki and Ruapehu) and the largest active volcanic field (Auckland).

The medium-threat group contains the less recently active calderas and smaller stratovolcanoes, while the low-threat group covers the inactive Kaikohe / Bay of Islands and Whangārei volcanic fields and the distal island volcanoes.

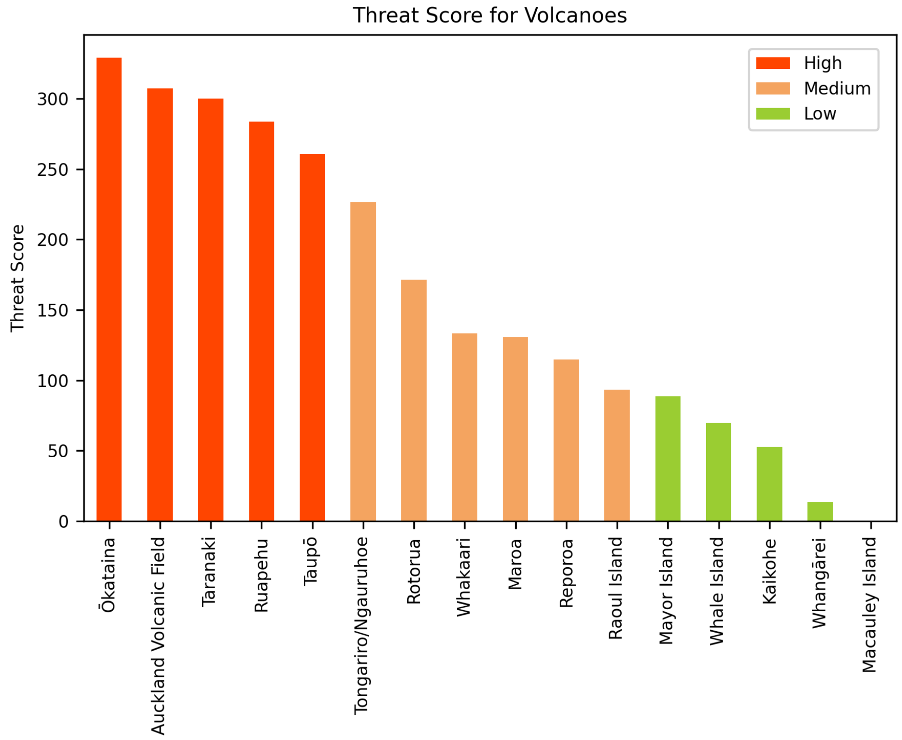

Figure 4.6 Threat ranking of New Zealand's volcanoes coloured by high, medium and low groups.

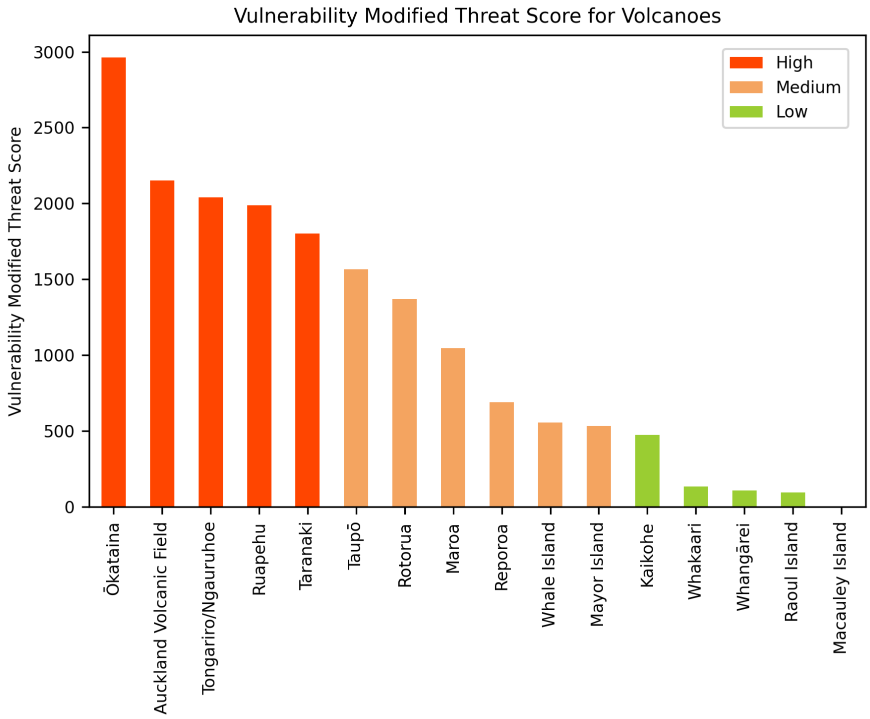

Figure 4.7 Vulnerability-modified threat ranking of New Zealand's volcanoes coloured by high, medium and low groups.

5.0 DISCUSSION

Our assessment of the threat posed by New Zealand’s volcanoes is deliberately simplified to produce a relative ranking of threat for the purpose of identifying which volcanoes warrant greater levels of monitoring instrumentation. We initially simply define threat as *Hazard x Exposure*. Recent studies have included vulnerability (which increases the impact of hazard) and mitigation (which decreases the impact of hazard) metrics to make the threat assessment closer to a quantitative risk assessment (e.g. Nieto-Torres et al. 2021).

To progress toward a more quantitative risk assessment of New Zealand’s volcanoes, we incorporate a vulnerability calculation based on the 2018 NZDEP and examine its impact on our threat scores. The NZDEP was created following the 1991 census following similar international indices and uses nine census values as factors.

Broadly applicable social vulnerability metrics are hard to design, especially when they need to be applicable on a national scale, or transferable on an international scale, as the consistent, continuous databases typically required for this are often absent, incomplete or irregular in their composition. Vulnerability measures derived from global datasets may miss the fine-scale detail important for quantifying vulnerability at a local level. As such, we use existing indices for this study, rather than design our own, and we use the NZDEP as a nationally consistent proxy.

Our use of the NZDEP is purely for the purpose of investigating how the inclusion of a nationally consistent vulnerability metric in our threat assessment might affect threat assessment outcomes.

There are some caveats with using the NZDEP as a proxy for vulnerability, including that the index represents relative socioeconomic deprivation for areas, not people in those areas. Communities with lower economic resources may also exhibit factors that make them more resilient in times of disaster, e.g. closer social connections.

Atkinson et al. (2019a) stress that the Deprivation Index and deprivation score are only measures of deprivation and do not represent whether an area is truly deprived or if its communities suffer because of deprivation. It is also important to note that the Deprivation Index is only a proxy for geographically vulnerable areas and does not fully represent all aspects of vulnerability or consider resilience or connection that local people have to volcanoes that may reduce their vulnerability.

An alternative index of Multiple Deprivation (IMD) has been developed by the University of Auckland (Exeter et al. 2017). This index takes a broader view of deprivation and includes 28 factors across seven domains of employment, income, crime, housing, health, education and access to services. The overall distribution of deprivation between the IMD and NZDEP are broadly similar; however, it is beyond the scope of this study to undertake a full comparison of the two indices.

A final step in our ranking process is to group volcanoes into high-, medium- or low-threat groups. To resolve discrepancies in threat grouping between threat and vulnerability-modified threat scores, we adopt the maximum threat group from either method for use in a final threat grouping (Table 5.1). For example, Whakaari is in the medium threat group and the low vulnerability-modified threat group, so we assigned it to the medium group.

Table 5.1 Grouping of volcanoes by threat and vulnerability-modified threat scores.

Volcano	Threat Group	Vulnerability-Modified Threat Group	Adopted Threat Group
Ōkataina	High	High	High
Auckland	High	High	High
Taranaki	High	High	High
Ruapehu	High	High	High
Taupō	High	Medium	High
Tongariro/Ngauruhoe	Medium	High	High
Rotorua	Medium	Medium	Medium
Whakaari	Medium	Low	Medium
Maroa	Medium	Medium	Medium
Reporoa	Medium	Medium	Medium
Raoul Island	Medium	Low	Medium
Mayor Island	Low	Medium	Medium
Whale Island	Low	Medium	Medium
Kaikohe / Bay of Islands	Low	Low	Low
Whangārei	Low	Low	Low
Macauley Island	Low	Low	Low

It is important to recognise that hazard, exposure, vulnerability and mitigation are dynamic factors that vary over time and at different time scales, hence periodic updates of the scoring are advisable. Such updates could be done if there are new eruptions from a previously quiet volcano (e.g. Te Maari 2012 eruption after 123 years of quiescence) that alter the hazard scoring.

Factors used in exposure scores and deprivation indices, such as population distribution, can also vary over time, typically adding more factors to take a broader view of society. Most of these factors are determined from census data, so updates on census timeframes (5–10 years) could also be considered.

5.1 Changes since the 2012 Review

Figure 5.1 illustrates the changes in volcano ranking between the 2012 review and this review, as well as between the threat and vulnerability-modified threat scores.

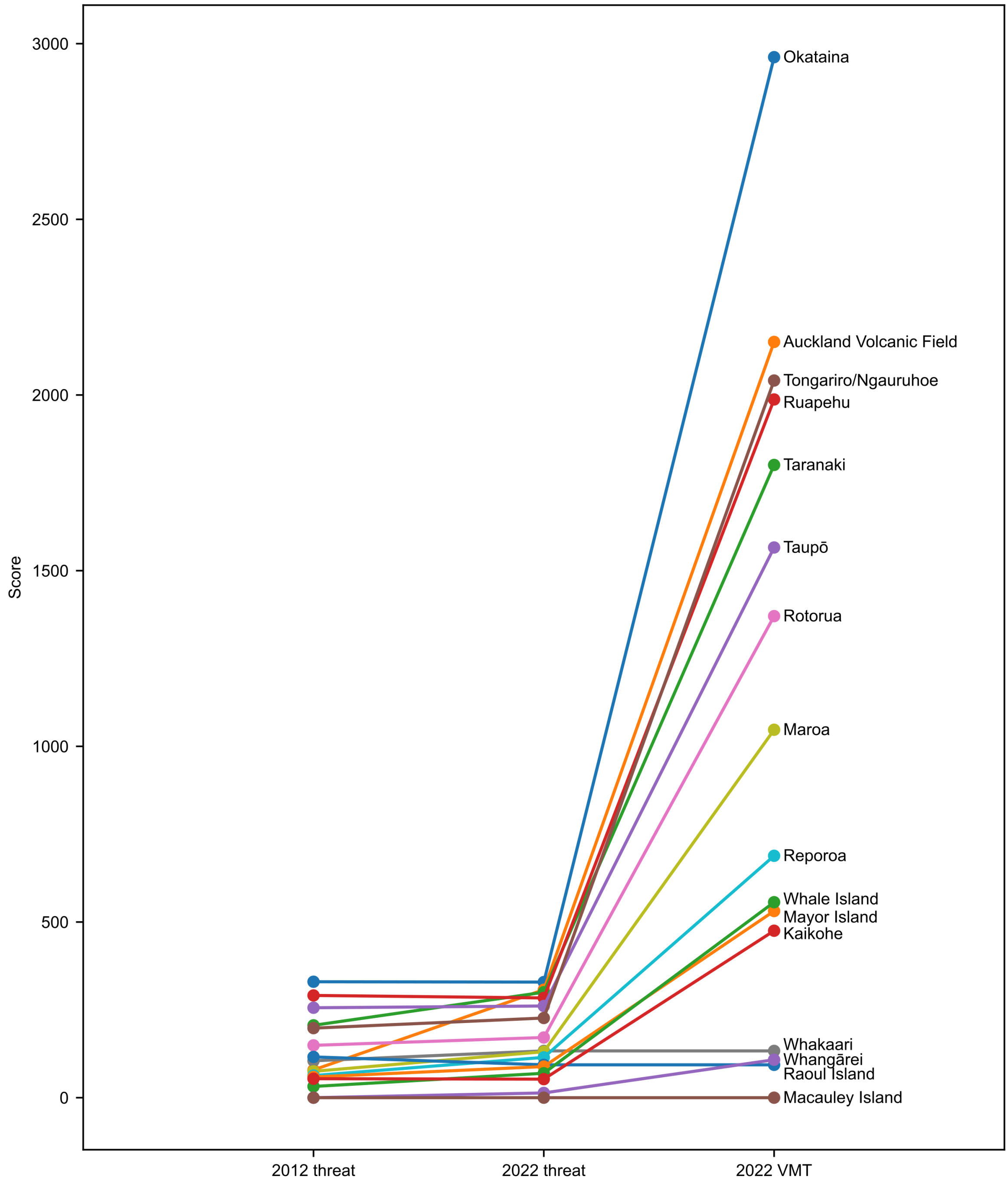

Figure 5.1 Changes in scoring between the 2012 review and 2022 threat and vulnerability-modified threat (VMT) scores.

Ōkataina remains the highest-threat volcano across reviews and scoring methods. Auckland Volcanic Field moves into being the second-highest threat in both 2022 measures on account of the new method of calculating GDP impact on the threat score. Taranaki also moves up rankings from 2012 to 2022, based on the threat score, but moves down slightly when vulnerability is considered. Tongariro/Ngauruhoe also move up when vulnerability is considered. Despite a fatal eruption in 2019, Whakaari remains relatively lowly ranked, reflecting its distance from the mainland and no permanent population.

6.0 CONCLUSIONS AND NEXT STEPS

This report ranks and groups New Zealand volcanoes for the purposes of determining priorities for future monitoring instrumentation upgrades based on the threat that they pose to New Zealand society and infrastructure.

We investigated calculating threat as both *hazard x exposure* and *hazard x exposure x vulnerability* using New Zealand SA2 blocks for areal- and population-based calculations and the NZDEP as a proxy for vulnerability.

We grouped the volcanoes into high-, medium- or low-threat categories based on the maximum of their respective threat and vulnerability threat groupings. The highest threat volcanoes are Ōkataina Volcanic Centre, Auckland Volcanic Field, Taranaki, Ruapehu, Taupō and Tongariro/ Ngauruhoe.

It is intended that these threat groups form the basis for prioritisation of future instrumentation investment, details of which will be developed in a future report.

7.0 ACKNOWLEDGMENTS

Thank you to Josh Hayes and Paul Jarvis for substantive reviews that improved this report.

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APPENDICES

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APPENDIX 1 HAZARD AND EXPOSURE FACTOR SCORES

Table A1.1 Hazard factor scores.

Hazard Factors	Ōkataina	Auckland Volcanic Field	Taranaki	Ruapehu	Taupō	Tongariro/ Ngauruhoe	Rotorua	Whakaari	Maroa	Reporoa	Raoul Island	Mayor Island	Whale Island	Kaikohe	Whangārei	Macauley Island
Volcano type	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1
Maximum volcano explosivity index	3	0	2	2	3	2	3	2	3	3	2	2	1	0	0	2
Eruptive activity in last 500 years	1	1	1	1	0	1	0	1	0	0	1	0	0	0	0	0
Major explosive activity in last 5000 years	1	0	1	1	1	1	0	1	0	0	1	1	0	0	0	1
Eruption recurrence	2	2	3	4	2	4	0	4	0	0	4	2	0	0.5	0	2
Holocene pyroclastic flows	1	1	1	1	1	1	0	1	0	0	1	1	0	0	0	1
Holocene lahars	1	0	1	1	1	1	0	1	0	0	1	0	0	0	0	0
Holocene lava flows	1	1	1	1	1	1	0	0.5	0	0	0.5	1	0	0.5	0	0
Hydrothermal explosion potential	1	0	0.5	1	1	1	1	1	1	1	1	0.5	1	1	0	0.5
Holocene tsunami	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0.5
Sector collapse potential	1	0	1	1	0	1	0	1	0	0	1	0	1	0	0	1
Primary lahar source	1	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0
Observed seismic activity	1	1	1	1	1	1	1	1	1	1	1	1	1	0.5	0.5	0.5
Observed ground deformation	1	0.5	0.5	0	1	1	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Observed fumarolic or magmatic degassing	1	0.5	0.5	1	1	1	1	1	1	1	1	0.5	1	1	0	1
Sum of Hazard Factors	**17**	**7**	**14.5**	**17**	**15**	**18**	**8.5**	**18.5**	8.5	7.5	**17**	**11.5**	**6.5**	**4**	**1**	**11**

Table A1.2 Exposure factor scores.

Exposure Factors	**Ōkataina**	**Auckland Volcanic Field**	**Taranaki**	**Ruapehu**	**Taupō**	**Tongariro/ Ngauruhoe**	**Rotorua**	**Whakaari**	**Maroa**	**Reporoa**	**Raoul Island**	**Mayor Island**	**Whale Island**	**Kaikohe**	**Whangārei**	**Macauley Island**
Log10 of population at 30 km	4.9	6.1	4.9	3.6	4.5	3.7	4.9	0.5	4.5	4.1	1.0	1.8	4.5	4.6	4.9	0.0
Log10 of population exposed to flow hazards	2.5	3.8	3.5	2.5	3.5	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Percentage Gross Domestic Product within 50 km	3.2	24.3	1.7	0.6	2.4	0.9	3.1	0	3	3.3	0	0.5	1.5	1.2	1.2	0
Historic fatalities	1	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0
Historic evacuations	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Local aviation exposure	2	2	2	2	2	2	2	2	2	2	0	2	2	2	2	0
Regional aviation exposure	2.8	4.7	3.1	0	2	0	3.2	1.7	2.9	2.9	0	2.9	1.7	2.4	2.4	0
Power infrastructure	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	0
Transport infrastructure	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	0
Major development or sensitive areas	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	0
Significant part of populated island	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Short-term visitors exposed to local hazard	0	0	2.5	4	0	3	0	2	0	0	0.5	0.5	1	0	0	0
Sum of Exposure Factors	**19.4**	**43.9**	**20.7**	**16.7**	**17.4**	**12.6**	**20.2**	**7.2**	**15.4**	**15.3**	**5.5**	**7.7**	**10.7**	**13.2**	**13.5**	**0.0**

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