Bull Volcanol (2005) 67:340–349
DOI 10.1007/s00445-004-0375-5

RESEARCH PAPER

Christina Magill · Russell Blong

Volcanic risk ranking for Auckland, New Zealand. II: Hazard consequences and risk calculation

Received: 16 April 2003 / Accepted: 29 April 2004 / Published online: 10 July 2004

Abstract In a companion paper, a methodology for ranking volcanic hazards and events in terms of risk was presented, and the *likelihood* and *extent* of potential hazards in the Auckland Region, New Zealand investigated. In this paper, the effects of each hazard are considered and the risk ranking completed. Values for *effect* are proportions of total loss and, as with *likelihood* and *extent*, are based on order of magnitude.

Two outcomes were considered – building damage and loss of human life. In terms of building damage, tephra produces the highest risk by an order of magnitude, followed by lava flows and base surge. For loss of human life, risk from base surge is highest. The risks from pyroclastic flows and tsunami are an order of magnitude smaller. When combined, tephra fall followed by base surge produces the highest risk. The risks from lava flows and pyroclastic flows are an order of magnitude smaller. For building damage, the risk from Mt. Taranaki volcano, 280 km from the Auckland CBD, is largest, followed by Okataina volcanic centre, an Auckland volcanic field eruption centred on land, then Tongariro volcanic centre. In terms of human loss, the greatest risk is from an Auckland eruption centred on land. The risks from an Auckland eruption centred in the ocean, Okataina volcanic centre, and Taupo volcano are more than an order of magnitude smaller. When combined, the risk from Mt. Taranaki remains highest, followed by an Auckland eruption centred on land. The next largest risks are from the Okataina and Tongariro volcanic centres, followed by Taupo volcano.

Three alternative situations were investigated. As multiple eruptions may occur from the Auckland volcanic field, it was assumed that a local event would involve two eruptions. This increased risk of a local eruption occurring on land so that it was equal to that of an eruption from Mt. Taranaki. It is possible that a future eruption may be of a similar, or larger size, to the previous Rangitoto eruption. Risk was re-calculated for local eruptions based on the extent of hazards from Rangitoto. This increased the risk of lava flow to greater than that of base surge, and the risk from an Auckland land eruption became greatest. The relative probabilities used for Mt. Taranaki volcano and the Auckland volcanic field may only be minimum values. When the probability of these occurring was increased by 50%, there was no change in either ranking.

Keywords Auckland region · Auckland volcanic field · Mt. Taranaki · Multiple hazards · Risk assessment · Taupo volcanic zone · Volcanic loss

Editorial responsibility: J. S. Gilbert

C. Magill (✉) · R. Blong
Risk Frontiers, Macquarie University,
NSW 2109, Australia
e-mail: cmagill@els.mq.edu.au
Tel.: +61-2-98506310
Fax: +61-2-98509394

Introduction

In Magill and Blong (2004) a methodology was presented for ranking volcanic hazards and events in terms of risk. This was then applied to the Auckland Region, New Zealand. Events, in this sense, include only eruptions that impact the Auckland Region and may, in the case of the Auckland volcanic field, include multiple eruptions from more that one location.

Risk is calculated as the product of *likelihood*, *extent* and *effect* of a hazard, the relative probability of the event occurring ($probability_e$) and, if more than one outcome is considered, the relative importance of the outcome ($importance_o$). The first three parameters are proportions, where *likelihood* is the probability of the hazard occurring conditional on the volcanic event occurring, *extent* is the spatial proportion of the study area affected and *effect* is the proportional outcome within the area affected. Values for these three parameters are obtained by assigning hazards to order of magnitude categories, with values assigned to each category.

In the previous paper, $probability_e$ was determined for each volcanic source potentially impacting the Auckland

Region, and *likelihood* and *extent* values were assigned to individual hazards. In this paper two outcomes of volcanic hazards are considered – building damage and the loss of human lives. Values for *effect* are assigned to individual hazards and *importance*$_o$ is calculated for each outcome. Using the values determined in both papers, a risk ranking is carried out using the method outlined in the companion paper. An advantage of this method is that uncertainties can be easily tested. This is demonstrated for several alternative situations.

Outcomes

The possible impact on Auckland from a future eruption was highlighted by the relatively small 1995–1996 eruptions of Ruapehu. Tephra fall only occurred in trace amounts, and was not thick enough to be preserved, but did close the Auckland International Airport for a day on 18 June 1996, resulting in lost revenue and travel disruptions (Johnston et al 2000; Auckland Engineering Lifelines Group 2001).

A number of studies have assessed the effects of a future Auckland volcanic field eruption. Johnston et al (1997) assessed the likely impact on buildings, infrastructure, critical facilities, population, economic activities and natural features, and Paton et al (1999) included calculations of the costs of tephra clean-up and removal. The Auckland Regional Council (1999) investigated a variety of natural perils, including both local and distal volcanic eruptions, to assess risks to critical utility networks within the Auckland Region. Auckland Engineering Lifelines Group (2001) focused on the impact of tephra fall on lifelines within the Region, and included assessments of the quantity of ash to be removed, transportation methods, health and safety, and environmental and legal issues.

In this study the outcomes investigated are building damage and the loss of human life. These two outcomes represent two major impacts that future volcanic events may generate within the Auckland Region.

The relative importance of each outcome (*importance*$_o$) was calculated by comparing total possible losses. Mrozek and Taylor (2002) estimated the value of a statistical life (via a meta-analysis of 33 previous studies) to be between approximately \$1.5 and \$2.5 million (1998) US dollars. For the present purpose, a single value of NZ\$4 million dollars (approximately US\$2.2 million in March 2003) is used. On the night of the 2001 census, the population of the Auckland Region was approximately 1,173,000. Using these values, a total value of NZ\$4,700 billion can be assigned to the population of Auckland. Cousins and Heron (2001) give a total replacement value of NZ\$88.2 billion dollars for all commercial, industrial, recreational and residential buildings within Auckland. Therefore, human inventory is approximately 50 times more important, in dollar terms, than building inventory and *importance*$_o$ values of 0.98 and 0.02 were assigned.

Table 1 Minimum proportions of total building loss for each category and associated average cost per building based on a replacement value of NZ\$200,000

Category	Value	Minimum proportion of total loss	Minimum average cost
1	1	0.316	63,000
2	0.1	0.0316	6300
3	0.01	0.00316	630
4	0.001	0.000316	63

Hazard effects

The effect of a hazard depends on the susceptibility of the item affected and the properties of the hazard. Proportions of total loss for buildings and human life, within the *extent*, were determined and *effect* values assigned. For simplicity, we assumed the population to be evenly distributed throughout the affected area.

Building damage

In this study only direct building damage was considered. Clean up and removal costs were not included. Order of magnitude categories for *effect* were based on the proportion of total building loss. So that values could be more easily assigned to categories, a minimum proportion of total loss was given to each category based on an average total replacement value of \$200,000 (Table 1). This was calculated using Eq. 8 in Magill and Blong (2004):

$$\text{Minimum}_n = 10^{(0.5-n)} \quad (1)$$

Each hazard was assigned to categories (Table 2), in a relative manner, based on the following observations:

The greatest damage to buildings would occur as the result of pyroclastic flows, base surge, lava flow and scoria fall. Pyroclastic flows and base surge will cause almost total damage to buildings due to their extreme velocity and temperature. If a building were impacted by either of these hazards total replacement would be necessary. Because of extremely high temperatures and pressures, lava and scoria fall will also destroy any building they come in contact with.

Much of the literature dealing with building damage due to tephra fall assesses structural failure of buildings due to a large thickness of tephra (Spence et al 1996; Pomonis et al 1999; Blong 2003). Sandiford et al (2001) and Shane and Hoverd (2002) listed thicknesses for each tephra layer identified within the Pukaki and Onepoto cores (Table 3). The median thickness of tephra fall from the Auckland volcanic field is 4 mm, from andesitic centres, 1.5 mm, and from distal rhyolitic sources, 3 mm. This thickness would not cause any structural damage to buildings. Damage would be mainly due to corrosion of paintwork and roof coatings (Blong 1984; Johnston et al 2000; Blong 2003) and damage to air conditioning units (Johnston et al 2000). Dry tephra could penetrate inside

Table 2 Hazards assigned to *effect* categories based on building damage, and values given to each

Category	Value	$Auckland_o$	$Auckland_l$	Tuhua	Okataina	Taupo	Tongariro	Taranaki
1	1	lava surge	lava scoria surge		flow	flow		
2	0.1	tsunami	flooding					
3	0.01	flooding mudflow	earthquake mudflow	flooding mudflow	flooding mudflow	flooding mudflow	flooding mudflow	flooding mudflow
4	0.001	earthquake gases lightning tephra	gases lightning tephra	gases tephra	gases tephra	gases tephra	gases tephra	gases tephra
No effect	0			climate earthquake	climate earthquake	climate earthquake	climate	climate

Events are: Auckland volcanic field eruption in ocean ($Auckland_o$); Auckland volcanic field eruption on land ($Auckland_l$); Tuhua volcanic eruption (Tuhua); Okataina volcanic centre eruption (Okataina); Taupo volcano eruption (Taupo); Tongariro volcanic centre eruption (Tongariro); Mt. Taranaki volcano eruption (Taranaki). Hazards are: climate variation (climate); earthquakes and ground deformation (earthquake); flooding (flooding); pyroclastic flow (flow); poisonous gases and acid rain (gases); lava flow (lava); lightning (lightning); mudflow and mudfills (mudflow); scoria fall and ballistic impacts (scoria); base surge (surge); tephra fall (tephra); tsunami (tsunami)

Table 3 Number of tephra layers identified from each source, eruption type, and for all sources combined, from the Pukaki and Onepoto cores and median and mean thickness. Data from Sandiford et al (2001) and Shane and Hoverd (2002)

Source	Pukaki			Onepoto			Combined		
	Layers	Mean thickness (mm)	Median thickness (mm)	Layers	Mean thickness (mm)	Median thickness (mm)	Layers	Mean thickness (mm)	Median thickness (mm)
Auckland volcanic field	7	8.5	1.0	8	30	8.0	15	20	4.0
Tuhua volcano[a]	1	70	70	0	-	-	1	70	70
Okataina volcanic centre	9	4.9	3.0	14	54	2.0	17	44	2.5
Taupo volcano	3	8.8	3.5	4	9.3	4.5	4	8.8	4.9
TVZ[b]	0	-	-	11	5.6	3.0	11	5.6	3.0
Tongariro volcanic centre	5	1.1	1.0	3	1.7	2.0	7	1.3	1.0
Mt. Taranaki volcano	14	1.8	1.0	39	3.0	2.0	50	2.7	1.8
Local basalt	7	8.5	1.0	8	30	8.0	15	20	4.0
Distal andesite	19	1.6	1.0	42	2.9	2.0	57	2.5	1.5
Distal rhyolite	13	11	3.0	29	29	2.0	33	28	3.0
All sources	39	5.9	1.0	79	15	2.0	105	13	2.0

[a] Values likely to be overestimated, as they are based on one tephra layer; [b] older rhyolitic tephra, from Okataina, Taupo or possibly Maroa volcanic centre

buildings (Johnston et al 2000; Blong 2003) and damage carpets, walls, ceilings and possibly electrical appliances. Tephra also has the potential to short-circuit electrical systems, resulting in fires (Blong 1984). Although these problems would be costly, it is unlikely that every building would be affected. However, we believe the value assigned to tephra fall may still be conservative.

Because the expected thickness of tephra fall is small, associated mudflows are also likely to be of small volume. Damage will occur to buildings if mud enters under doorways. This may be common in the case of garage doors at the end of steep driveways. Gases and acid rain may cause corrosion to the exterior of buildings, although this could be reduced if cleaning occurs following the eruption.

Strong earthquakes and ground deformation could result in structural damage to buildings although this will be restricted to areas close to the vent of a local eruption. Earthquakes from distal eruptions will be of very small shaking intensity in Auckland and will not result in building damage.

Flooding caused by lava could displace large amounts of water and potentially damage both the interior and exterior of buildings. If flooding occurs due to tephra accumulation, the volume of water will be less and less damage will occur. Tsunami generated by an eruption in the ocean are only likely to be of a small height and so would result in only small amounts of damage.

Lightning is distinct from other hazards in that it only affects a small percentage of buildings within the extent. Although the percentage of buildings affected is likely to be small, lightning may result in fires, completely destroying the building.

Table 4 Minimum proportions of human loss for each category and approximate number of deaths, based on a population of 1,173,000 over an area of 5000 km^2, for various minimum extents

Category	Value	Minimum proportion of total loss	Minimum number of deaths for various minimum extents					
			1600 km^2	160 km^2	16 km^2	1.6 km^2	0.16 km^2	0.016 km^2
1	1	0.316	120,000	12,000	1200	120	12	1.2
2	0.1	0.0316	12,000	1200	120	12	1.2	-
3	0.01	0.00316	1200	120	12	1.2	-	-
4	0.001	0.000316	120	12	1.2	-	-	-
5	0.0001	0.0000316	12	1.2	-	-	-	-
6	0.00001	0.00000316	1.2	-	-	-	-	-

Table 5 Hazards assigned to *effect* categories based on human loss, and values given to each

Category	Value	Auckland$_o$	Auckland$_l$	Tuhua	Okataina	Taupo	Tongariro	Taranaki
1	1				flow	flow		
2	0.1	surge	surge					
3	0.01	tsunami						
No effect	0	earthquake flooding gases lava lightning mudflow tephra	earthquake flooding gases lava lightning scoria mudflow tephra	climate earthquake flooding gases mudflow tephra	climate earthquake flooding gases mudflow tephra	climate earthquake flooding gases mudflow tephra	climate flooding gases mudflow tephra	climate flooding gases mudflow tephra

Events and hazards as in Table 2

It is widely considered that climate variation associated with volcanic eruptions will be within normal annual variations (Self et al 1981; Sadler and Grattan 1999). Therefore climate variation is not expected to result in any extra damage to buildings.

Loss of human life

Categories determined for loss of life (Table 4) were based on minimum proportions of the Auckland population. These were calculated for each *extent* so *effect* values could be easily assigned (Table 5). Only direct deaths due to hazards were considered. Injuries, health problems and deaths due to associated accidents were not included. The proportion of deaths is equal to the probability that people will remain within the extent, multiplied by the probability that people remaining will be killed. Hazards were assigned to categories using the following assumptions.

It is probable that in a future Auckland volcanic field eruption successful evacuation would mean that very few people would remain close to the vent. Warning of an eruption would probably occur a few days to a few weeks before, with evacuation planned for an initial 3 km radius from the vent (Beca Carter & Ferner 2002). Deaths would be restricted to people who refuse to leave, or return to their homes, and possibly people involved in emergency management. In the case of a distal eruption it is likely that most of the population will remain within the Auckland area. It is also likely that the population of Auckland will increase due to people relocating from areas closer to the volcanic source.

The hazards that will potentially produce the largest loss of life within the Auckland population are base surge and pyroclastic flows. In the literature the effects of these have been largely grouped together. Deaths may occur from thermal burns, asphyxia due to inhaling volcanic material, burial, severe trauma and collapse of buildings (Baxter 1990). Within Auckland, the differences in potential death tolls between these hazards result from different concentrations of people remaining within the area affected. It is probable that evacuation will occur within the area affected by base surge. However, because base surge may occur quickly and unexpectedly the probability of deaths remains reasonably high. If a pyroclastic flow was to impact the Region it is likely that no evacuation would have occurred.

Buildings have been known to protect people from pyroclastic flows and surges (Baxter 1990; Baxter et al 1998). In the case of base surge from an Auckland eruption the casualties are still likely to be very high. By the time a pyroclastic flow reaches Auckland from a distal source its intensity would be greatly reduced. Therefore, people remaining within their houses may have a better chance of survival.

Tsunami may also cause deaths due to their largely unexpected nature. A tsunami is unlikely to penetrate a large distance inland. However, in the case of an offshore eruption in the Auckland volcanic field, increased numbers of people may flock to the coast and therefore be at risk.

Inhaling tephra can result in various health problems, particularly for asthma sufferers and people with chronic respiratory conditions. However, during the Mount St. Helens eruption no deaths were recorded as a result of these conditions (Baxter 2000). Deaths from tephra fall are only likely to occur due to large volumes resulting in building collapse. As this is only expected at distances very close to source, it will be assumed for this purpose that successful evacuation would have occurred. It is therefore unlikely that any deaths will occur as a direct result of tephra fall within Auckland.

Lava travels very slowly; even if evacuation has not occurred people would manage to escape and deaths are not expected to occur (Tanguy et al 1998; Peterson and Tilling 2000). This is also the case for flooding due to lava flows. The magnitude of flooding caused by tephra is very small and will not result in any deaths.

Close to the source, where ground deformation will occur, it is expected that evacuation would take place. Further from the source, earthquakes would be small and not result in any deaths. The intensity of earthquakes from a distal eruption would be far too small to result in deaths within Auckland.

As previously discussed, the likely thickness of mudflows will be small. Therefore it is not expected that any direct deaths will result. In the area affected by scoria fall and ballistic impacts, evacuation would have almost certainly occurred. This is also the case for the area affected directly by large amounts of volcanic gases. Acid rain should not result in any deaths.

The probability of lightning resulting in deaths, within the expected extent, is too small to be included. It is likely that the population within this area will be further reduced due to evacuation. As previously mentioned, climate variation is unlikely to be large and, as the population does not rely on agriculture for survival, deaths are therefore not expected.

Risk calculation

Risk was calculated for building damage (Table 6) and loss of human life (Table 7) for every hazard caused by each volcanic event, using Eq. 3 in Magill and Blong (2004):

$$risk = likelihood \times extent \times effect \times probability_{\mathrm{e}} \qquad (2)$$

The values calculated for building damage vary by six orders of magnitude. It is interesting to note that the largest risks are associated with tephra fall from distal locations. Although these tephra falls will be thin, high *likelihood* and large *extent* means that risk is high. The next largest risks are from lava flow and base surge from an Auckland eruption centred on land. Although the *extent* of these hazards is small their *effect* is very large and therefore so is their risk. Risks for pyroclastic flows from Okataina and Taupo rate higher than would be expected and have the same order of magnitude as mudflows from most other centres. Although *likelihood* is very small the huge impact means that risk is high. The smallest risks are associated with flooding.

Direct loss of human life is only expected to occur from three hazards. The largest risk, by an order of magnitude, is from base surge from an Auckland eruption on land. This is followed by the risk of pyroclastic flows from Okataina, base surge and tsunami from an Auckland eruption centred in the ocean, and pyroclastic flows from Taupo.

These values of *risk* were further multiplied by the relative importance of the outcome using Eq. 4 in Magill and Blong (2004):

$$risk = likelihood \times extent \times effect \times probability_{\mathrm{e}} \times importance_{\mathrm{o}} \qquad (3)$$

As determined earlier, total building and human loss have $importance_{\mathrm{o}}$ values of 0.02 and 0.98 respectively. Individual risk values for human loss were added to those for building damage to determine a combined risk rating (Table 8). Risk from base surge from an Auckland

Table 6 Risk of building damage due to volcanic events and hazards after relative probability (*probability*$_e$) has been assigned to each event. Highest values in bold

Hazard	Volcanic event							Total
	Auckland$_{\mathrm{o}}$	Auckland$_{\mathrm{l}}$	Tuhua	Okataina	Taupo	Tongariro	Taranaki	
Climate	0	0	0	0	0	0	0	0
Earthquake	1.1×10^{-6}	5.4×10^{-6}	0	0	0	0	0	6.5×10^{-6}
Flooding	1.1×10^{-9}	5.4×10^{-8}	2.0×10^{-10}	1.8×10^{-9}	8.2×10^{-10}	1.2×10^{-9}	4.3×10^{-9}	6.3×10^{-8}
Flow	0	0	0	1.8×10^{-7}	8.2×10^{-8}	0	0	2.7×10^{-7}
Gases	1.1×10^{-7}	5.4×10^{-8}	2.0×10^{-7}	1.8×10^{-6}	8.2×10^{-7}	1.2×10^{-6}	4.3×10^{-6}	8.5×10^{-6}
Lava	1.1×10^{-6}	$\mathbf{5.4\times10^{-5}}$	0	0	0	0	0	5.5×10^{-5}
Lightning	1.1×10^{-8}	5.4×10^{-8}	0	0	0	0	0	6.5×10^{-8}
Mudflow	1.1×10^{-7}	5.4×10^{-8}	2.0×10^{-8}	1.8×10^{-7}	8.2×10^{-8}	1.2×10^{-7}	4.3×10^{-7}	1.0×10^{-6}
Scoria	0	5.4×10^{-6}	0	0	0	0	0	5.4×10^{-6}
Surge	1.1×10^{-6}	$\mathbf{5.4\times10^{-5}}$	0	0	0	0	0	5.5×10^{-5}
Tephra	$\mathbf{1.1\times10^{-5}}$	5.4×10^{-6}	$\mathbf{2.0\times10^{-5}}$	$\mathbf{1.8\times10^{-4}}$	$\mathbf{8.2\times10^{-5}}$	$\mathbf{1.2\times10^{-4}}$	$\mathbf{4.3\times10^{-4}}$	8.5×10^{-4}
Tsunami	1.1×10^{-6}	0	0	0	0	0	0	1.1×10^{-6}
Total	1.5×10^{-5}	1.2×10^{-4}	2.0×10^{-5}	1.9×10^{-4}	8.5×10^{-5}	1.2×10^{-4}	4.3×10^{-4}	–

Events and hazards as in Table 2

Table 7 Risk of human loss due to volcanic events and hazards after relative probabilities (*probability*$_e$) have been assigned to each event. Highest values in bold

Hazard	Volcanic event							
	Auckland$_o$	Auckland$_l$	Tuhua	Okataina	Taupo	Tongariro	Taranaki	Total
Climate	0	0	0	0	0	0	0	0
Earthquake	0	0	0	0	0	0	0	0
Flooding	0	0	0	0	0	0	0	0
Flow	0	0	0	**1.8×10^{-7}**	8.2×10^{-8}	0	0	2.7×10^{-7}
Gases	0	0	0	0	0	0	0	0
Lava	0	0	0	0	0	0	0	0
Lightning	0	0	0	0	0	0	0	0
Mudflow	0	0	0	0	0	0	0	0
Scoria	0	0	0	0	0	0	0	0
Surge	**1.1×10^{-7}**	**5.4×10^{-6}**	0	0	0	0	0	5.5×10^{-6}
Tephra	0	0	0	0	0	0	0	0
Tsunami	**1.1×10^{-7}**	0	0	0	0	0	0	1.1×10^{-7}
Total	2.2×10^{-7}	5.4×10^{-6}	0	1.8×10^{-7}	8.2×10^{-8}	0	0	–

Events and hazards as in Table 2

Table 8 Total risk (building damage and humans loss) due to volcanic events and hazards after relative importance has been assigned to each outcome (*importance*$_o$). Highest values in bold

Hazard	Volcanic event							
	Auckland$_o$	Auckland$_l$	Tuhua	Okataina	Taupo	Tongariro	Taranaki	Total
Climate	0	0	0	0	0	0	0	0
Earthquake	2.2×10^{-8}	**1.1×10^{-7}**	0	0	0	0	0	1.3×10^{-7}
Flooding	2.2×10^{-11}	1.1×10^{-9}		4.0×10^{-12}	3.7×10^{-11}	1.6×10^{-11}	2.4×10^{-11}	8.6×10^{-11}
1.3×10^{-9}								
Flow	0	0	0	**1.8×10^{-7}**	8.2×10^{-8}	0	0	2.7×10^{-7}
Gases	2.2×10^{-9}	1.1×10^{-9}	4.0×10^{-9}	3.7×10^{-8}	1.6×10^{-8}	2.4×10^{-8}	8.6×10^{-8}	1.7×10^{-7}
Lava	2.2×10^{-8}	**1.1×10^{-6}**	0	0	0	0	0	1.1×10^{-6}
Lightning	2.2×10^{-10}	1.1×10^{-9}	0	0	0	0	0	1.3×10^{-9}
Mudflow	2.2×10^{-9}	1.1×10^{-9}		4.0×10^{-10}	3.7×10^{-9}	1.6×10^{-9}	2.4×10^{-9}	8.6×10^{-9}
2.0×10^{-8}								
Scoria	0	**1.1×10^{-7}**	0	0	0	0	0	1.1×10^{-7}
Surge	**1.3×10^{-7}**	**6.4×10^{-6}**	0	0	0	0	0	6.5×10^{-6}
Tephra	**2.2×10^{-7}**	**1.1×10^{-7}**	**4.0×10^{-7}**	**3.7×10^{-6}**	**1.6×10^{-6}**	**2.4×10^{-6}**	**8.6×10^{-6}**	1.7×10^{-5}
Tsunami	**1.3×10^{-7}**	0	0	0	0	0	0	1.3×10^{-7}
Total	5.2×10^{-7}	7.8×10^{-6}	4.0×10^{-7}	3.9×10^{-6}	1.7×10^{-6}	2.5×10^{-6}	8.7×10^{-6}	–

Events and hazards as in Table 2

eruption on land increased to second highest after tephra fall from Taranaki. Risk from pyroclastic flows also increased significantly.

Risk ranking

Total risk from each hazard and event (Table 8) were calculated using Eqs. 5 and 6 in Magill and Blong (2004):

$$TotalRisk_{\mathrm{h}} = \sum risk_{\mathrm{h}} \tag{4}$$

$$TotalRisk_{\mathrm{e}} = \sum risk_{\mathrm{e}} \tag{5}$$

Results were ranked in order of importance and normalised so that the sum was equal to 1. This allowed comparisons to be made more easily. In terms of building damage (Fig. 1a) tephra has the highest total risk by an order of magnitude. This is significant as the *effect* values assigned to tephra fall were conservative. Risk from tephra fall is followed by lava flow and base surge. For loss of human life (Fig. 1b), risk from base surge is highest. The risks from pyroclastic flows and tsunami are an order of magnitude smaller. When combined (Fig. 1c), tephra followed by base surge produce the highest risks. The risks from lava and pyroclastic flows are an order of magnitude smaller.

It is instructive to look at these rankings separately for local and distal events. For local hazards (Fig. 2a), lava flow and base surge produced the largest risk in terms of building damage followed by tephra fall. In terms of human loss (Fig. 2b), base surge is by far the highest risk, followed by tsunami, more than order of magnitude smaller. When these risks are combined (Fig. 2c), risk from base surge is largest followed by lava flow.

The risk of building damage from distal hazards (Fig. 3a) is greatest from tephra fall. The risks from poisonous gases and acid rain are two orders of magnitude

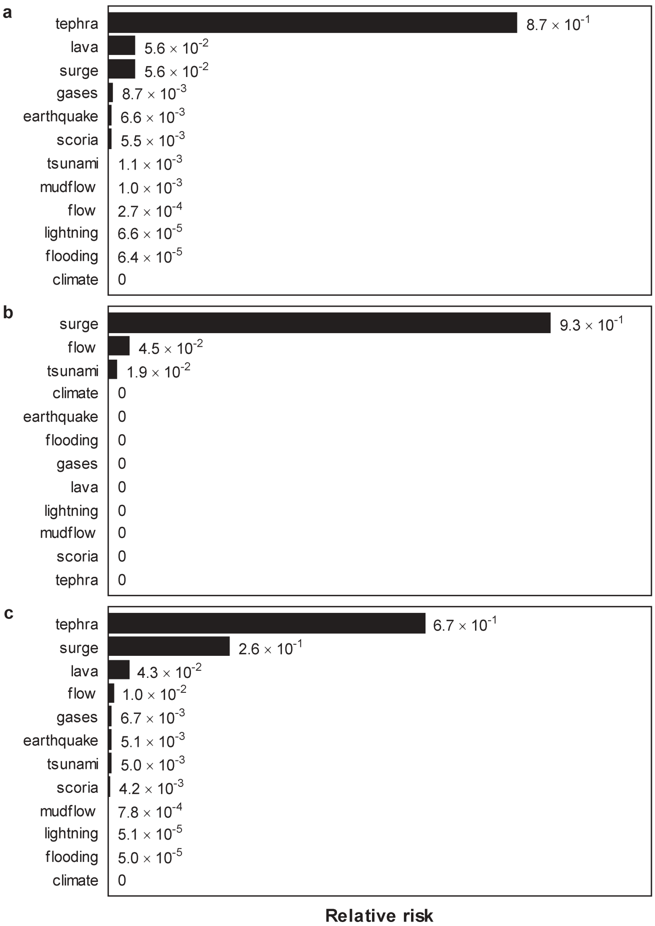

Fig. 1 Hazard ranking for local and distal events showing normalised relative risk values for: **a** building damage, **b** human loss, and **c** combined loss

smaller. The only risk to human life from a distal eruption is from pyroclastic flows (Fig. 3b). When these risks are combined (Fig. 3c), risk from tephra fall remains largest. The risk from pyroclastic flows is more than an order of magnitude smaller, followed closely by poisonous gases and acid rain.

Ranking of volcanic events was also carried out. For building damage (Fig. 4a), risk from Taranaki was highest, due to the large probability of occurrence. Next was Okataina, followed by an Auckland eruption centred on land, and a Tongariro eruption. The greatest risk to human life (Fig. 4b) comes from an Auckland eruption on land. The risks from an Auckland eruption centred in the ocean and from Okataina and Taupo events are more than an order of magnitude smaller. When these risks are combined (Fig. 4c), the risk from Taranaki volcano remains highest, followed by an Auckland eruption centred on land. The next largest risks are from the Okataina and Tongariro volcanic centres, followed by Taupo volcano.

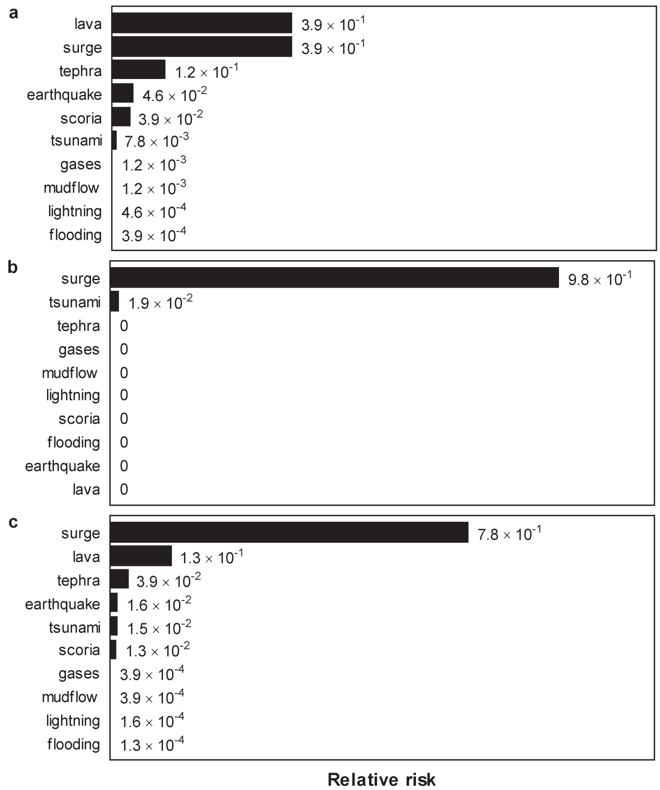

Fig. 2 Hazard ranking for local events showing normalised relative risk values for: **a** building damage, **b** human loss, and **c** combined loss

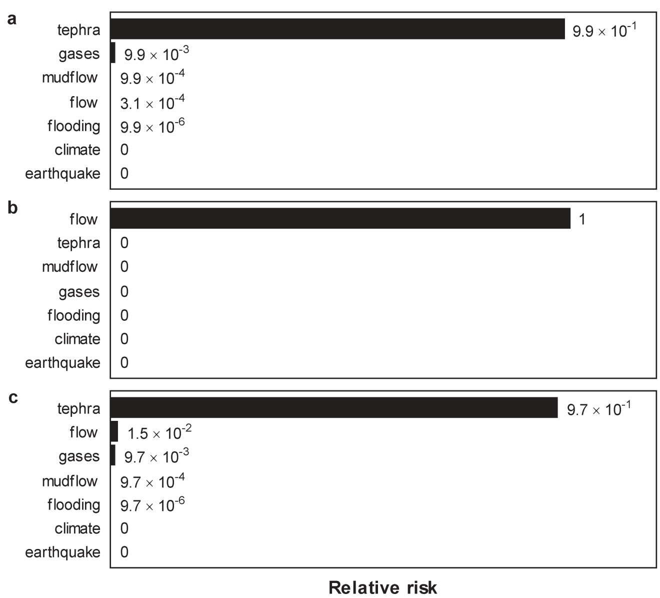

Fig. 3 Hazard ranking for distal events showing normalised relative risk values for: **a** building damage, **b** human loss, and **c** combined loss

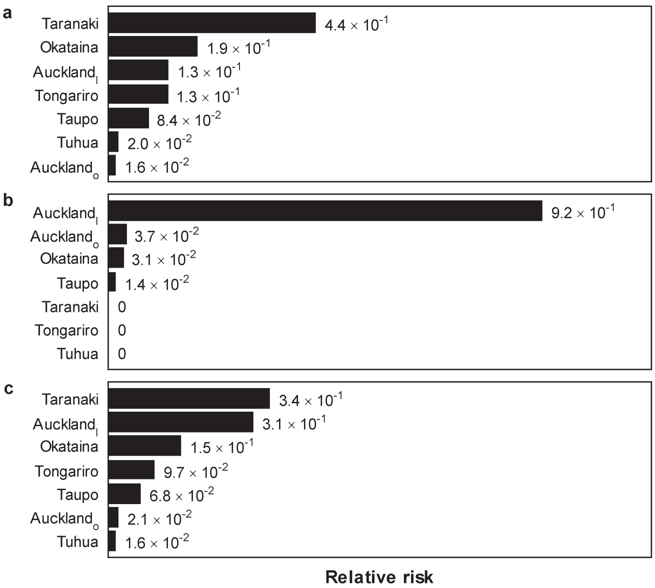

Fig. 4 Event ranking showing normalised relative risk values for: **a** building damage, **b** human loss, and **c** combined loss

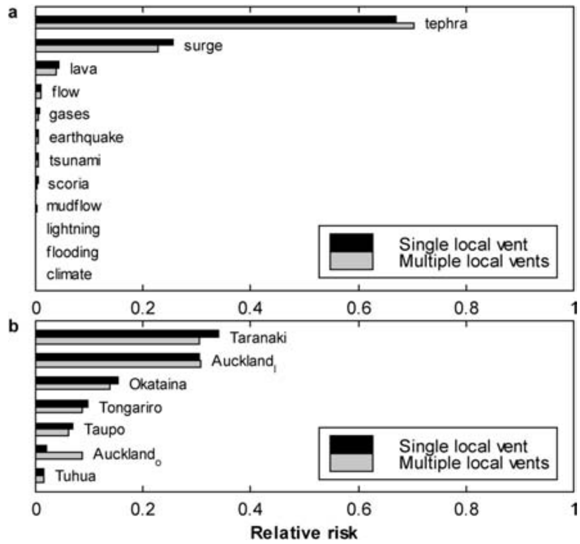

Fig. 5 Normalised relative risk values for **a** volcanic hazards and **b** volcanic events, comparing local events from one and two locations

Alternative rankings

Using the methodology set out here, uncertainties can be quickly tested to see if any changes in ranking occur. Three alternative situations are discussed.

Multiple local eruptions

It is possible that multiple eruptions may occur from the Auckland volcanic field, either simultaneously or within a short period of time (Rout et al 1993; Cassidy et al 1999). This would increase the area affected by the event.

The same calculations were carried out, assuming the next local event would involve two eruptions of the size already calculated. Although it is possible that hazards from both eruptions could impact the same area, it was assumed that eruptions would be far enough apart so that the localised hazards – base surge, scoria fall, and lava flow – would not overlap.

The *extent* of tephra – and therefore mudflow – increases, moving into the next higher category. Although the area affected increases, earthquakes, gases, lava flow, lighting, scoria, base surge, and tsunami remain within the same category and *extent* does not change.

Increasing *extent* for tephra fall and mudflows by an order of magnitude increased the risk values of these hazards slightly but did not affect the hazard risk ranking (Fig. 5a). Risk from a local eruption on land increased so that it was equal to that of a Taranaki eruption, and risk from an eruption in the ocean increased to slightly larger than a Tongariro eruption (Fig. 5b).

Larger local eruption

In this study, *extent* has been based on median values of previous Auckland volcanic field eruptions. This eliminates the characteristics of the few larger eruptions that account for a large percentage of the volume of the field. However, it has been shown by Allen (1992) and Allen and Smith (1994) that there is a general increase in the size of eruptions with time. It is therefore possible that Rangitoto (representing 59% of the total volume of the field) could represent a new phase of activity and that future eruptions may be of a similar, or larger size.

In this example, risk was re-calculated for local eruptions based on the extent of hazards from the Rangitoto eruption. The *extent* of earthquakes, flooding, poisonous gases and acid rain, lighting and tsunami remained at the same order of magnitude. The *extent* of base surge from Rangitoto is unknown, as it has been covered by later lava flows; however, it is likely to be of the same scale as those from Lake Pupuke and Three Kings, approximately 10 km^2 (Allen and Smith 1994). This did not result in a change in the order of magnitude. Tephra is likely to cover a much larger proportion of the region, increasing *extent* to 1. The *extent* of mudflows also increased by an order of magnitude, as did lava.

Increasing the order of magnitude of tephra fall, mudflows and lava flows only changed the ranking of lava flows, which increased so that the risk is greater than that of base surge (Fig. 6a). Event ranking changed greatly so that risk from an Auckland eruption occurring on land became largest. Risk from an eruption occurring in the ocean also increased so that only risks from Taranaki and Okataina were higher (Fig. 6b).

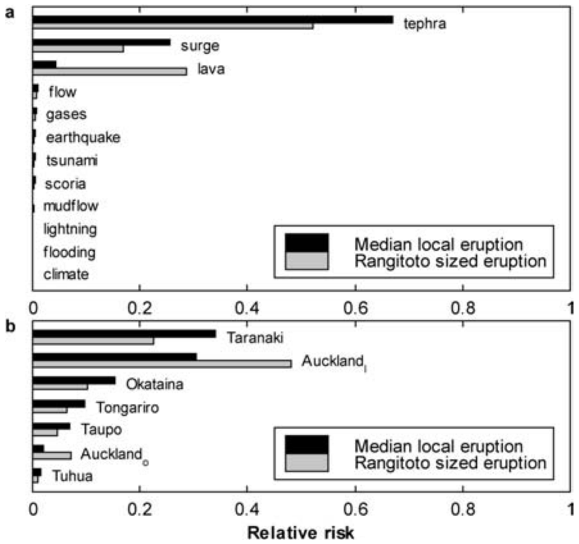

Fig. 6 Normalised relative risk values for **a** volcanic hazards and **b** volcanic events, comparing local events with characteristics equal to the median size of previous eruptions and to the size of the Rangitoto eruption

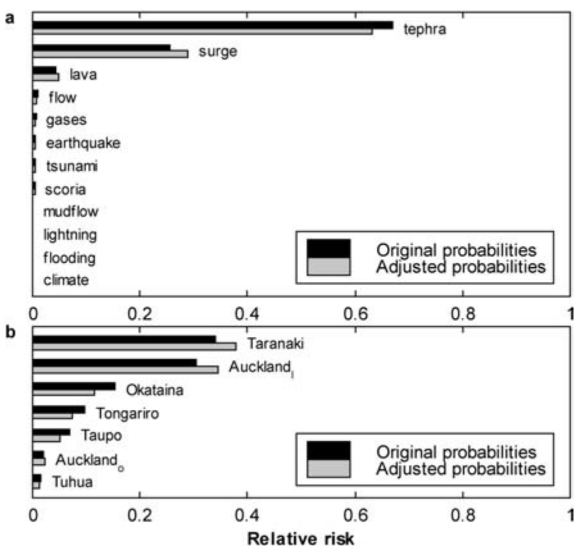

Fig. 7 Normalised relative risk values for **a** volcanic hazards and **b** volcanic events, comparing original event probabilities with those adjusted so that Auckland and Taranaki events are 50% more likely

Adjusted relative event probabilities

It was pointed out by Shane and Hoverd (2002) that some tephra layers from the Auckland volcanic field and Taranaki volcano are not represented in both the Pukaki and Onepoto sequences and that other events may have occurred during this time period that are not preserved in either core. The actual frequency of these events is unknown. As an example, the probability of Auckland and Taranaki eruptions were increased by 50%. This adjusted the relative probabilities of events to: an Auckland volcanic field eruption centred in the ocean (0.190) and on land (0.063), Tuhua volcano (0.016), Okataina volcanic centre (0.143), Taupo volcano (0.063), Tongariro volcanic centre (0.095), and Mt. Taranaki volcano (0.492). Risk was then recalculated using these values.

These results are interesting in that, although risk from Taranaki and Auckland increased slightly, neither the hazard or event risk rankings changed (Fig. 7).

Summary and conclusions

This paper is a continuation of the project outlined in Magill and Blong (2004). In the previous paper, return periods and spatial extents of particular hazards were investigated. In this paper *effect* values, based on order of magnitude, were assigned to hazards from particular sources for two outcomes – building damage and loss of human life. These outcomes were assigned $importance_o$ values of 0.02 and 0.98 respectively.

Risk was calculated for building damage and loss of human life from the Auckland volcanic field, Tuhua volcano, Okataina volcanic centre, Taupo volcano, Tongariro volcanic centre, and Mt. Taranaki volcano. Risk from a local event was calculated separately for an Auckland eruption occurring on land, defined as being less than a kilometre from the coast, and in the ocean. The hazards considered for local eruptions were earthquakes and ground deformation, flooding, poisonous gases and acid rain, lava flows, lightning, mudflows and mudfills, scoria fall, base surge, tephra fall and tsunami. For distal eruptions the hazards were climate variations, earthquakes, flooding, pyroclastic flows, poisonous gases and acid rain, mudflows and mudfills, and tephra fall.

The largest risk to the Auckland Region is from tephra fall, followed by base surge. The risks from lava flow and pyroclastic flows are an order of magnitude smaller. Risk from Taranaki is largest, followed by an Auckland volcanic field eruption occurring on land.

Three alternative situations were tested using this methodology. Risk was re-calculated for an event where two Auckland volcanic field eruptions occurred simultaneously. This did not affect the hazard ranking but increased the risk from a local eruption centred on land so that it was equal to that of a Taranaki eruption. A future eruption from the Auckland volcanic field could be of a similar magnitude to the Rangitoto eruption. The calculations were carried out using the dimensions of deposits from this eruption, which increased risk from lava flows to greater than base surge. The event ranking changed so that risk from an Auckland eruption occurring on land became largest. Event probabilities used in the initial calculations for the Auckland volcanic field and Taranaki volcano may be minimum values. These probabilities were increased by 50% but this did not affect either the hazard or event rankings.

Several major assumptions have been made in this study. This is a preliminary risk assessment and may be refined as further research is carried out. In particular, the relative probabilities of each event ($probability_e$) may be adjusted. However, we note that varying relative probabilities had little effect on the overall risk ranking. Risk is also strongly influenced by the area considered. For example, if the study area is reduced to Auckland City, a larger percentage of the total area will be affected by an Auckland eruption, increasing the relative risk from the Auckland volcanic field.

Our results show that future hazard studies within the Auckland region should focus on the lesser, but widespread, effects of tephra fall from distal sources. Base surge is a large risk that must be considered. The possibility of another large Auckland volcanic field eruption means that risk from lava flows should also be fully investigated.

This methodology is useful for assessing risk from volcanic hazards, as in many cases characteristics are uncertain. The methodology can easily be applied to other areas at risk from multiple volcanic events and hazards, for a variety of different outcomes. It can also be readily applied to other natural perils and may be used to compare contrasting hazards such as volcanic hazards with, for example, riverine flooding.

Acknowledgements We would like to thank Professor John McAneney and Dr. Keping Chen for helpful reviews of an early draft, and Dr. Ian Smith for valuable discussions. The manuscript has benefited from reviews and advice from Dr. David Johnston, Dr. Steve Oldfield, and an anonymous referee. Risk Frontiers is grateful for the strong support of a number of sponsors in the insurance industry. This work was completed while Christina Magill was holding a Macquarie University Research Award for Areas and Centres of Excellence (RAACE).

References

Allen SR (1992) Volcanic hazards in the Auckland volcanic field. Unpublished MSc thesis, University of Auckland, Auckland, New Zealand, pp 1–153

Allen SR, Smith IEM (1994) Eruption styles and volcanic hazard in the Auckland volcanic field, New Zealand. Geosci Rep Shizuoka Univ 20:5–14

Auckland Engineering Lifelines Group (2001) Volcanic ash review, Part 1. Auckland Regional Council Technical Publication No 144. Auckland Regional Council, Auckland, New Zealand, pp 1–50

Auckland Regional Council (1999) Auckland engineering lifelines project, final report, stage one. Auckland Regional Council Technical Publication No 112. Auckland Regional Council, Auckland, New Zealand, pp 1–286

Baxter PJ (1990) Medical effects of volcanic eruptions. Bull Volcanol 52:532–544

Baxter PJ (2000) Impacts of eruptions on human health. In: Sigurdsson H, Houghton BF, McNutt SR, Rymer H, Stix J (eds) Encyclopedia of volcanoes. Academic, San Diego, CA, pp 1035–1043

Baxter PJ, Neri A, Todesco M (1998) Physical modelling and human survival in pyroclastic flows. Nat Hazards 17:163–176

Beca Carter & Ferner (2002) Contingency plan for the Auckland volcanic field. Prepared for the Auckland Regional Council, Auckland, New Zealand, pp 1–65

Blong RJ (1984) Volcanic hazards: A sourcebook on the effects of eruptions. Academic, Sydney, Australia, pp 1–424

Blong RJ (2003) Building damage in Rabaul, Papua New Guinea, 1994. Bull Volcanol 65:43–54

Cassidy J, Locke CA, Miller CA, Rout DJ (1999) The Auckland volcanic field, New Zealand: geophysical evidence for its eruption history. In: Firth CR, McGuire WJ (eds) Volcanoes in the Quaternary. Geological Society Special Publication No 161. The Geological Society, London, pp 1–10

Cousins WJ, Heron DW (2001) An assets model for New Zealand buildings for use in risk studies. Institute of Geological and Nuclear Sciences 2001/3, Lower Hutt, New Zealand, pp 1–19

Johnston DM, Nairn IA, Thordarson T, Daly M (1997) Volcanic impact assessment for the Auckland volcanic field. Auckland Regional Council, Auckland, New Zealand, pp 1–208

Johnston DM, Houghton BF, Neall VE, Ronan KR, Paton D (2000) Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. Geol Soc Am Bull 112:720–726

Magill CR, Blong RJ (2004) Volcanic risk ranking for Auckland, New Zealand. I: Methodology and hazard investigation (this volume)

Mrozek JR, Taylor LO (2002) What determines the value of life? A meta-analysis. J Policy Anal Manag 21:253–270

Paton D, Johnston DM, Gough J, Dowrick D, Manville V, Daly M, Batistich T, Baddon L (1999) Auckland volcanic risk project: Stage 2. Auckland Regional Council, Auckland, New Zealand, pp 1–99

Peterson DW, Tilling RI (2000) Lava flow hazards. In: Sigurdsson H, Houghton BF, McNutt SR, Rymer H, Stix J (eds) Encyclopedia of volcanoes. Academic, San Diego, CA, pp 957–971

Pomonis A, Spence RJS, Baxter PJ (1999) Risk assessment of residential buildings for an eruption of Furnas Volcano, São Miguel, The Azores. J Volcanol Geoth Res 92:107–131

Rout DJ, Cassidy J, Locke CA, Smith IEM (1993) Geophysical evidence for temporal and structural relationships within the monogenetic basalt volcanoes of the Auckland volcanic field, northern New Zealand. J Volcanol Geoth Res 57:71–83

Sadler JP, Grattan JP (1999) Volcanoes as agents of past environmental change. Global Planet Change 21:181–196

Sandiford A, Alloway BV, Shane P (2001) A 28 000–6600 cal yr record of local and distal volcanism preserved in a paleolake, Auckland, New Zealand. New Zeal J Geol Geop 44:323–336

Self S, Rampino MR, Barbera JJ (1981) The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures. J Volcanol Geoth Res 11: 41–60

Shane P, Hoverd J (2002) Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand: implications for volcanic chronology, frequency and hazards. Bull Volcanol 64:441–454

Spence RJS, Pomonis A, Baxter PJ, Coburn AW, White M, Dayrit M, Field Epidemiology Training Program Team (1996) Building damage caused by the Mount Pinatubo eruption of June 15, 1991. In: Newhall CG, Punongbayan RS (eds) Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, University of Washington Press, Seattle, WA, pp 1055–1061

Tanguy J-C, Ribière C, Scarth A, Tjetjep WS (1998) Victims from volcanic eruptions: a revised database. Bull Volcanol 60:137–144