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VolcaNZ—A volcanic loss model for Auckland, New Zealand

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Abstract

VolcaNZ is a probabilistic volcanic loss model developed for the Auckland Region in New Zealand that currently considers tephra fall hazards from the Auckland Volcanic Field (AVF), Tuhua volcano, Okataina volcanic centre, Taupo volcano, Tongariro volcanic centre and Egmont volcano. In this first version of the model, structural and non-structural damage to residential building envelopes and associated cleanup costs are calculated using Monte Carlo simulation.

VolcaNZ assigns a Minimum and Maximum Damage Value to groups of buildings for every simulation, dependent on tephra thickness. A Central Damage Value, representing loss as a percentage of total replacement cost, is then randomly selected between these limits. Even with small-thickness falls, non-structural damage is expected to roof and wall coatings, air-conditioning units, aerials and satellite dishes due to the corrosive and abrasive properties of tephra. An average loss of $583, attributed to non-structural damage, was assigned to all residential buildings impacted by any thickness of tephra greater than 0.1 mm. The costs of tephra removal from buildings, cleaning of building exteriors and tephra transport and disposal are also calculated within the model, assuming much of the cleanup process will be carried out by homeowners.

Losses from all simulations are plotted against calculated Average Recurrence Intervals (ARIs) to produce loss curves. Structural damage does not become apparent until ARIs of approximately 8000 years. $1 billion losses, due to structural damage, occur at about 35,000 years and this increases to about $26 billion at 1 million years. Loss due to non-structural damage is constant at approximately $160 million for ARIs above about 600 years. Between 600 and 3000 years, cleanup loss is approximately $50 million, increasing to over $450 million at a return period of 1 million years. At ARIs between 600 and 3000 years, total loss is approximately $210 million, increasing to $10 billion at 100,000 years and over $26 billion at 1 million years. Because we only consider residential building damage and associated cleanup, these values greatly underestimate total loss from the next volcanic event to impact Auckland. Loss calculations will be improved by adding additional hazard and loss modules to *VolcaNZ*, resulting in a complete catastrophe loss model.
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1. Introduction

Catastrophe loss models are an essential tool within the insurance industry. Loss models have been developed for natural hazards such as earthquake, hurricane, hail and flood. In contrast to these perils, a volcanic loss model must consider complex events that may extend over long periods of time and include multiple hazards

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at various magnitude and spatial scales. Previous models have calculated volcanic loss based on specific scenarios (Blong and Aislabie, 1988; Paton et al., 1999). We present *VolcaNZ*, developed for the Auckland Region in New Zealand, which we believe to be the first commercial probabilistic volcanic loss model for any city worldwide. In addition to insurance applications, this model may be used by businesses and government organisations to analyse their risk from a future volcanic event.

Auckland (Fig. 1), New Zealand's most populous Region, is home to over 1.2 million people and a high proportion of the nation's commerce and industry. Centred within the region is the monogenetic Auckland Volcanic Field (AVF) (Fig. 2), which currently contains 49 small-volume basaltic volcanoes (Allen and Smith, 1994). In addition, recent work (e.g. Newnham and Lowe, 1991; Sandiford et al., 2001; Shane and Hoverd, 2002; Turner et al., 2002) identified tephra layers within Auckland originating from the more distant rhyolitic Tuhua (Mayor Island), Okataina and Taupo volcanic centres and the andesitic Tongariro and Egmont (Mt. Taranaki) centres (Fig. 1).

An initial risk assessment (Magill and Blong, 2005a,b) identified tephra fall as the most significant volcanic hazard facing the Auckland Region. In this study, we therefore focus on this hazard, describe methodology developed for *VolcaNZ* and provide some initial loss calculations for residential building damage resulting from air-fall tephra within Auckland. This is the first stage of what will become a sophisticated catastrophe loss model with numerous hazard and loss modules.

As work towards event and hazard modules has been described in previous publications (Magill et al., 2005, in press, submitted for publication), this paper, after giving an overview of the model, concentrates on the residential building loss module, presents damage

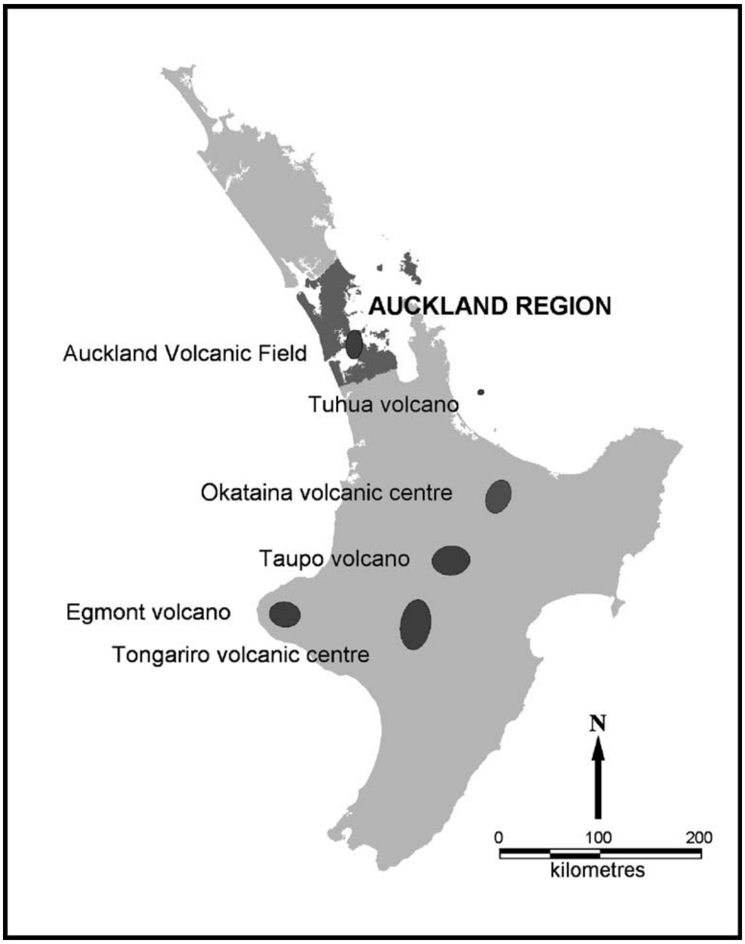

Fig. 1. North Island, New Zealand and the volcanic centres identified as posing a risk to the Auckland Region.

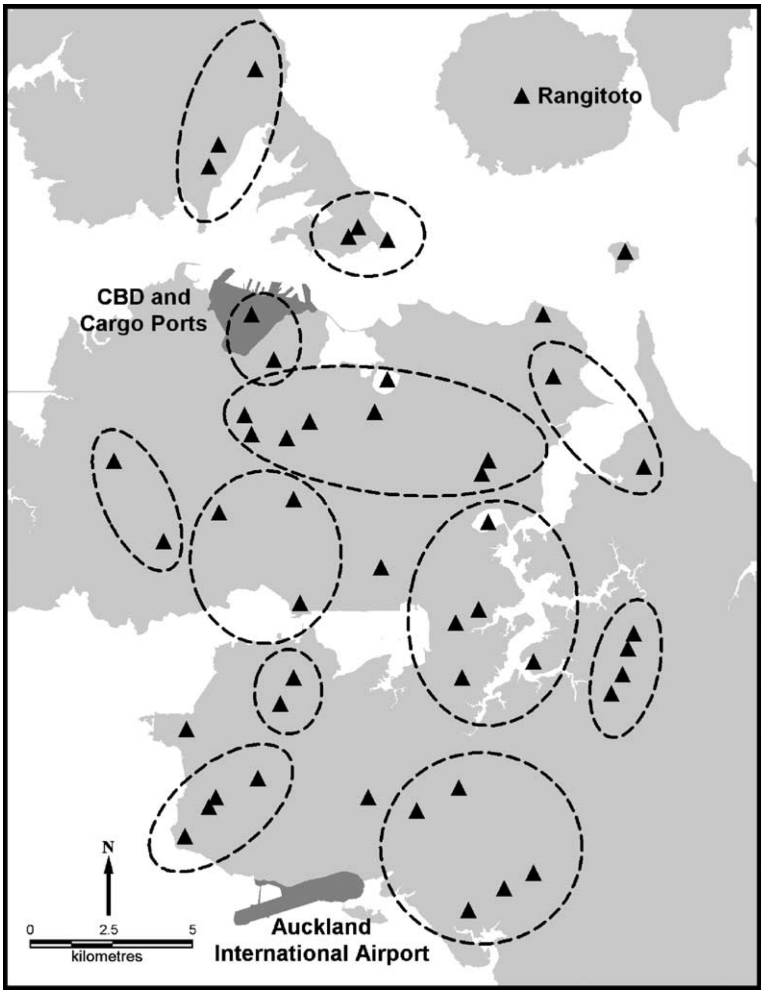

Fig. 2. Previous eruption centres within the Auckland volcanic field. Spatial and temporal clusters of eruption points, identified by Magill et al. (2005), are indicated by dashed lines.

assumptions for residential buildings and provides preliminary loss calculations.

2. Modelling a volcanic event

Probabilistic loss models typically simulate large numbers of discrete natural hazard events and their consequences using Monte Carlo methods. However, a volcanic event is complicated by the fact that it may involve many eruptive phases, styles, hazards and eruption locations with consequential risk varying in magnitude and aerial extent throughout. Because of computing restrictions, it is not currently possible to simulate the full range of event characteristics.

A volcanic event is typically referred to as an *eruption*. However, this term can cause confusion as individual eruptive phases within longer periods of volcanic activity may also be referred to as eruptions. For our purposes, we define a *volcanic event* as an extended period of activity that may consist of multiple *eruptions* of varying magnitudes. We also consider temporal clusters of eruption points within the AVF (Fig. 2) to be single events, although the total duration of activity is uncertain.

Activity within an event is not uniform with time (Simkin and Siebert, 1994, 2000). Therefore, we model each event as a single paroxysmal eruption, likely to occur over only a short time period. These eruptions are likely to generate the largest losses and, in the case of distal eruption sources, be of sufficient magnitude to deposit tephra within Auckland.

This approach may underestimate the area impacted by an event from the AVF, as a number of small volume eruptions are expected as new volcanoes are formed.

Areas may also be impacted more than once, over an extended period of time, increasing the costs of clean-up. These problems will be addressed in future versions of the model by combining eruptions to form more realistic events. However, at this stage the thickness and dispersal area of tephra modelled as a single eruption provides a first approximation of the degree of damage expected.

2.1. VolcaNZ

VolcaNZ is a probabilistic volcanic loss model developed for the Auckland Region that considers hazards from both the AVF and more distant volcanic centres. The aim of this first version of the model is to provide a first estimate of expected loss for residential buildings as the result of tephra fall. The losses calculated represent only a small proportion of the total loss expected from a future event but provide a methodological framework to which additional modules can be added.

Only damage to the building envelope and associated cleanup is considered. We are only interested in losses associated with fine-grained air-fall tephra that has been convected into the atmosphere. The secondary hazard of tephra remobilised by rain is ignored and, in

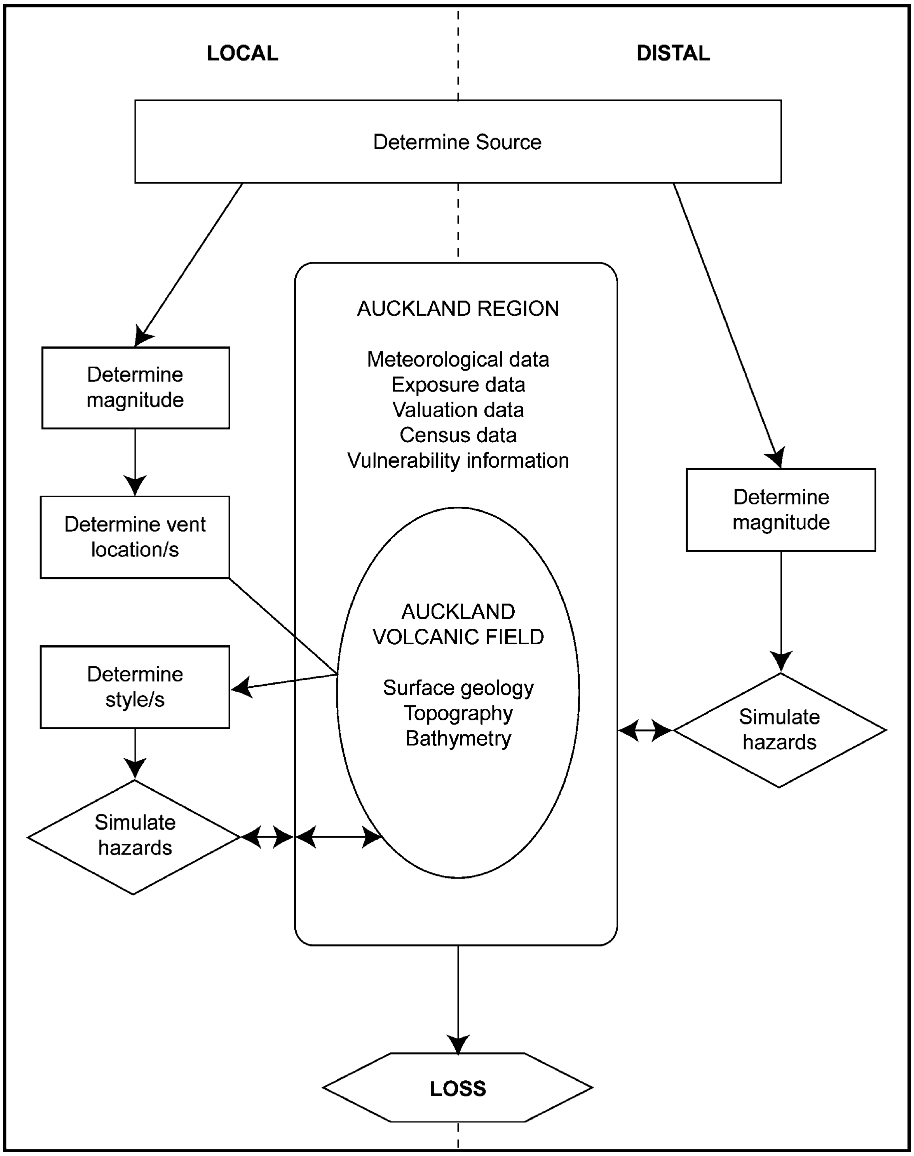

Fig. 3. Schematic summary of *VolcaNZ*. Event module is represented by rectangles, hazard modules by diamonds and the loss module by a hexagon.

the case of the AVF, we have not considered ballistic or surge deposited tephra.

Catastrophe loss models typically comprise a series of modules, with the first generating large numbers of discrete events or loss occurrences. Further modules combine hazard, exposure and vulnerability data so that damage and associated loss can be calculated. The results of many individual simulations are then combined to provide loss statistics. In a similar fashion, *VolcaNZ* contains event, hazard (tephra fall) and loss (residential building damage) modules. Each module calls upon spatial, environmental, exposure and valuation data as well as assumptions regarding vulnerability (Fig. 3). All of these data may be adjusted by the model user.

The characteristics of each event are chosen randomly within the event module using Monte Carlo simulation methods. The first step selects the eruption source for each simulation using relative probabilities for AVF (0.169), Tuhua (0.019), Taupo (0.067), Tongariro (0.053), Okataina (0.156) and Egmont (0.536) events affecting Auckland (Magill et al., submitted for publication). These values are based on geological evidence for previous tephra fall events within central Auckland (Newnham and Lowe, 1991; Newnham et al., 1999; Sandiford et al., 2001; Shane and Hoverd, 2002; Magill et al., submitted for publication). Event magnitude is also determined randomly using probability density distributions that describe the geological evidence. Remaining calculations determine the number of eruption points and their locations for the next event from the AVF (Magill et al., 2005) and, by combining this information with underlying geology, associated eruption styles and hazards (Magill et al., submitted for publication) (Fig. 4). However, in this current version of the

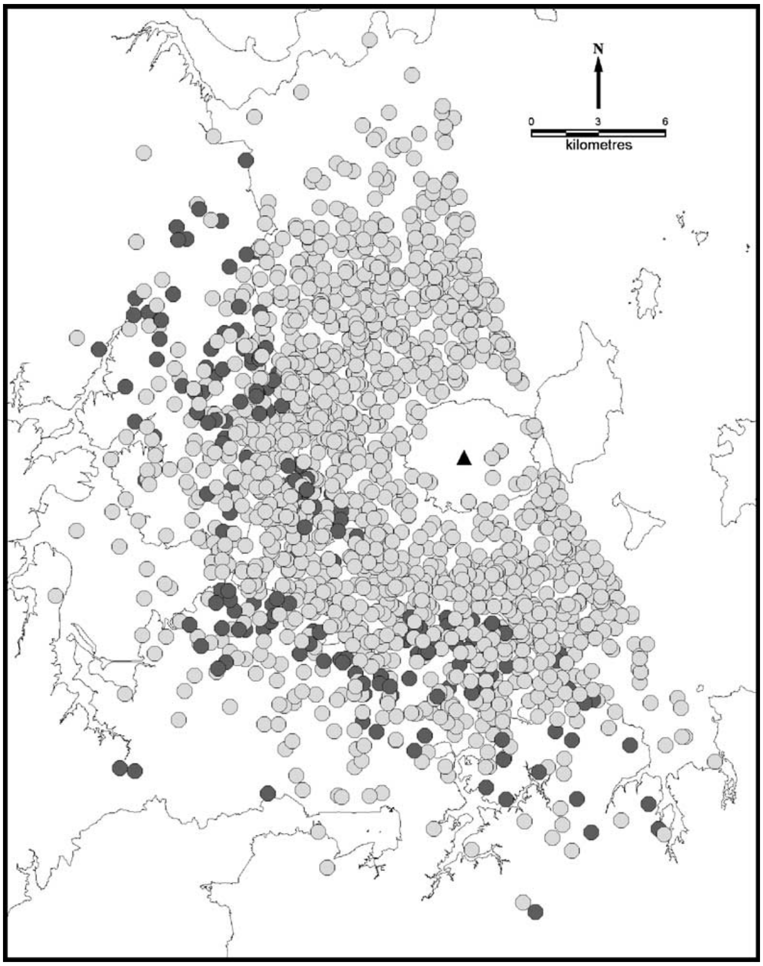

Fig. 4. Example of 1000 randomly generated eruption locations. Simulated eruptions determined to be phreatomagmatic are in pale grey and magmatic in dark grey (from Magill et al., submitted for publication). The most recent Rangitoto event is marked by a triangle.

model tephra characteristics are assumed to be independent of style.

As discussed earlier, this first version of *VolcaNZ* considers only air-fall tephra. Within the hazard module, tephra dispersal patterns are randomly sampled from a database developed to replicate expected future eruptions from each source. Dispersal patterns were created using ASHFALL (Hurst, 1994) and the modelling described in Magill et al. (2005a). This modelling took into account expected meteorological conditions over the Auckland Region. Future hazard modelling, such as for lava flows and base surge from the AVF, will also need to consider topography and bathymetry (Fig. 3).

Because tephra dispersal modelling itself is not carried out within *VolcaNZ*, many event simulations are able to be conducted efficiently on a single PC. Tephra thickness is calculated as points on a 1000-m grid and converted to a surface so that thickness may be calculated, for every simulation, at any point within the Region.

3. Loss module

Losses from a future volcanic event may include deaths and injuries, damage to buildings and infrastructure, impacts to agriculture and horticulture and the costs of business interruption. At this stage, we consider only losses associated with residential building damage and associated cleanup activities. Unless otherwise specified, all values given are in New Zealand dollars and exclude Goods and Services Tax.

Risk can be expressed as the expected loss from a future volcanic event. Because of the long return periods between events, and changes in eruption characteristics with time, *VolcaNZ* calculates only risk associated with the next volcanic event to impact the Auckland Region.

When calculating risk it is necessary to consider the *likelihood* of an event occurring, the spatial *extent* or footprint it impacts and the *effect* of the event within that area. The *likelihood* of an event is considered in the event module, as already described, and the *extent* is determined by randomly selecting a tephra dispersal pattern within the hazard module. Within this loss module the *effect* is considered and risk estimated by spatially combining hazard characteristics with building exposure, vulnerability and valuation data.

Expected building damage from a tephra-fall event may be either structural or non-structural. The main focus of research to this point has been structural damage to buildings from large-thickness falls (e.g. Pomonis et al., 1995; Spence et al., 1996; Pomonis, 1997; Pomonis et al., 1999; Blong, 2003; Luongo et al., 2003; Baratta et al., 2004). Although large thickness falls are possible within the Auckland Region, small thickness (1–10 mm) falls are expected to be much more frequent (Magill et al., in press). These thicknesses are expected to result in non-structural damage such as corrosion. For all events, additional costs will be involved with tephra removal and cleaning of building exteriors. The losses to Auckland's residential building stock associated with structural damage, non-structural damage and cleanup costs are calculated within this module.

3.1. Auckland residential buildings

For every simulation, it is possible to determine tephra thickness for every building location within Auckland and, if individual building information is available, calculate losses for specific groups of buildings or insurance portfolios. However, at this stage valuation and construction information is not available for individual buildings and we have chosen to assume typical characteristics.

A uniform distribution of replacement building valuations between $150,000 and $250,000 New Zealand dollars is considered. Buildings are assumed to be of typical timber-framed construction with an average projected roof area of 150 m^2. A random survey of approximately 1500 residential buildings within Auckland showed that about 67% were single storied, 29% two storied, 4% three storied and only a fraction of a percentage multi-storied apartments. We considered these percentages are consistent throughout the Region and, assuming an average height per storey of 4 m, calculated an average exterior wall area of 270 m^2.

Auckland contains very few large apartment blocks and buildings containing multiple dwellings tend to be restricted to small unit blocks or larger houses that have been subdivided. Of 137 multi-dwelling buildings observed in our survey, 65% contained two dwellings, 15% three, 11% four, 4% five and only 5% more than five. Because of their typically small size, multi-dwelling buildings are very similar in construction to normal single-dwellings and losses are calculated by assuming each has the characteristics of an individual residential building. We also considered that multi-dwelling buildings have the same distribution of replacement values as single-dwelling buildings, although this may slightly underestimate calculated losses.

New Zealand's smallest geographic and census collection unit is a meshblock. Within Auckland, these contain an average of 44 buildings, a sum which may include both residential and non-residential structures. Because buildings are assumed to be similar, in the simulations presented here, individual buildings are grouped into meshblocks. This substantially decreases model run times.

From 2001 census data, we know the number of occupied and unoccupied dwellings for each meshblock within Auckland on the night of 6th March. In addition, our field survey considered 48 randomly selected meshblocks and identified the number of residential and non-residential buildings within each. In total, 1716 buildings were counted, with 1531 being, at least partly, residential. We also identified a total of 1783 dwellings, with counts for individual meshblocks corresponding very closely to census values.

For each surveyed meshblock, the number of residential buildings was compared to the number of occupied dwellings at the time of the census (Fig. 5). This provided a good relationship showing approximately 0.82 residential buildings for each dwelling. Using this value within *VolcaNZ* provides an approximation of the number of residential buildings per meshblock given the number of dwellings from census data.

Tephra thickness and consequential building damage were calculated for a single building assumed to be at the centre of each meshblock. Resulting loss was then scaled by the estimated number of residential buildings contained within the meshblock. This method is acceptable, as the mean meshblock size is less than 0.5 km^2, a finer resolution than modelled tephra fall thickness (1 km^2).

3.2. Structural damage

Structural damage may occur when large loads of tephra are deposited directly on roofs or when tephra drifts against walls, foundations or chimneys (Blong, 1981, 1984). For our purposes, we consider that structural damage ranges from failure of weak elements such as guttering and carports through to collapse of both external and internal walls.

VolcaNZ assigns a Minimum Damage Value (MinDV) and Maximum Damage Value (MaxDV) to each meshblock for every simulation, dependent on tephra thickness. A Central Damage Value (CDV), representing loss as a percentage of total replacement cost, is then randomly selected between these limits assuming a uniform distribution of outcomes without any central tendency (Fig. 6).

MinDV and MaxDV are based largely on the scale of damage following the 1994 Rabaul eruptions in Papua New Guinea that destroyed large areas of Rabaul town. Buildings within Rabaul were assigned a Volcanic Damage Index (VDI) based on 5 levels of damage

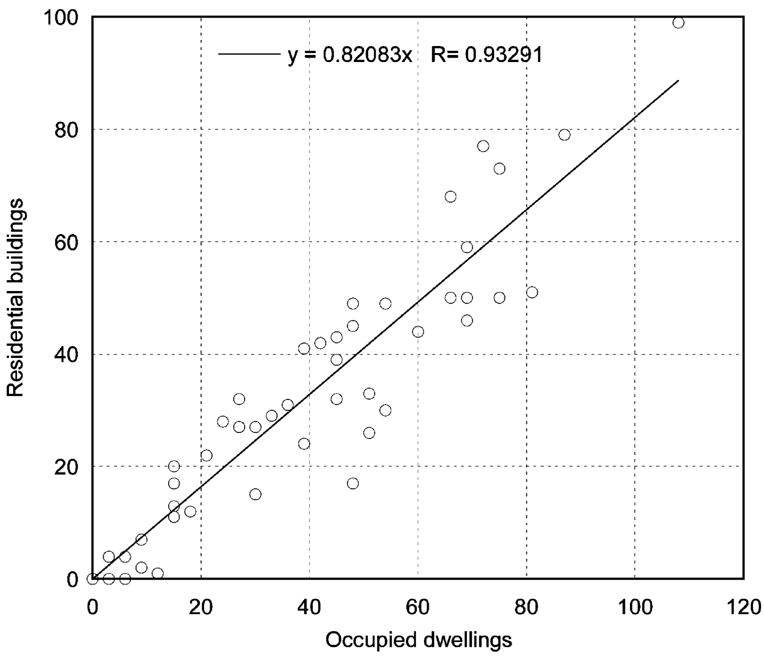

Fig. 5. Relationship between the number of residential buildings, identified from a survey of 48 meshblocks, and the number of occupied dwellings from census data.

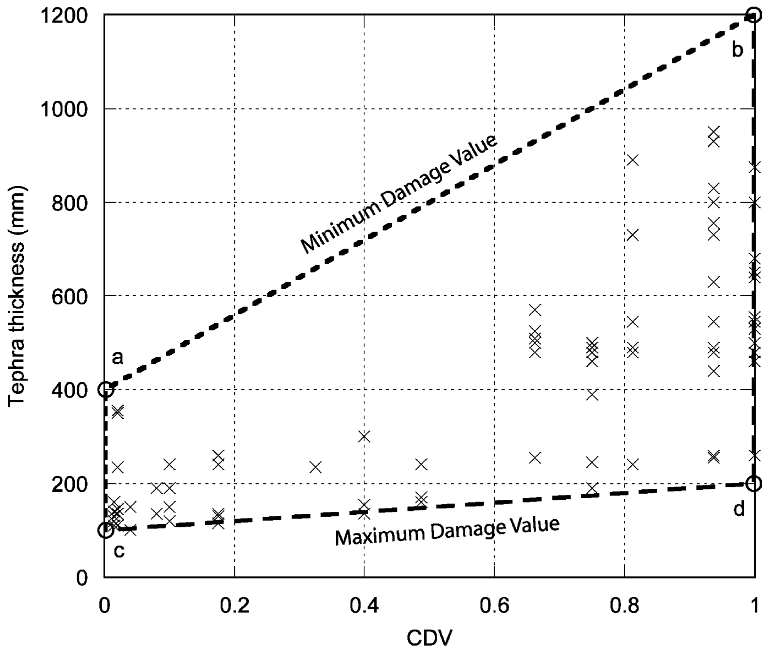

Fig. 6. Tephra thickness versus Central Damage Value (CDV) for timber-framed buildings following the 1994 Rabaul eruption (Blong, 2003). Dashed lines indicate the Minimum Damage Value (MinDV) and Maximum Damage Value (MaxDV) used in our calculations. Point (a) is the maximum thickness where no structural damage may occur, (b) is the maximum thickness at which 100% of buildings would be completely destroyed, (c) is the minimum thickness at which structural damage would occur and (d) is the minimum thickness at which total damage may occur.

(Table 1) and tephra thickness and total load were recorded at each location (Blong, 2003). In cases where there was sufficient evidence, intermediate values were also given. Categories were modified from Spence et al. (1996) who created a damage scale based on the MSK earthquake intensity scale (Karnik et al., 1984) and carried our a similar survey following the 1991 Mt. Pinatubo eruption in the Philippines.

Following the Rabaul survey, Blong (2003) assigned a CDV to each category indicating average damage as a proportion of the total replacement value of the building (Table 1). In our study, we considered the relationship between tephra thickness and the CDVs assigned to 97 timber-framed buildings (Fig. 6), as this is the most common residential structural type within Auckland. We also considered the expected higher resilience of Auckland buildings in comparison to those in Rabaul.

Ideally, when considering structural damage, tephra load and not thickness should be analysed. However, as we only have a record of tephra thickness within Auckland we assume that these layers, and therefore our simulations, were deposited wet with a compacted density of approximately 1600 kg m^{-3}, as was the case during the Rabaul eruption. The uncertainty in tephra density is not accounted for explicitly within the model, but is assumed to be included in the uncertainty surrounding building damage values for given tephra thicknesses.

Table 1
Volcanic Damage Index (VDI), Central Damage Value (CDV) and damage description from Blong (2003)

VDI	CDV	Description
1	0.02	Light damage: damage to gutters and/or water tanks.
2	0.10	Moderate damage: bending or excessive damage to as much as half roof sheeting and/or purlins. Damage to roof overhangs or verandas. Slight roof structural damage possible.
3	0.40	Heavy damage: damage to roof structure and some damage to walls; at least one wall damaged/misaligned.
4	0.75	Severe damage: roof collapse and moderate to severe damage to the rest of the building. Failure of roof trusses and supporting structure. At least half of the external walls and/or internal walls deformed or collapsed. For two-storey buildings, collapse of external and internal walls of upper floor.
5	1.00	Collapse: collapse of roof and supporting external walls over more than 50% of the floor area of building. Internal walls collapsed. Damage to floor and/or foundations.

For our purposes, four values are important (Fig. 6):

a. maximum thickness where no structural damage may occur,
b. maximum thickness at which 100% of buildings would be completely destroyed,
c. minimum thickness at which structural damage would occur, and
d. minimum thickness at which total damage may occur.

Points a, c and d have been obtained solely from Rabaul damage data. At 400 mm of tephra it is still possible that no damage may occur to the building structure. Above this it is almost certain that damage, at least to guttering indicated in VDI 1, will occur. During the Rabaul eruption, when thicknesses were less than 100 mm, roofs and gutters remained intact (Blong and McKee, 1995). Although it is possible that small amounts of damage may occur with wet tephra less than 100 mm in thickness (Blong, 1984) we assume that significant damage, requiring replacement, will only occur with greater thicknesses. With 200 mm of wet tephra it is possible that complete collapse of poorly constructed buildings could occur.

Point b is the maximum thickness at which all buildings would be destroyed, i.e. if tephra is this thick or greater, loss will be equal to the total replacement cost of all buildings within the meshblock. In Rabaul no buildings survived approximately 1000 mm of wet compacted tephra. It is also important to note that at least some buildings collapsed before the full thickness of tephra was deposited and therefore failed under a smaller thickness than that recorded (Blong and McKee, 1995; Blong, 2003). A thickness of 1000 mm is consistent with Einarsson (1974) who observed that during the 1973 Heimaey eruption in Iceland, roofs in Vestmannaeyjar collapsed under an average thickness of 800–1000 mm of wet tephra. However, we believe that in general Auckland buildings will withstand a larger tephra load than those in Rabaul and have increased this threshold to 1200 mm.

Using these four values allows lines of minimum and maximum damage, for various tephra thicknesses, to be plotted (Fig. 6). For structural damage to occur total thickness must be at least 100 mm and total replacement is required for all buildings when tephra is thicker than 1200 mm. For each meshblock, for every simulation, MinDV and MaxDV are calculated within *VolcaNZ* dependent on tephra thickness at that location and a CDV is then randomly selected from a uniform distribution between these values. For each meshblock, the CDV is then multiplied by the randomly selected building replacement value, calculated earlier, and scaled by the number of residential buildings it contains. If the CDV is greater than 0.8 we assume that it would not be economical to rebuild and loss is therefore equal to the total replacement cost. This method predicts overall slightly less percentage damage than that observed in Rabaul. However, this is expected due to higher construction standards within Auckland.

3.3. Non-structural damage

Damage is still expected to residential buildings from tephra falls thinner than that estimated to cause structural damage. This arises because of the corrosive and abrasive properties of tephra and we therefore assume this non-structural damage to be independent of thickness. An average dollar value per house has been calculated for all residential buildings impacted by any thickness of tephra greater than 0.1 mm compacted thickness. Non-structural damage is not added to total loss if the previously calculated CDV is greater than 0.8 and buildings within the effected meshblock are considered irreparable.

3.3.1. Roof coatings

Galvanised roofing was badly damaged in the city of Yakima, impacted by approximately 10 mm of tephra during the 1980 eruption of Mount St. Helens, USA (Blong, 1984). Similarly, both old and new galvanised steel roofs became corroded following the Rabaul eruption, even when thicknesses were small (Framework Architects et al., 1996; Blong, 2003). Corrosion of iron roofs and guttering occurred following the 1995–1996 Ruapehu eruption from the Tongariro volcanic centre, particularly when tephra had not been removed (Becker et al., 2001). Following this eruption, it was also found that recently applied acrylic paint was susceptible to acidic tephra (Johnston et al., 2000).

We assume that in a future event to impact Auckland, 5% of metal roofs will need to be replaced. This ranges between either 5% of buildings with roofs needing complete replacement or 100% of buildings needing 5% of their roof replaced. We assume that the typical residential building has a square gable roof with a 30° pitch and no over-hanging eaves, carports or balconies. Therefore, a projected roof area of 150 m^2 requires approximately 173 m^2 of roofing material, with an average value of $50 per m^2. This includes ridge and barge flashings, fixings, wire netting and underlay. The cost is for an installed roof and includes overheads and profit (Rawlinsons, 2003).

We also assume an additional 5% of houses will require roofs to be repainted at an average cost of \$13.60 per m^2 including labour, based on average paint prices (Rawlinsons, 2003). This cost is based on \$2 per m^2 to prepare the existing surface and \$10 per m^2 to paint a roof with one coat of primer and two of acrylic. An additional 16% of the painting cost was added for corrugated roof types, which are typical within Auckland (Rawlinsons, 2003).

After multiplying by the probabilities of damage, each residential building with a metal roof has an average loss attributed to roof replacement of \$433 and repainting \$118. Assuming that the 56% of metal roofs observed in our survey are consistent throughout Auckland, this gives an average roof coating loss per residential building of \$308.

3.3.2. Wall coatings

During the Mount St. Helens eruption it was observed that wet tephra leached the colour from dark paints and produced a grey stain on dark wood stains. Fresh paint that had not hardened was also damaged (Blong, 1984). We assume that similar damage will occur from a future event impacting Auckland and estimate that 5% of exterior walls will require re-painting.

We use a value of \$13.30 per m^2 to re-paint walls. This includes \$10 per m^2 for three coats of semi-gloss or gloss, \$2 per m^2 to prepare the existing surface and 13% added to the painting cost for a typical bevel back surface (Rawlinsons, 2003). As most buildings are low-rise we do not include the added cost of painting from ladders or a swinging stage.

Therefore, using our average wall area of 270 m^2 and multiplying by the probability of damage, the average cost of re-painting the walls of each house is \$178. Assuming, based on our survey, that 81% of house walls within Auckland are painted, the average loss per building for wall coating damage is \$146.

3.3.3. Air-conditioning units

During the recent Ruapehu eruptions, there were many cases of minor damage to air-conditioning units; more serious problems occurred when systems were not turned off when tephra was present in the atmosphere (Johnston et al., 2000). These problems occurred as far away as Tauranga and Hamilton (Becker et al., 2001) approximately 180 km from the volcano, which experienced only trace amounts of ash.

We assume that similar damage will occur in Auckland, with even very small thicknesses of tephra. Although we do not have statistics on the number of air-conditioning units within Auckland, we assume that 5% of buildings will experience damage, with an average value of \$500. This gives an average loss per residential building of \$25.

3.3.4. Aerials and satellite dishes

We do not have any data regarding damage to aerials and satellite dishes. However, we expect that wet conductive tephra will adhere to these items and affect reception. At least, this will require cleaning and re-alignment to be carried out. We assume that 10% of buildings will be impacted, with an average repair cost of \$50. This equates to an average loss per residential building of \$5.

3.3.5. Miscellaneous

We added \$100 to each building impacted by tephra for miscellaneous costs. This will cover incidental damage to items such as awning and patio covers and the costs of any cleanup equipment that must be purchased.

3.3.6. Cost per building

The expected average costs per residential building are damage to roof coatings (\$308), wall coatings (\$145), air-conditioning units (\$25), aerials and satellite dishes (\$5) and miscellaneous costs (\$100). This equates to an average non-structural loss per building of approximately \$583. This is calculated for every meshblock where tephra thickness is greater than 0.1 mm and the CDV less than 0.8, and scaled by the total number of residential buildings within the meshblock.

3.4. Cleanup activities

Costs associated with cleanup activities are likely to comprise a high proportion of the total loss from the next volcanic event to impact Auckland. Following the 1995–1996 eruptions of Mt. Ruapehu, the cost of cleanup within Rotorua alone was estimated at \$53,000 (Johnston et al., 2000), although the thickness of tephra was less than a few mm. However, this included the costs of cleaning the central business district and curbs in all urban areas, which we do not consider in this study.

Many hours work and large losses were associated with cleanup following the eruption of Mount St. Helens. A survey carried out after the event showed that 85% of residents spent at least some time in cleanup activities, 50% spent more than 10 h and 23% more than 30 h (Dillman and Roberts, 1982). An interesting point to note is that, following this eruption, about 90% of insurance companies covered the hourly personal costs of cleanup carried out by their clients. Most homeowners were paid at a rate of US$5 per hour for between 40 and 100 h work (Blong, 1984).

In our calculations we assume that much of the cleanup process will be carried out by homeowners and have calculated losses based on a ‘labourer hourly rate’ of $16 (Rawlinsons, 2003). The costs of tephra removal from buildings, cleaning of building exteriors and tephra transport and disposal are calculated independently within the model. The total volume of tephra is calculated by multiplying thickness at each mesh-block by the average roof area of 150 m^2. We again calculate losses for thicknesses greater than 0.1 mm as thin falls still require removal from roofs, exterior walls, screens and windows.

3.4.1. Removal

Auckland Engineering Lifelines Group (2001) suggest that, in the case of a future volcanic event, tephra removed from residential properties should be placed on the roadside so that it can be collected during the clearing of roads. Losses associated with the removal of tephra from residential buildings are calculated only for the time it would take a single person to remove tephra from the roof of a building, and directly adjacent to exterior walls, and place it on the roadside for collection.

We have estimated that it would take 2 h to remove each square metre of tephra from the building (Table 2). When thicknesses are small, i.e. less than 1 mm, this may involve simply sweeping or hosing the roof area, taking only a small amount of time.

3.4.2. Cleaning

Once tephra is removed, a larger job may be to thoroughly scrub and clean the exterior of buildings. As the majority of buildings are low-rise, we have assumed that all residential buildings will require an average 10 h of cleaning (Table 1).

Again, only the hourly costs of homeowners undertaking this work have been calculated. Purchase of cleanup equipment has been covered under the miscellaneous costs associated with non-structural damage. If structural damage to a building is greater than 80% we assume that the house will be completely re-built and cleaning is therefore unnecessary.

Table 3
Transport and disposal costs for various thicknesses of tephra based on values given by Auckland Engineering Lifelines Group (2001)

Thickness (mm)	Volume (m^3)	Transport ($)	Disposal ($)	Loss ($)
1	0.15	–	–	–
10	1.5	22.50	4.50	27.00
100	15	225.00	45.00	270.00
1000	150	2250.00	450.00	2700.00

3.4.3. Transport and disposal

Large volumes of tephra must be removed from properties. We use the transport and disposal costs estimated by Auckland Engineering Lifelines Group (2001) (Table 3). Although not specified, we assume these values include labour costs.

It was estimated by Auckland Engineering Lifelines Group (2001) that the transportation cost of tephra would be approximately $0.30 per cubic metre, per kilometre for a return trip. These authors assumed an average distance to the disposal site of 50 km, which we have also adopted. This equates to $15 per cubic metre of tephra removed from the building. In addition to this, Auckland Engineering Lifelines Group (2001) gave a value of $3 per cubic metre for the disposal of tephra. We assumed that if the total volume of tephra is less than 1 m^3, tephra would not have to be removed from properties and would most likely be absorbed into garden areas, or worse, washed into the storm water system.

4. Results

The maximum number of residential buildings within Auckland that may be impacted by tephra fall, as calculated by this model, is 284,256. For 10,000 simulations we calculated the number of build-

Table 2
Removal and cleaning costs for various thicknesses of tephra

Thickness (mm)	Volume (m^3)	Hours removing	Hours cleaning	Total hours	Loss ($)
1	0.15	0.3	10	10.3	164.80
10	1.5	3	10	13	208.00
100	15	30	10	40	640.00
1000	150	300	10	310	4960.00

It has been assumed that all houses have an average roof area of 150 m^2 and that it takes 2 h to remove each m^2 of tephra. The loss per hour of work has been calculated at $16.

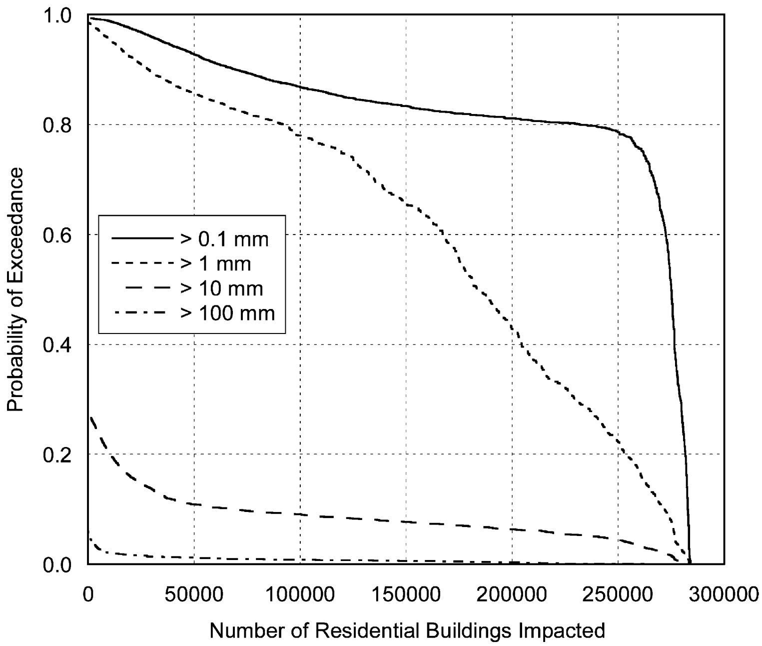

Fig. 7. Conditional on a volcanic event affecting Auckland, probability of tephra falls thicker than 0.1, 1, 10 and 100 mm impacting more than the given numbers of buildings.

ings impacted by more than 0.1, 1, 10 and 100 mm of tephra (Fig. 7).

During most events, the majority of the region is covered by at least 0.1 mm of tephra. In approximately 80% of events, more than 240,000 buildings are affected. The distribution describing the number of buildings impacted by more than 1 mm of tephra is reasonably uniform. In 80% of events more than 80,000 buildings are impacted, in 50% more than 190,000 and in 20% more than 250,000.

The probability of a large number of buildings being impacted by more than 10 mm of tephra is much smaller. In only 25% of simulated events are any buildings impacted and more than 100,000 buildings are affected in approximately 10% of simulations. Only in about 5% of simulations are any buildings impacted by more than 100 mm of tephra and in less than 1% of events more than 50,000 buildings are impacted.

The number of buildings impacted per simulation was analysed for individual volcanic centres (Fig. 8). For tephra falls thicker than 0.1 mm (Fig. 8A), AVF events typically impacted the smallest number of buildings followed by events from Tongariro. Events from the other centres tend to impact most of the region by more than this thickness and therefore affect most buildings. When we look at buildings impacted by more than 1 mm of tephra there is greater variation between eruption centres (Fig. 8B). The AVF and Tongariro still affect the smallest number of buildings, followed by Egmont. Approximately 80% of events from the rhyolitic centres impact more than 200,000 buildings with more than 1 mm of tephra.

For thicknesses greater than 10 mm (Fig. 8C) and 100 mm (Fig. 8D), only the AVF and rhyolitic centres produce events that impact buildings. In both cases, Taupo and Okataina affect the largest number of buildings. In 80% of simulations from Taupo, and 55% from Okataina, at least some buildings are impacted by more than 10 mm of tephra. Potentially, eruptions from any of the rhyolitic centres can impact the whole region with more than 10 mm of tephra. In comparison, events from the AVF never cover more than 50,000 buildings with this thickness. Events from Taupo and Okataina may cover up to 250,000 buildings with 100 mm of tephra, although the probability is very small. Taupo events have the highest probability of impacting Auckland with more than 100 mm of tephra. However, less than 20% of Taupo simulations impact any buildings by more than this thickness.

Fig. 9 shows event losses from 10,000 simulations plotted against calculated Average Recurrence Intervals (ARIs). Simulated losses were first ranked in descending order and then assigned ARIs in years using:

$$\mathrm{ARI} = (N+1)/R \quad (1)$$

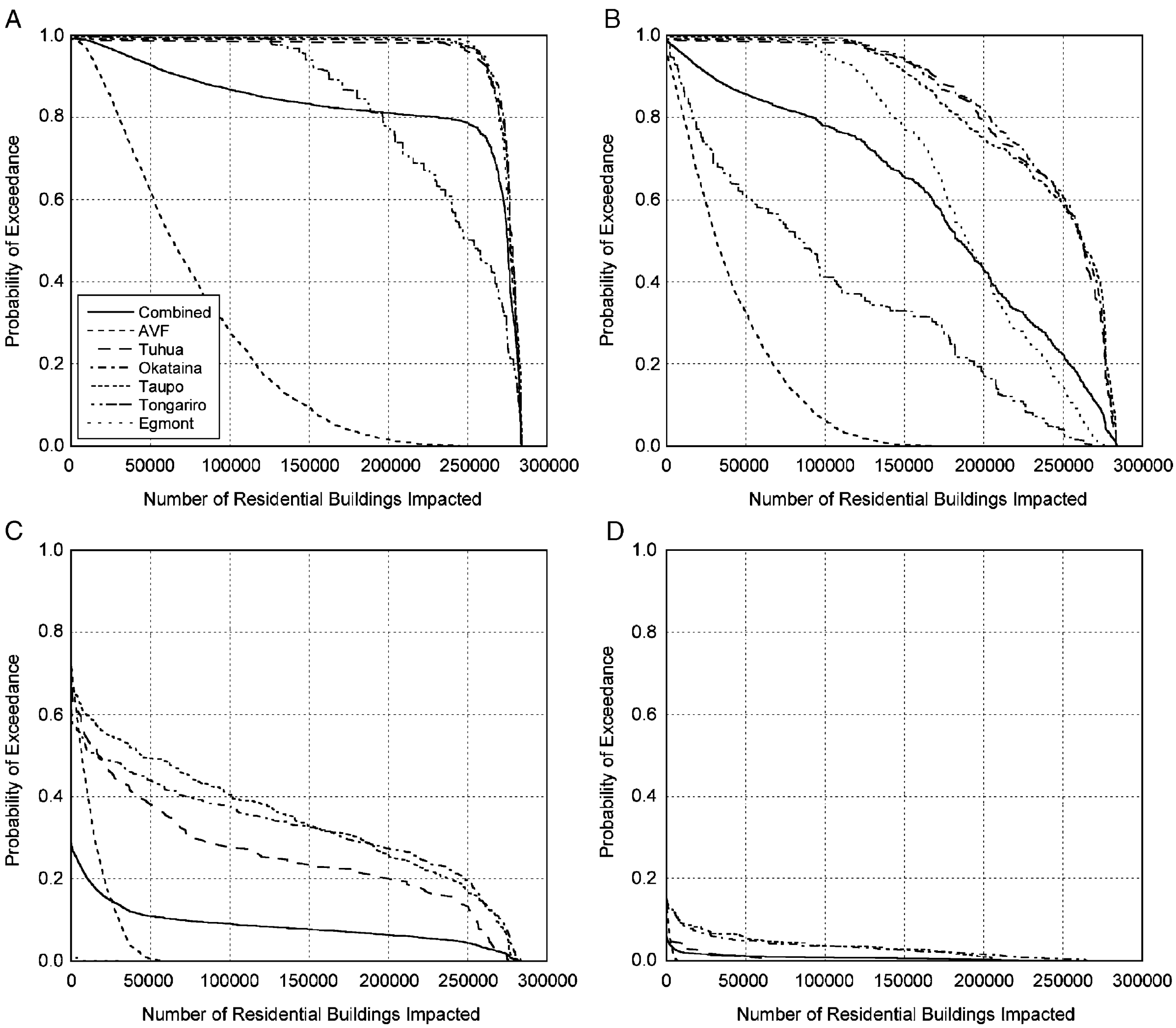

Fig. 8. Conditional on a volcanic event affecting Auckland, probability of tephra falls from each centre, and all centres combined, impacting more than the given numbers of buildings with (A) greater than 0.1 mm of tephra, (B) greater than 1 mm of tephra, (C) greater than 10 mm of tephra and (D) greater than 100 mm of tephra. Legend in (A) is applied to all plots.

where N is the number of years simulated (10,000 simulations × an average event return period of 470 years) and R is the rank of the simulated loss (Bell et al., 1989).

Structural damage does not become apparent until ARIs of approximately 8000 years. $1 billion losses occur at about 35,000 years and this increases to about $26 billion at 1 million years. Loss due to non-structural damage is constant at approximately $160 million for ARIs above about 600 years. This is due to a consistent loss resulting from any tephra thicker than 0.1 mm and because most simulations impact the entire region with more than this thickness. Between 600 and 3000 years, cleanup loss is constant at about $50 million, increasing to over $450 million at a return period of 1 million years. This means that between return periods of 600 and 3000 years, total loss is approximately $210 million, increasing to $10 billion at an ARI of 100,000 years and over $26 billion at 1 million years.

Loss curves were also calculated for individual volcanic centres (Fig. 10). In general, for all losses combined (Fig. 10A), the smallest losses are from the AVF, followed by Egmont and Tongariro. This is due to the smaller areas that are generally impacted by eruptions from these centres. The remaining three volcanic centres have constant losses of approximately $200 million until losses from Taupo and Okataina begin to increase

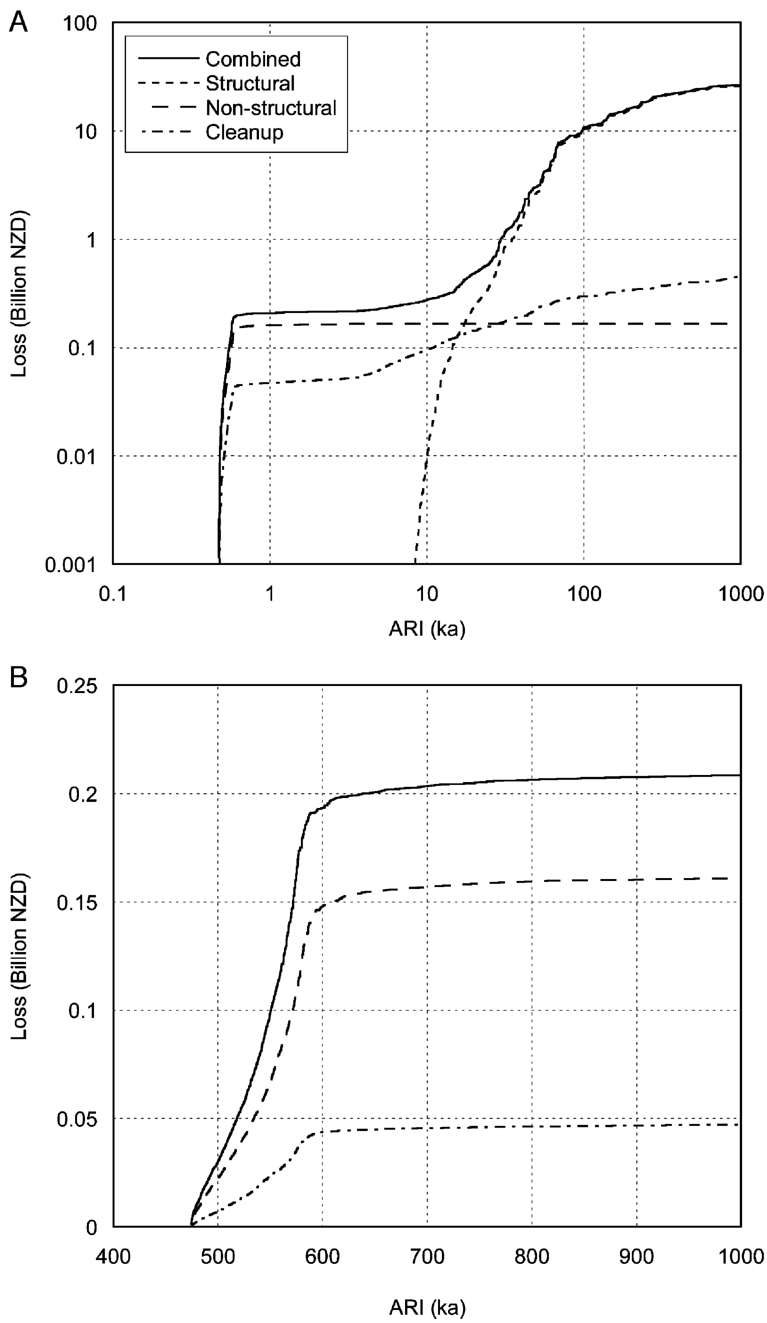

Fig. 9. Expected loss versus the Average Recurrence Interval (ARI) calculated from 10,000 random simulations. Losses have been calculated for structural damage, non-structural damage, clean-up costs and all losses combined. (A) shows loss in billions of New Zealand dollars to an ARI of 1 million years and (B) of 1000 years. Legend in (A) is also applied to (B).

after return periods of about 10,000 years. Significant structural loss (Fig. 10B) only occurs due to large thickness falls from the AVF, Taupo, Okataina and Tuhua. Structural damage from Okataina, the AVF, Taupo and Tuhua begins at return periods of 17,000, 22,000, 47,000 and 224,000 years respectively.

In terms of non-structural damage (Fig. 10C), the smallest losses occur from simulated AVF events, again due to the smaller areas impacted. Apart from the AVF, all centres have almost constant non-structural losses of about $160 million. Cleanup losses (Fig. 10D) are smallest from the AVF, Tongariro and Egmont, with

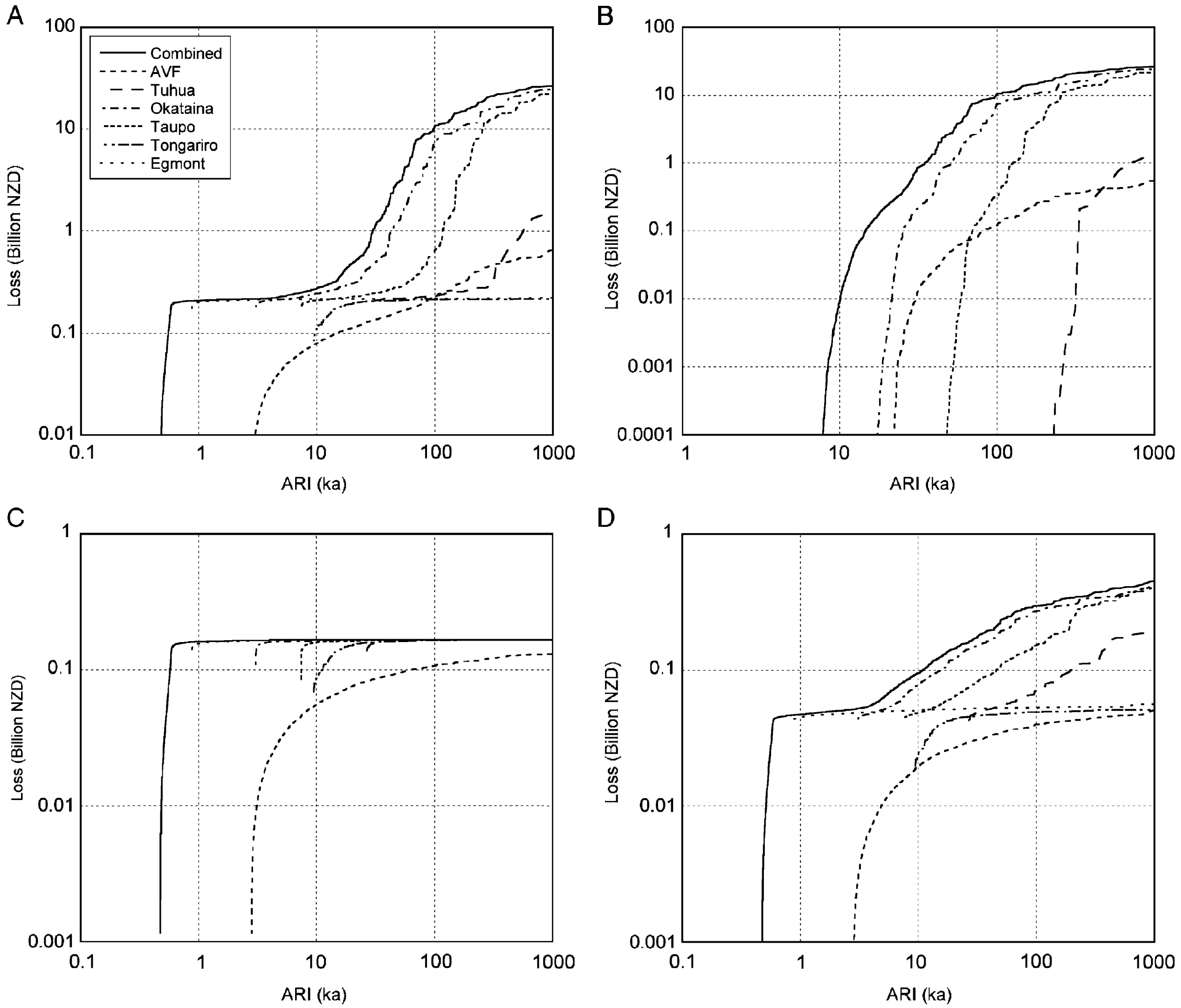

Fig. 10. Expected loss in millions of New Zealand Dollars versus the Average Recurrence Interval (ARI) calculated from 10,000 random simulations, broken down to show losses from individual centres and all centres combined for (A) combined losses, (B) structural damage, (C) non-structural damage and (D) cleanup costs. Legend in (A) applies to all plots.

Okataina, Taupo and Tuhua contributing the largest losses at longer return periods.

5. Discussion

Losses calculated by this first version of *VolcaNZ* are conservative in the sense that they significantly underestimate total loss from the next volcanic event to impact Auckland. In particular, we have only considered direct damage to residential buildings and the costs of cleanup. We have not looked at damage to building interiors, such as carpets, furnishings or electrical appliances, or cleanup and damage to gardens, driveways, swimming pools and outdoor furniture.

Losses to commercial and industrial buildings, lifelines and the costs associated with business interruption are also expected to be much larger than those calculated here. A volcanic event may also consist of a number of eruptions; whereas, we have modelled each event as a single paroxysmal eruption.

Modelled tephra thickness and frequency are based on preserved tephra layers and therefore represent a minimum thickness and maximum average return period. Although tephra fall produces the largest risk to Auckland, large losses due to intense localised hazards such as lava flow and base surge should also be calculated.

Also, it may be necessary to consider the possibility that: (a) labour costs could increase due to demand following a volcanic event, (b) cleanup costs would be much larger for sustained events and (c) further damage will be caused by the cleanup process itself.

Lastly, we have only calculated losses to Auckland. Although this is the largest Region that may be impacted by a volcanic eruption in New Zealand, losses from distal events will be much larger for towns and cities closer to these volcanoes.

These deficiencies will be addressed by adding more hazard and loss modules to *VolcaNZ*, resulting in a complete catastrophe loss model. At this early stage we can already see that potential loss from the next volcanic event to impact Auckland is significant.

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