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Exploring the potential of probabilistic Bayesian event tree tools for volcanic hazard analysis, risk assessment, and hazard and risk communication in New Zealand

Mary Anne Thompson

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Geology, the University of Auckland, 2014
Methodologies to assess hazard footprints in probabilistic terms have developed together with quantitative approaches to risk assessment. The importance of evaluating uncertainties is becoming ever more apparent. That said, there is a significant gulf between quite advanced academic research and routine practice in ‘applied volcanology’.

ABSTRACT

In recent years, the emergence of free, robust, user-driven Bayesian event tree tools for probabilistic volcanic hazard analysis (PVHA) has introduced new opportunities for building comprehensive hazard analyses for volcanoes worldwide. This thesis investigates the potential for Bayesian event tree tools for volcanic hazard analysis, risk assessment, and hazard and risk communication in New Zealand.

A long-term PVHA for one of New Zealand’s most recently active and complex volcanoes, the Okataina Volcanic Centre (OVC), was performed by integrating past eruption records, geospatial analyses, expert elicitation data, and TEPHRA2 models into BET_VH (Bayesian Event Tree for Volcanic Hazards). This represents the first tephra hazard analysis for the OVC that assesses different possible vent areas and eruption styles, quantitatively defines the OVC’s linear vent zones (LVZs), and presents hazard information at multiple levels of uncertainty (average, 10th and 90th percentiles). Results revealed that in order to estimate the full potential distribution and magnitude of tephra hazard, all possible vent locations and both basaltic and rhyolitic Plinian eruption styles should be considered in OVC tephra hazard analyses.

A new approach for developing PVHA-based quantitative risk assessments is presented through a study of OVC ashfall risk to farms in the Bay of Plenty (BOP) region. By integrating TEPHRA2 and BET_VH seasonal hazard datasets with agriculture fragility functions and seasonal vulnerability coefficients, a robust risk assessment is achieved, which quantifies potential damage (loss) over a continuum of hazard and vulnerability, at multiple levels of uncertainty, and in the context of fluctuating hazard and vulnerability environments. A risk uncertainty matrix is presented as a scheme to guide evaluation and communication of the level of uncertainty related with such robust quantitative risk assessments, based on combining different levels of uncertainty available in each of the hazard and vulnerability datasets used. Fruit farms were found to be more at risk of OVC ashfall than dairy farms, and farms east of the OVC were found to be more at risk than farms north of the OVC. Detailed assessment revealed that the volcanic ashfall risk at fruit farms is cyclic and fluctuates with time of year and harvest season, with the highest risk experienced during peak harvest season (15 October – 14 April).

Fourteen interviews and a survey of 110 organisational stakeholders and scientists in New Zealand revealed that simple visual design properties can have significant influences on the communication and interpretation of hazard information from probabilistic volcanic hazard maps and hazard curves designed with BET_VH data. Such examples include colour scheme and data classification style. Based on these findings, a set of empirically-based recommendations are presented for consideration in the design of probabilistic volcanic hazard maps, the first such recommendations for volcanic hazard maps worldwide.

Through these three interdisciplinary and methodological case studies based on the tool BET_VH, this thesis finds that Bayesian event tree tools for PVHA have encouraging potential to contribute to applied volcanological practices in New Zealand.
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# I. TABLE OF CONTENTS

Abstract ......................................................................................................................................................... v
Acknowledgements ..................................................................................................................................... vi

II. List of figures ............................................................................................................................................. xi

III. List of tables ........................................................................................................................................... vi

IV. Glossary of abbreviations ....................................................................................................................... vi

Chapter 1: Introduction ........................................................................................................................... 13

1.1 Introduction .................................................................................................................................... 15
1.2 Volcanic hazards and the evolution of PVHA ................................................................................ 16

1.2.1 Probabilistic volcanic hazard analysis (PVHA) ..................................................................... 17

1.2.1.1 PVHA for tephra hazard ............................................................................................ 19
1.2.1.2 PVHA using Bayesian event trees ............................................................................ 20

1.3 Volcanic hazard and risk in society ................................................................................................ 23

1.3.1 Hazard and risk communication ............................................................................................ 24

1.3.1.1 Volcanic hazard maps ............................................................................................ 25
1.3.1.2 Volcanic hazard curves ........................................................................................... 27

1.4 Significance, aims, and structure of the thesis .............................................................................. 27

1.4.1 Aims ...................................................................................................................................... 28
1.4.2 Structure and content of the thesis ....................................................................................... 28

Chapter 2: BET_VH (Bayesian Event Tree for Volcanic Hazards):
A tool for long-term probabilistic volcanic hazard analysis ......................................................... 31

2.1 Introduction .................................................................................................................................... 33

2.2 Bayesian inference ........................................................................................................................ 33

2.3 Bayesian Event Tree for Volcanic Hazards (BET_VH) .................................................................. 34

2.3.1 Previous BET_VH studies ..................................................................................................... 36
2.3.2 Other Bayesian event tree PVHA tools ................................................................................. 38

2.4 Model caveats ................................................................................................................................ 38

2.4.1 Uncertainties ......................................................................................................................... 39
2.3.2 Subjectivities ......................................................................................................................... 39
2.3.2 BET in practice ...................................................................................................................... 40

Chapter 3: Exploring the influence of vent location and eruption style on tephra
fall hazard from the Okataina Volcanic Centre, New Zealand ....................................................... 41

Preface to Chapter 3 ............................................................................................................................ 43

Abstract ................................................................................................................................................ 44

3.1 Introduction .................................................................................................................................... 45
3.2 Geologic setting ............................................................................................................................... 49
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.4 Okataina Volcanic Centre (OVC)</td>
<td>85</td>
</tr>
<tr>
<td>4.3 Methods</td>
<td>87</td>
</tr>
<tr>
<td>4.3.1 TEPHRA2</td>
<td>87</td>
</tr>
<tr>
<td>4.3.2 BET_VH</td>
<td>88</td>
</tr>
<tr>
<td>4.3.3 Risk assessment</td>
<td>90</td>
</tr>
<tr>
<td>4.4 Results</td>
<td>92</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>95</td>
</tr>
<tr>
<td>4.5.1 OVC ashfall risk to BOP fruit and dairy farms</td>
<td>95</td>
</tr>
<tr>
<td>4.5.2 Capturing uncertainties in risk assessment</td>
<td>99</td>
</tr>
<tr>
<td>4.5.3 Challenges in quantitative in risk assessment</td>
<td>99</td>
</tr>
<tr>
<td>4.6 Conclusion</td>
<td>100</td>
</tr>
</tbody>
</table>

Chapter 5: The influence of probabilistic volcanic hazard map properties on hazard communication

Preface to Chapter 5

Abstract

5.1 Introduction

5.2 Properties and users of probabilistic volcanic hazard maps

5.3 Methods

5.3.1 Interviews

5.3.2 Survey

5.4 RESULTS

5.4.1 Interviews

5.4.1.1 Map data classification

5.4.1.2 Map colour scheme

5.4.1.3 Map key expression

5.4.1.4 Map content

5.4.1.5 Revisions to maps for survey

5.4.2 Survey

5.4.2.1 Map data classification

5.4.2.2 Map content

5.4.2.3 Map key expression

5.4.2.4 Hazard curves

5.4.2.5 Map colour scheme

5.4.2.6 Map explanatory text and map format

5.5 Discussion

5.5.1 Data classification and uncertainty
II. LIST OF FIGURES

Fig 1.1 Images of local and distal tephra hazard ................................................................. 17
Fig 1.2 Examples of traditional volcanic hazard map styles from New Zealand .................. 18
Fig 1.3 Example of an event tree used in the Montserrat eruption 1996-97 ......................... 21
Fig 1.4 Maps showing BET_EF outputs during Exercise Ruaumoko ............................... 26
Fig 1.5 Probabilistic tephra fall hazard curves from past studies ....................................... 27
Fig 2.1 Schematic representation of the BET_VH tool ....................................................... 35
Fig 2.2 Maps showing short- and long-term applications of BET_VH from Exercise Ruaumoko ......... 38
Fig 3.1 Map of the Taupo Volcanic Zone, New Zealand and location of the OVC ................. 46
Fig 3.2 Map of the OVC, showing topographic structures, faults, LVZs, and past deposits and vents .......... 47
Fig 3.3 Map illustrating past and prior data input into BET_VH Node 4 for the OVC .............. 59
Fig 3.4 Maps showing the results of BET_VH Node 4 analyses with and without prior data .... 66
Fig 3.5 Maps showing the BET_VH results for absolute P of accumulating ≥ 10 kg m⁻² of tephra ...... 67
Fig 3.6 Absolute hazard curves for the town of Kawerau based on BET_VH results .............. 69
Fig 3.7 Maps showing the BET_VH average absolute P of ≥ 10 kg m⁻² of tephra for all vent locations ... 70
Fig 3.8 Maps showing the BET_VH results for conditional P of accumulating ≥ 10 kg m⁻² of tephra .... 72
Fig 4.1 Maps showing the location of the Bay of Plenty (BOP), OVC, TVZ and BOP agricultural land ... 83
Fig 4.2 Annual and peak fruit farm season wind roses for approx. 20 km above vent .......... 89
Fig 4.3 Volcanic risk uncertainty matrix .................................................................................. 91
Fig 4.4 Maps showing average probability of accumulating ≥ 100 mm of OVC ash at BOP dairy farms .. 92
Fig 4.5 Maps showing average probability of accumulating ≥ 10 mm of OVC ash at BOP fruit farms .... 93
Fig 4.6 Graph showing fruit farm fragility function and hazard curves for fruit farms N and E of OVC .... 94
Fig 4.7 Graph showing seasonal fluctuations in the volcanic ash risk at a fruit farm E of the OVC ... 95
Fig 4.8 Maps showing ashfall risk in the event of OVC eruptions during peak fruit farm season ... 96
Fig 4.9 Maps showing ashfall risk in the event of different OVC eruption styles .................... 97
Fig 5.1 Maps used in in-person interviews ......................................................................... 112
Fig 5.2 Maps with different data classification styles used in questions in the survey .......... 113
Fig 5.3 Maps with different probabilistic content styles used in questions in the survey ...... 114
Fig 5.4 Two different hazard map styles used in questions in the survey .............................. 114
Fig 5.5 Maps with different colour scheme styles used in questions in the survey .............. 115
Fig 5.6 Explanatory text provided with one of the maps in a question in the survey .......... 116
Fig 5.7 Survey results for map data classification ............................................................... 123
Fig 5.8 Survey results for map probabilistic content ............................................................ 125
Fig 5.9 Survey results for map key expression ...................................................................... 125
Fig 5.10 Survey results for two types of hazard curves ...................................................... 126
III. LIST OF TABLES

Table 3.1 OVC intracaldera (26 ka – present) eruption history ................................................. 48
Table 3.2 Parameters used in TEPHRA2 model simulations for the OVC .................................. 55
Table 3.3 BET_VH input parameters for the OVC ..................................................................... 60
Table 3.4 BET_VH Node 4 prior data input from expert elicitation session ................................. 63
Table 4.1 Fruit farm seasonal vulnerability coefficients from Wilson and Kaye (2007) ............... 86
Table 4.2 Average maximum estimate of risk of 90% damage to dairy farms from OVC ashfall .... 98
Table 4.3 Maximum estimate of risk for fruit farms from OVC ashfall ....................................... 98
Table 5.1 Summary of questions asked in the survey ................................................................. 118
Table 5.2 Survey participants occupational discipline .............................................................. 119
Table 5.3 Survey participant demographics ............................................................................. 121

IV. GLOSSARY OF ABBREVIATIONS

BBN  Bayesian belief network
BET_VH Bayesian Event Tree for Volcanic Hazards
BOP  Bay of Plenty region
CDEM Civil Defence and Emergency Management
GIS  Geographic information systems
LVZ  Linear vent zone
OVC  Okataina Volcanic Centre
P    Probability
PVHA Probabilistic volcanic hazard analysis
TEPHRA2 Version 2 of Tephra
VEI  Volcanic explosivity index
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*Chapter 4: Integrated BET_VH-based assessment of risk to agriculture from local-source volcanic ash fall: a case study from the Bay of Plenty, New Zealand* is a manuscript which is in preparation for submission to Natural Hazards and Earth System Sciences

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CHAPTER 1
Introduction
Introduction

1.1 INTRODUCTION

Managing volcanic risk is a complex and ongoing challenge for communities in volcanically active regions. Urbanisation, population growth, and environmental degradation are among the many factors working to increase the vulnerability of communities worldwide. As these trends continue, and more people settle in areas near hazardous active volcanoes (Chester et al. 2001, Small and Naumann 2001), the need for sociologically and economically realistic risk assessments becomes more critical (Woo 2009, Marzocchi et al. 2012). Volcanic risk assessments combine knowledge about potential volcanic hazards with information about the vulnerability, or potential for loss, from those hazards (UNISDR 2009, Woo 2009). These assessments have become essential for guiding informed and cost-effective volcanic risk reduction practices in both long-term planning and crisis management.

Understanding the type, intensity, and likelihood of volcanic hazards that pose a threat to a region is essential for constructing an effective and relevant evaluation of volcanic risk. However, the interdependent processes that drive volcanic systems are complex, non-linear, stochastic, and not fully-understood (Sparks et al. 2003). These unknowns introduce uncertainty which limits scientists’ ability to deliver precise or definitive predictions of volcanic behaviour and its hazards. Modern probabilistic volcanic hazard analysis (PVHA) methods allow scientists to capture and address these uncertainties through probability distributions, and establish a way to quantify and forecast the likelihood of many different possible hazard scenarios which could occur. This presents many advantages for both hazard scientists and users of hazard information (Newhall and Hoblitt 2002, Marzocchi et al. 2012), and has led to an increasing number of PVHA methods being developed today. However, most of the tools and techniques for implementing these methods are young, and have not yet been widely tested, integrated into volcanic risk assessments, or investigated in a broader applied context (Sparks et al. 2013).

This thesis is a methodological study which aims to bridge the gap between recognising PVHA tools as a valuable scholarly scientific method, and actually evaluating their potential to become an active, integral part of applied volcanic hazard and risk reduction practices. An interdisciplinary approach is taken, in order to address the topic from multiple perspectives and develop a wide-ranging picture of the potential of PVHA tools. This introductory chapter provides a background to PVHA, introduces the specific Bayesian event tree PVHA tool explored here, and describes the need to investigate the application of such tools in the context of volcanic hazard analysis, risk assessment, and hazard and risk communication in New
Zealand. The chapter thus presents the guiding questions behind this research, significance of the work, as well as specific aims of this thesis, and concludes with a summary of the content and structure of the thesis.

1.2 VOLCANIC HAZARDS AND THE EVOLUTION OF PVHA

A hazard can be described as a threatening process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (CRED 2009, UNISDR 2009). Volcanoes are capable of generating a wide range of different types of hazards, which vary in magnitude, intensity, duration, and areal extent (Blong 1984). The generation of hazards is complex, and is controlled by many coupled, non-linear, and dynamic subsurface and eruptive processes (Sparks 2003). For example, in an explosive volcanic eruption, existing rock and rising magma are violently fragmented within the conduit of the volcanic vent and then expelled as pyroclastic material (termed tephra) which can become entrained in a buoyant plume of rising volcanic gases (Fig. 1.1A, Sparks et al. 1997). Tephra which rises in the plume into the atmosphere can be picked up and transported by the wind for very short to very long distances (Fig 1.1B), where it is suspended in the atmosphere until eventually falling out and depositing on the ground. Tephra particles can be abrasive, conductive, and invasive, and accumulation of tephra can lead to significant social and economic disruption and impacts on health (e.g., Horwell and Baxter 2006, Durant et al. 2010, Wardman et al. 2012, Wilson et al. 2014a,b). In addition to the prevailing wind patterns present during eruption, the volume of magma erupted, eruption duration, and eruption plume height will all have a strong influence on the characterisation of tephra fall hazard (Sparks et al. 1997). However, these eruption parameters are controlled by the interaction of many chemical and physical processes, and remain unknown prior to eruption.

Traditionally, this uncertainty has been addressed using indistinct qualitative statements such as “high,” “moderate,” “low,” or “likely” to describe potential volcanic hazard areas based on past eruption deposits or deterministic scenario-based hazard analysis, in both New Zealand (e.g., Johnston et al. 1993, 1997, Neall and Alloway 1993, Neall et al. 1999) (Fig 1.2) and worldwide (e.g., Crandell and Mullineaux 1978, Del Pozzo et al. 1996, Lindsay et al. 2005). However, these styles of hazard analysis are limited to consideration of a select number of specific past events or pre-defined scenarios, and are unable to capture the full scope of variability in volcanic systems or other unknowns in a structured and comprehensive manner (Newhall and Hoblitt 2002). For example, if a volcanic hazard analysis is based on the scenario of a VEI 3 eruption because that is the magnitude of eruption which has occurred most frequently in a volcano’s known eruption history, the hazard could be underestimated if a future eruption is actually a rarer, larger, VEI 4 event. Two separate hazard analyses based on a VEI 3 and a VEI 4 scenario would
help ensure that the potential hazard associated with both events is considered, but it would not capture information about the comparative likelihood of occurrence. Further, a substantial source of uncertainty lies in the defining of parameters for a specific scenario and in the reconstruction of past events (e.g., Biass and Bonadonna 2011). In many volcanic areas a future eruption could, for example, occur from a number of different possible locations (e.g., Auckland Volcanic Field, New Zealand, Bebbington and Cronin 2011; Okataina Volcanic Centre, New Zealand, Nairn 2002; Campi Flegri Caldera, Italy, Selva et al. 2012b; Harrat Rahat Volcanic Field, Saudi Arabia, Runge et al. 2014), and choosing one vent for a scenario could lead to inaccurate estimates of the spatial distribution of hazard.

1.2.1 Probabilistic volcanic hazard analysis (PVHA)

While conventional hazard analyses based on past deposits and deterministic scenarios are important methods for exploring the detailed impacts and consequences of particular event scenarios, the limitations of using these approaches to model stochastic volcanic systems has driven the development of an increasing number of probabilistic volcanic hazard analysis (PVHA) methodologies over the past decade (e.g., Mader et al. 2006, Sparks et al. 2013 and references therein). PVHA methods offer a way to consider the many variations possible in the hazard and eruption sequence, as well as their likelihood of occurrence, broadening the potential applications and relevance of hazard analyses for volcanic risk assessments. Short-term PVHA can be used to develop hazard forecasts for a time window of hours to months to respond to volcanic unrest, and can be valuable in managing short-term risk during a crisis.

Figure 1.1 A) A plume of tephra and volcanic gases rises above Puyehue-Cordón Caulle volcanic chain in Chile in an explosive eruption in June 2011. Image credit: Reuters/Ivan Alvarado. B) Ash (≤2 mm sized tephra particles) from the Puyehue-Cordón Caulle eruption captured in a satellite image taken above New Zealand. The ash erupted in Chile was transported by the wind for very long distances, affecting the airspace above New Zealand 9,000 km away. Image credit: NASA/Jeff Schmaltz.
Long-term PVHA can be used to develop hazard forecasts for a time window of years to decades, and to inform preparedness, mitigation, and response plans as part of wider risk reduction strategies (Marzocchi and Bebbington 2012, Cashman and Sparks 2013).

The earliest applications of probabilistic methods in volcanology were made by Wickman (1966) and Reyment (1969), who proposed stochastic models for analysing volcanic eruption patterns. However, it has only been in the past decade or so, with increased computational power, that PVHA has become an advanced, active, and prevalent area of volcanological research. Sophisticated modelling of different hazardous processes using numerical (e.g., Titan2D, Charbonnier and Gertisser 2009), empirical (e.g., LAHARZ, Iverson et al. 1998), analytical (e.g., TEPHRA2, Bonadonna et al. 2005) and Monte Carlo (e.g., ASHFALL, Hurst and Smith 2004) tools and techniques offers a way to explore different possible hazard scenarios in a probabilistic manner. Tens to thousands of runs of one specific model can be performed using variable or stochastically sampled input parameters within an expected range in order to generate a probabilistic assessment of hazard outcomes (e.g., out of 1,000 different runs within this range, how many times did the hazard reach an intensity of X in area A?).

The natural diversity of volcanic hazards requires that different models are needed in order to
analyse different hazardous phenomena. The dynamics of fall and flow processes, for example, require different sets of physical equations and empirical calibration in order to be modelled. Models to forecast tephra hazard are of particular demand and interest in PVHA because tephra is one of the most common products of explosive volcanic activity worldwide, and it is also the most widespread, with the potential to disrupt and impact society on many different levels and on both short and long time scales. Although thick, heavy loads (1 – 5 kPa) of tephra deposited proximal to a volcanic vent can lead to roof collapse (Spence et al. 2005) and other severe impacts, tephra deposits thin rapidly with distance from the vent (Bonadonna et al. 1998), and most widespread impacts are caused by moderate to thin accumulations. Accordingly, tephra fall is typically considered more of a disruptive hazard, than a destructive or lethal hazard such as a rapid pyroclastic flow (super-heated density flow of volcanic gas and tephra) or lahar (volcanic mudflow) (Tanguy et al. 1998, Spence et al. 2004, 2005). In many cases, this allows opportunities to plan for and mitigate risk from tephra based on tephra hazard forecasts. For example, airports can plan to optimise runway usage before eruptive events, move or cover parked aircraft, and develop efficient clean-up and recovery plans to mitigate tephra impacts (Guffanti et al. 2009). Scheduled outages and cleaning of infrastructure can mitigate impacts of tephra fall on electrical power systems (Wardman et al. 2012) and water supplies can be covered to prevent contamination (Stewart et al. 2006). Preventative measures such as masks can be taken to reduce human exposure to re-mobilised tephra (Baxter et al. 1983). High-technology farms can increase backup water and feed supply stores (Wilson and Cole 2007), and wind breaks and greenhouses can be installed to protect crops (Wilson et al. 2011).

1.2.1.1 PVHA for tephra hazard

Hazard models have been developed with varying degrees of complexity to describe tephra dispersion and fallout based on the relationship between different eruption and atmospheric parameters (Bonadonna and Costa 2013, Scollo et al. 2008). Particle-tracking tephra models numerically model the 3D evolution of a volcanic plume and its dispersion and transportation in the atmosphere. These models, such as CANERM (D’Amours 1998), PUFF (Searcy et al. 1998), and VAFTAD (Heffter and Stunder 1993), are used in Volcanic Ash Advisory Centres (VAACs) for tracking and forecasting plumes in the airspace for aviation safety purposes (Witham et al. 2007), but are not used for modelling fallout and deposition. Advection-diffusion-sedimentation tephra models are based on the mass conservation equation (Costa et al. 2006), and are used to describe the fallout and deposition of tephra on the ground. These models, such as TEPHRA2 (Bonadonna et al. 2005, Connor et al. 2001), ASHFALL (Hurst 1994) and HAZMAP (Barberi et al. 1990, Macedonio et al. 2005), are often used for hazard mapping and assessment purposes. Only a few complex models, such as FALL3D (Costa et al. 2006, Folch et al. 2009) and VOL-CALPUFF (Barsotti and Neri 2008, Barsotti et al. 2008), perform modelling of both particle transport and sedimentation.

The dispersal and fallout of tephra is controlled by a range of eruptive, particle and atmospheric
parameters (Carey and Sparks 1986, Sparks et al. 1997). Most of these parameters are highly variable and may fall within a range of different values for each individual eruption. This variability is a source of uncertainty in modelling tephra fall hazard, and probabilistic tephra dispersion models offer a way to consider these unknowns by analysing a range of possible values together through many repeated runs of a model. Field investigation of tephra deposits provides a significant amount of information about past eruptions, and is crucial for populating tephra model parameters. Isopach maps showing distributions of tephra thickness can be used to estimate past eruption volumes (Bonadonna and Houghton 2005, Pyle 1989), and isopleth maps showing the distribution of largest tephra clasts can be used to estimate past column heights and wind speeds (Carey and Sparks 1986). However, the ability to forecast future hazard using past deposits alone is limited. The record of past deposits is incomplete due to burial, erosion, and a preservation bias towards large events. Past deposits are also likely to have been affected by significantly different wind regimes. Atmospheric dynamics, including wind speed and wind direction, can experience multiple and substantial changes in the time span of one active volcano. For example, for eruptions that occurred greater than c. 13 ka ago in New Zealand, tephra dispersion, fallout and deposition would have been influenced by climatic and atmospheric processes and that are vastly different than those acting in New Zealand today (Stewart and Neall 1984, Pillans et al. 1993). A tephra hazard map based only on past eruption tephra deposits (e.g., Nairn 2002) has low resolution, and the shape and thickness of deposits may be unreliable for an assessment of tephra hazard under modern wind conditions.

Analytical and numerical models that estimate tephra dispersion and fallout according to plume dynamics, particle sedimentation, and modern atmospheric conditions can therefore play a very important role in making long-term assessments of tephra hazard. Validation studies show that many modern tephra models demonstrate good agreement with field data, supporting their use in hazard assessment applications (Bonadonna and Costa 2013). While PVHA models in general are still largely research tools explored within the boundaries of the scientific community (Sparks et al. 2013), tephra PVHA models are growing in accessibility, application, and scope more than any other class of hazard models (e.g., flow hazard models) (Sparks et al. 2003). The tephra fall model ASHFALL has been used in at least the past two eruption crises in New Zealand (Leonard et al. 2014) and a number of different particle-tracking tephra hazard models are in use at Volcanic Aviation Authority Centres around the world (Witham et al. 2007).

1.2.1.2 PVHA using Bayesian event trees

Unlike probabilistic tephra or flow models, which forecast the probable behaviour or outcome of a single specific hazardous process through repeated runs, Bayesian event trees are designed as a framework to probabilistically evaluate many different aspects of a volcanic eruption, as well as their associated uncertainties, in one interactive interface. Event trees are a conceptual hierarchical network, in which different levels, or nodes, of the tree represent different aspects of a volcanic eruption or pre-eruption
sequence in progressively higher detail. Links between these nodes are represented by branches, which are attached to a specific probability of occurrence. As specific branches, or pathways, through the tree are chosen, these probabilities are combined to result in a final probability of occurrence of that specific event (Newhall and Hoblitt 2002). By changing and choosing alternative pathways, these probabilities can be compared and evaluated (Fig 1.3). Applying Bayesian inference to this probability path introduces the ability to evaluate a probability distribution at each branch (instead of just one probability value) and the ability to merge statistical information about both past and modelled data to develop this distribution (Marzocchi et al. 2004, 2008; Marzocchi and Bebbington 2012). Such distributions allow for a robust representation of the uncertainties associated with event tree estimates.

The customisable nature of event trees allows them to be adopted in a variety of different hazard management contexts. Short-term PVHA event trees have been used to assess eruption hazard during crises at Mount St. Helens (Newhall 1982, 1984), Mount Pinatubo (Punongbayan 1996), and Soufrière Hills (Montserrat) (Aspinall et al. 2002). These early event trees were largely designed in the form of a Bayesian Belief Network (BBN) (Aspinall et al. 2003), in which probabilities are populated through expert elicitation sessions in which a group of people experienced with the volcano (e.g., scientists, monitoring technicians) estimate a probability to assign to each branch. In Montserrat, repeated formalised expert elicitation sessions were held in order to update the probabilities in the BBN structure over the course of

![Figure 1.3 A summarised version of the event tree used in the Montserrat eruption in 1996 – 97, which was based on a structured expert elicitation of probabilities. Figure from Aspinall et al. (2002)](image-url)
Chapter 1

Introduction

the eruption (Aspinall et al. 2002, 2006) (Fig 1.3). However, rigorous expert elicitation for updating a BBN, such as the Delphi method used in Montserrat (Aspinall et al. 2006), may not always be feasible, especially under time and expert availability constraints during an impending eruption crisis. Bayesian event tree (BET) tools (Marzocchi et al. 2004, 2010) introduce a way to capture expert opinion into a PVHA event tree before a crisis. In the short-term probabilistic event tree BET_EF (Bayesian Event Tree for Eruption Forecasting, Marzocchi et al. 2004), expert opinion is elicited regarding which monitoring signals would be considered important anomalies, and the tool is then populated with this information ahead of time. This means BET_EF can be ready to be employed for real-time analysis during a crisis, rather than used as a reactive tool developed in response to the onset of unrest (Lindsay et al. 2010, Marzocchi and Bebbington 2012). BET_VH (Bayesian Event Tree for Volcanic Hazards, Marzocchi et al. 2010) is a long-term implementation of BET_EF, which can be used to build a long-term PVHA which forecasts and evaluates variability in possible future activity over any user-defined time window (e.g., 1 year). In addition to expert elicitation data, BET_VH can be populated with many different types of information, including past activity, geospatial analyses, and the outputs of hazard-specific PVHA models (Marzocchi et al. 2010). It can also be used to evaluate many different hazard types, such as tephra fall, pyroclastic flow, and lahar (e.g., Sandri et al. 2014). HASSET (Sobradelo et al. 2014) is a recently-introduced tool which is similar to the BET tools, but incorporates both short- and long-term PVHAs in one Bayesian event tree.

The transparent structure of these quantitative Bayesian event tree assessments offers many advantages for risk assessment by calculating hazard from a traceable and customizable path of numerical variables, and by expressing associated uncertainties in the estimates (average, 10th, 50th, and 90th percentiles in BET tools) (Newhall and Hoblitt 2002, Woo 2009, Marzocchi et al. 2012). BBN have been recognised as valuable tools through use during volcanic unrest crises (e.g., Montserrat, Aspinall 2002; Santorini, Aspinall 2014), and when retrospectively applied to past crises (Galeras, Aspinall 2003). Studies of the younger BET tools have demonstrated the strong potential benefits of using BET_EF for short-term crisis management (e.g., Vesuvius, Marzocchi et al. 2004, Sandri et al. 2009; Auckland Volcanic Field, Lindsay et al. 2010) and BET_VH for long-term hazard forecasts (e.g., Campi Flegrei caldera, Selva et al. 2010), but research on these tools is still evolving. The long-term approach offered by BET_VH (Marzocchi et al. 2010) and HASSET (Sobradelo et al. 2014) is particularly new to volcanic hazard analysis, and while case studies in Italy (BET_VH, Campi Flegrei caldera, Selva et al. 2010, 2012b), Peru (BET_VH, El Misti, Sandri et al. 2014), Spain (HASSET, Teide-Pico Viejo, Canary Islands, Sobradelo et al. 2014), and New Zealand (BET_VH, Auckland Volcanic Field, Sandri et al. 2012) illustrate different specific aspects of the potential to enhance long-term hazard analyses, the overall potential for these tools to be integrated into risk assessment or to play a role in planning and practice has not yet been explored.
1.3 VOLCANIC HAZARD AND RISK IN SOCIETY

The goal of developing advanced volcanic hazard analysis methods such as PVHA is to provide reliable, timely, quantitative data to inform volcanic risk assessments and mitigate the negative impacts of volcanic activity on society (Newhall and Hoblitt 2002, Marzocchi and Bebbington 2012). Volcanic risk can be defined in a number of different ways, but it is typically expressed as a relationship between the likelihood of occurrence of a hazard and the vulnerability (potential for loss) to those hazards (CRED 2009, UNISDR 2009). While actual hazardous processes generated by a volcano cannot be reduced, volcanic risk can be reduced by increasing the resilience of vulnerable systems and communities. Vulnerability is a complex and multi-dimensional concept, which refers to resilience, coping capacity, and susceptibility to loss in the context of many different elements of society, including its social fabric, economy, built environment, and natural environment, as well as many others (Cutter 1996). Quantitative PVHA results can be used to identify areas potentially exposed to hazard and help prioritise areas that require vulnerability assessments. PVHA results can also be coupled with existing vulnerability assessments to achieve estimates of risk and guide risk reduction initiatives or decision-making. The social and human dimension of vulnerability and volcanic risk is complex, dynamic, variable, and generally unable to be captured within the limits of a quantitative risk assessment (Gaillard and Dibben, 2008 and references therein). However, quantitative risk assessments which capture quantifiable aspects of the economy, built environment, and natural environment could offer valuable knowledge for planning and mitigation purposes (e.g., land-use planning, Leone and Lesales 2009).

Marzocchi and Woo (2007, 2009), Woo (2008), and Sandri et al. (2014) illustrate how short-term PVHA-based cost-benefit analyses can be used to perform risk assessments regarding the decision to call an evacuation during an eruption crisis, based on volcano risk metrics (VRM) such as the cost to save a human life. However, because of the complex nature of both hazard and vulnerability, few volcanic risk studies to date have explored both concepts together in a long-term context. One such example is Spence et al. (2004), who performed a quantitative scenario-based assessment of risk by analysing the pyroclastic flow hazard in villages near Vesuvius as well as the vulnerability of exposed buildings and occupants to pyroclastic flows. The results were then combined to identify which buildings were most at risk and to suggest mitigation actions. However, Spence et al. (2004) conclude that the value of the study for planning purposes would be greatly enhanced by incorporating probabilistic methods which evaluate multiple different eruption scenarios and uncertainty. Similarly, Baxter et al. (2008) quantify volcanic risk to populations living near Mt. Vesuvius using both hazard and vulnerability analyses, but base their hazard assessment on the conditional occurrence of the “most-likely” eruption scenario. Long-term PVHA tools such as BET_VH introduce the potential to build probabilistic long-term forecasting abilities into risk assessments by incorporating the absolute probabilities of different potential eruption sequences and their
associated uncertainties in one structured, comprehensive framework for a user-defined time frame (Marzocchi et al. 2010).

Many volcanically active regions such as New Zealand have mandated the development of natural hazard and risk assessments (MCDEM 2002, RMA 1991), creating a demand for advanced, quantitative hazard and risk information at the governance stakeholder level. BET_EF was tested in a simulation of a volcanic unrest crisis at the Auckland Volcanic Field in the large-scale government disaster exercise Exercise Ruaumoko in 2009 (Lindsay et al. 2010). The tool, populated through expert elicitation independently of, and prior to, the exercise, corresponded well to the probabilities estimated during the exercise by the advising scientists. Based on these results, the Auckland Volcanic Field Contingency Plan produced by the Auckland Council and Auckland Civil Defence and Emergency Management Group advocates the use of such probabilistic event tree methods in a future crisis (Auckland Council and CDEM 2013). New Zealand’s leading government science institutes, GNS Science and NIWA (National Institute of Water and Atmospheric Research), are also working on the ongoing development of Regional RiskScape (Schmidt et al. 2011), a quantitative risk assessment and multihazard loss modelling software program, which could integrate long-term probabilistic volcanic hazard and risk assessments into its framework (Kaye 2007). While probabilistic hazard and risk assessments offer many advantages to managing volcanic crises, they also introduce important new challenges. The communication and transfer of information between scientists and stakeholders is a fundamental aspect of volcanic hazard and risk management (e.g., Punongbayan et al. 1996, Aspinall et al. 2002, Leonard et al. 2014). Introducing sophisticated probabilistic datasets and uncertainties into this exchange, and into an environment where they are not traditionally used, could lead to potentially significant communication issues (Sparks et al. 2013, Doyle et al. 2014).

1.3.1 Hazard and risk communication

Although there is a growing body of work on how people perceive volcanic hazard and risk and how people react to volcanic hazard and risk information (e.g., Gaillard 2008, Gaillard and Dibben 2008, Paton et al. 2008, Wachinger et al. 2013), little work has focused on the communication exchange of volcanic hazard and risk information between groups. Many different methods exist for communicating volcanic hazard and risk information, depending on the audience, message, and state of the volcano. The flow of these communications can be unidirectional, bidirectional, or multidirectional (e.g., Adams 2009). In New Zealand, information on volcanic activity is communicated through a variety of flows and channels, including through the GeoNet website (www.geonet.org.nz/volcano), volcanic alert bulletins (VABs), volcanic alert levels (VALs), press conferences, workshops, public lectures, informational posters (Wilson et al. 2014b), social media, academic and non-academic publications, and the media, as well as other traditional communication channels, such as e-mail, fax, pager alerts, and SMS messaging (Potter et al. 2014).
The messages shared about volcanoes via these communication channels also vary in content and format. Due to the inherently spatial nature of volcanic hazards, the primary communication medium for content regarding volcanic hazards is a map.

1.3.1.1 Volcanic hazard maps

Hazard maps have been the dominant volcanic hazard communication tool for the past four decades (Sparks et al. 2013). Hazard maps in New Zealand are used to communicate both long-term (e.g., Volcanic hazards information series, e.g., Neall and Alloway 1993) and short-term volcanic hazards (Leonard et al. 2014). As there are no existing guidelines or recommendations within the volcanological research community for how to build volcanic hazard maps, a vast variety of methodologies and visual representations have been used worldwide (Calder et al. 2012). Although scientific map makers strive for the highest degree of objectivity in designing hazard maps, fundamental choices for map properties are largely driven by subjective preference and judgement. However, geography (e.g., Robinson 1967, Bertin 1983, MacEachren 1995, Monmonier 1996, Kunz and Hurni 2011) and communication (e.g., Broad et al. 2007, Severtson et al. 2012, Severtson and Myers 2013) research literature suggests that aspects of the visual representation properties of a map, such as symbols, colours, and contours, may play an important role in how the user interprets the information on the map. Little work has been done to explore the influence of these properties on the interpretation of hazard in any class of hazard map, including volcanic hazard maps. However, studies by Haynes et al. (2007) and Nave et al. (2010) found that the background content, or base map used in a volcanic hazard map, can have a significant influence on how well local populations living proximal to the volcano understand the hazard information on a map. Their work suggests that features in volcanic hazard map design do in fact play an important role in the way people read and understand hazard information.

Similarly, design factors are likely to have an important influence on maps that communicate PVHA data. As with traditional sources of volcanic hazard data, the outputs of Bayesian event tree and other PVHA tool suites in the current body of literature have primarily been communicated using maps (e.g., Lindsay et al. 2010; Selva et al. 2010, 2012b; Sandri et al. 2014; Blass et al. 2012, 2013a). These maps show, in varying ways, the probability of certain hazardous events occurring (e.g., Figure 1.4). However, many studies across many different disciplines (e.g., Fisher 1991; Stone et al. 1994, 2003; Reyna and Brainerd 1991, 2008; Hoffrage et al. 2000; McComas 2006; Lipkus 2007; Budescu et al. 2009; Keller and Seigrist 2009; Visschers et al. 2009) have found that interpretation of probabilistic information about hazard and risk is generally difficult for people of all backgrounds and is strongly influenced by the communication format in which it is presented. Doyle et al. (2011, 2014) also found this was the case in volcanic hazard and risk communication contexts. They found that hazard forecast time windows (e.g., “in the next…years”) were poorly and inconsistently understood, and that scientist and emergency manager stakeholders had
Chapter 1

Chapter 1

Introduction

The new and different nature of PVHA tools in applied volcanological practice, together with the difficulties which could arise in the communication and interpretation of PVHA information, pose potentially significant challenges to operational applications of BET tools. For example, maps which show BET_EF probabilistic data outputs generated during Exercise Ruaumoko (Fig 1.4, Lindsay et al. 2010) differ very much in style and content to traditional style hazard maps (e.g., Figure 1.2). These BET-derived maps, which show the distribution of probability of vent opening (i.e., where the impending eruption is likely to occur) within a certain number of hours would have been critical graphics to aid discussion, decision-making, and planning had they been used in the exercise (the maps were developed parallel the exercise as part of calibration and testing of BET_EF for the AVF). Accordingly, the visual and verbal communication choices used for the BET_EF maps might have had a notable influence on the decisions made. Tufte (1997) illustrates that the quality of scientific graphics has played a pivotal role in the outcomes of hazard crises in the past. Crisis hazard maps, such as those in Figure 1.4, are developed and disseminated rapidly during a crisis (Leonard et al. 2014). It is important to investigate the role, influence, and importance of communication factors in times of volcanic dormancy in order to inform future map representation choices in times of urgency and pressure. In addition, studies suggest that people are more likely to rely on affective

Figure 1.4 Maps showing BET_EF outputs for spatial distribution of the average probability of vent opening, on selected days of Exercise Ruaumoko, an exercise which simulated a volcanic unrest crisis in the Auckland Volcanic Field (AVF). BET_EF was run alongside the exercise, to test and calibrate the tool for the AVF. The purple ellipses show likely vent locations estimated by the scientists independently of the tool (i.e., without seeing these BET_EF maps). Arrow points to the final activated vent opening. Maps from Lindsay et al. (2010).
heuristics (or intuitive feelings) regarding hazard and risk maps and graphics during crisis situations (Finucane et al. 2000). Therefore, it is similarly important to understand user attitudes and preferences towards such types of information.

1.3.1.2 Volcanic hazard curves

Probabilistic hazard curve graphics have also been used to depict PVHA outcomes to a lesser extent. Hazard curves use a graph to show the relationship between a hazard intensity (e.g., mm of tephra), typically on the x-axis, and its probability of occurrence, typically on the y-axis. Conditional hazard curves (i.e., hazard curves which show probabilities given the event of a specific set of eruption conditions) have been generated for areas of importance, such as airports or city centres, in some past PVHA studies (e.g., Conner et al. 2001, Bonadonna et al. 2005, Magill et al. 2006) (Fig 1.5A). The curves help illustrate the full continuum of hazard at that particular point. Absolute and conditional hazard curves are commonly used in probabilistic seismic hazard analysis (e.g. New Zealand Probabilistic Seismic Hazard Model, Stirling et al. 2002) (Fig 1.5B), and similar robust information sets could be helpful communication tools in PVHA (Tonini et al. submitted/Appendix A). However, hazard curves are rooted in statistical concepts and typically displayed in a fundamentally scientific way, and the effectiveness of such curves to communicate with non-scientific groups has not yet been investigated.

1.4 SIGNIFICANCE, AIMS, AND STRUCTURE OF THE THESIS

The way in which scientists analyse and communicate volcanic hazards is entering a phase of transition (e.g., Leonard et al. 2014, Sparks et al. 2013), and so is the way that this type of information is used and incorporated into volcanic hazard and risk decision-making (e.g., Lindsay et al. 2010, Marzocchi et al. 2012). As these processes become more quantitative, and scientists become more closely involved...
in the management of volcanic crises, it is important and timely to explore how the PVHA approaches central to these changes fit into different volcanic contexts, and different uses in applied practice.

Probabilistic event tree logic has been well-established in the management of scientific uncertainty during short-term volcanic crises and eruption forecasting (e.g., Aspinall et al. 2002, 2003). The relative success of these tools has led to the development of increasingly robust event tree tools for long-term PVHA, such as BET_VH (Marzocchi et al. 2010) and HASSET (Sobradelo et al. 2014). However, many of these event tree tools for long-term PVHA are in their infancy, and the ability of the tools to be A) adopted in different volcanic environments and B) integrated into wider hazard and risk management contexts, has not yet been widely tested or explored. This thesis seeks to address these gaps in our knowledge of Bayesian event tree tools as a methodology, and to answer the question: what is the potential for Bayesian event tree tools to contribute to volcanic hazard analysis and risk assessment in New Zealand, and what is the clearest way to communicate the information provided by such tools with key volcanic hazard and risk stakeholders? This question is explored through the lens of the probabilistic Bayesian event tree tool BET_VH, the Okataina Volcanic Centre (OVC), and tephra fall hazard, and through a specific set of interrelated aims.

1.4.1 Aims

This thesis has four central aims:

1) to assess BET_VH’s suitability as a methodology for performing volcanic hazard analysis at one of New Zealand’s most complex volcanoes, the OVC;

2) to develop and test a technique for integrating BET_VH data into a multi-dimensional quantitative risk assessment which considers a spectrum of both hazard and vulnerability and associated uncertainties;

3) to understand how the representation of BET_VH data on hazard maps and hazard curves affects the way that BET_VH data is interpreted, and develop recommendations for communication of such data; and

4) to gain insight into the potential for PVHA tools, such as BET_VH, to contribute to volcanic hazard and risk management in New Zealand.

These aims are achieved using an interdisciplinary mixed methods approach which combines both physical science and social science methods. A series of three case studies are used to address these aims, and the collective findings of the case studies are then used to develop a well-rounded and multiple-perspective understanding of the potential for Bayesian event tree tools in volcanic hazard analysis, risk assessment, and hazard and risk communication in New Zealand.
1.4.2 Structure and content of the thesis

This thesis is presented in the form of two background chapters which introduce the focus and significance of the work and the specific PVHA tool being explored, three research articles which have been submitted or are in preparation for submission for peer review in international scientific journals, a synthesis chapter which summarises and merges the findings of the research, and a conclusion chapter. Each research paper is preceded by a short preface which contextualises the paper within the broader scope of the thesis.

Chapter 1 presented an overview of PVHA and Bayesian event tree tools, and explored the gap between PVHA as a valuable academic and scientific method and PVHA as a tool for applied practice. The chapter introduced the aims, structure, and content of the thesis and outlined the significance of the work.

Chapter 2 presents a detailed introduction to the Bayesian event tree PVHA tool BET_VH, which serves as the basis for this investigation. The model and design behind this tool are described, as well as previous studies of the tool, and the rationale for using BET_VH as the focus of this research.

Chapter 3 addresses aim 1 through a case study of how the tool BET_VH can be customised to perform a PVHA for the OVC, New Zealand’s most recently active caldera volcano, which has a complex eruption history comprising multiple eruption styles and locations. A tephra hazard analysis is carried out using evaluation of the eruption catalogue, expert elicitation, geospatial analysis, and semi-analytical advection-diffusion tephra model TEPHRA2 as input into BET_VH. Both the advantages and limitations of applying the tool in such settings are rigorously assessed. This chapter is in the form of a paper which has been revised and resubmitted to the Bulletin of Volcanology.

Chapter 4 addresses aim 2, by exploring how BET_VH-derived data can be integrated into quantitative risk analyses, through a case study which investigates the risk of damage to agriculture associated with accumulation of volcanic ash from the OVC. A quantitative risk assessment is developed for the risk of damage to agricultural production from OVC tephra fall, using BET_VH data, agricultural fragility functions, seasonal vulnerability data, and geospatial analysis. The chapter introduces a new, simple approach to using BET_VH for quantitatively assessing long-term risk and addresses the strengths and limitations of this approach. This chapter is in the form of a paper which is in preparation for submission to Natural Hazards.

Chapter 5 addresses aim 3, through a mixed methods social science investigation into communication of BET_VH data using hazard maps, a common and widely-used volcanic hazard communication medium. The results of in-person interviews and an online survey conducted with key New Zealand organisational stakeholders, including scientists, are presented and analysed. The chapter
explores how communication format affects the way stakeholders interpret probabilistic volcanic hazard information, and presents a number of recommendations for future probabilistic volcanic hazard maps. This chapter is in the form of a paper which has been revised and resubmitted to the Journal of Applied Volcanology.

**Chapter 6** synthesises and discusses the findings presented in chapters 3, 4, and 5, by exploring their relationship and overlapping context in order to achieve overarching insight into the potential of probabilistic Bayesian event tree tools for volcanic hazard analysis, risk assessment, and hazard and risk communication in New Zealand.

**Chapter 7** outlines conclusions and suggestions for future work based on the work presented and discussed in the thesis.
CHAPTER 2

Bayesian Event Tree for Volcanic Hazards
(BET_VH): A tool for long-term probabilistic
volcanic hazard analysis
2.1 INTRODUCTION

This chapter describes the long-term probabilistic volcanic hazard analysis (PVHA) tool BET_VH
(Bayesian Event Tree for Volcanic Hazards) which was introduced by Marzocchi et al. (2010). The tool
was developed by a volcanological research team at the Istituto Nazionale di Geofisica e Vulcanologia
(INGV) in Italy and can be downloaded for free from their website at http://bet.bo.ingv.it. This chapter gives
an overview of BET_VH, including the concepts and theorem behind the tool, its structure, and previous
work which has been done using the tool.

2.2 BAYESIAN INFERENCE

Bayesian inference is used to analyse and manage uncertainty in many scientific fields, such as
ecology (e.g., Kuhnert et al. 2010), forensics (e.g., Biedermann and Taroni 2012), climatology (e.g. Chu
and Zhao 2011), economics (e.g., Harvey et al. 2007), and medicine (e.g., Cruz-Ramirez et al. 2007), and
the number and methods of applications across disciplines continues to grow dramatically (Berger 2000).
Bayesian modelling has recently gained momentum in the field of volcanic hazard analysis, where
constraining uncertainty is a fundamental challenge (e.g., Aspinall et al. 2006; Lindsay et al. 2010;
et al. 2010; Sobradelo and Marti 2010; Sobradelo et al. 2014). Although a variety of different statistical
techniques exist for implementing Bayesian analysis both in volcanic hazards and in other fields, all
Bayesian techniques are founded in Bayes’ theorem.

Bayesian inference is helpful for fields associated with great levels of uncertainty because
knowledge about an event is reflected as a probability distribution, rather than a single value. This allows
data to be treated as a degree of belief about the occurrence of an uncertain event, which can then be
updated and changed in light of new observed data. Bayes’ theorem provides an expression for this
process of updating the degree of belief about an uncertain parameter according to new data and
information – a formal method for merging data about current knowledge (prior data) with observed or past
data to calculate a new, updated knowledge based on all available knowledge sources (posterior

Bayes’ theorem asserts that if $P(A)$ denotes the probability of an event $A$, and $P(B|A)$ denotes the
probability of an event $B$ conditional on knowing $A$, then:

$$P(B|A) = \frac{P(A|B)P(B)}{P(A|B)P(B) + P(A|\overline{B})P(\overline{B})}$$

where $\overline{B}$ denotes the complementary event to event $B$ (i.e., not $B$), $P(B)$ denotes the prior belief about $B$, $P(B|A)$ denotes the posterior belief about $B$ once knowing $A$, and $P(A|B)$ denotes the process that generates the event $A$ based upon knowing $B$ (Bayes 1763, Press 2003). In volcanic hazards, for example, if $P(VEI4)$ denotes the probability that an eruption will be of magnitude VEI4, and $P(\text{tephra}|VEI4 \text{ eruption})$ denotes the probability that a certain load of tephra (e.g., 10 kg m$^{-2}$) will be produced conditional on knowing if the eruption will be VEI4, then:

$$P(\text{tephra}|VEI4) = \frac{P(VEI4|\text{tephra}) \cdot P(\text{tephra})}{P(VEI4|\text{tephra}) \cdot P(\text{tephra}) + P(VEI4|\overline{\text{tephra}}) \cdot P(\overline{\text{tephra}})}$$

where $P(\text{tephra})$ is the probability that 10 kg m$^{-2}$ of tephra is not produced, $P(\text{tephra})$ is the prior belief about 10 kg m$^{-2}$ of tephra being produced, $P(\text{tephra}|VEI4)$ is the posterior belief about 10 kg m$^{-2}$ of tephra being produced based upon knowing the probability of occurrence of a VEI4 eruption, and $P(VEI4|\text{tephra})$ is the probability that a VEI4 eruption generates 10 kg m$^{-2}$ of tephra. Here, the prior beliefs about reaching a 10 kg m$^{-2}$ load of tephra from a VEI4 eruption (from current volcanological understanding and knowledge, e.g., modelling), are informed by data about the probability of that particular eruption being VEI4 in size and its likelihood of generating 10 kg m$^{-2}$ of tephra, and of not generating 10 kg m$^{-2}$ of tephra (observed data from the geological record) to deliver an updated, posterior belief about the probability of accumulating 10 kg m$^{-2}$ of tephra. This process of modifying a prior belief about an event based on informative probabilistic data learnt from another related event to create an updated posterior belief provides the foundation of the BET_VH tool (Marzocchi et al. 2010).

### 2.3 BAYESIAN EVENT TREE FOR VOLCANIC HAZARDS (BET_VH)

BET_VH is a PVHA tool built for analysing long-term volcanic hazard (i.e., years to decades). It calculates prior and posterior probability distributions from data that the user inputs about a specific volcano and hazard of interest into an event tree comprised of 8 nodes (Fig 2.1). Prior belief data may be sourced from any quantifiable knowledge about the volcano, such as modelling, theory, expert opinion, or a priori beliefs. The prior distribution is modelled with a Beta distribution (nodes 1-2-3, 6, 7, and 8) or Dirichlet (nodes 4, 5) distribution, where $\Lambda$, termed the equivalent number of data, measures the dispersion around
Chapter 2

**Chapter 2**

BET_VH tool

The data, $\Lambda$, is decided by the user, and reflects the degree of confidence in the prior belief probabilities (aleatory uncertainty). Higher values of $\Lambda$ correspond to higher confidence and weighting to the prior data (e.g., the model data), and lower $\Lambda$ values correspond to lower confidence in the prior data and greater weighting to the past data (Marzocchi et al. 2004, 2010; Selva et al. 2010). Posterior probability distributions are updated with past data where it is available through sources such as geological or historical records, to fit the probability model to a set of data (Marzocchi et al. 2004, 2010; Selva et al. 2010).

BET_VH is built in an event tree style, structured by the major stages of an eruption hazard sequence (Fig 2.1). A posterior probability is calculated for each hierarchical stage in the sequence through unique prior and past data input by the user at each event tree node. Eight different nodes describe theoretical stages of the eruption hazard sequence: node 1-2-3 (eruption), node 4 (eruption vent location), node 5 (eruption size/type), node 6 (hazard phenomena produced), node 7 (hazard reaching area), and node 8 (hazard exceeding an intensity threshold) (Marzocchi et al. 2010). Nodes 4-5 are designed as multivariate nodes which allow the user to define and add information for multiple event selections within that node (e.g., multiple vent locations at node 4 or multiple eruption style outcomes at node 5) for the volcano of interest (Marzocchi et al. 2010). This allows for targeted probabilistic analysis of many different types of eruption hazard scenario possibilities. Nodes 1-2-3, 6, 7 and 8 are bivariate nodes, where only two mutually exclusive options may be selected (e.g., eruption occurs or does not occur at node 1-2-3).

The first node is labelled as “1-2-3” because it represents nodes 1, 2, and 3 of BET_EF (Bayesian Event Tree for Eruption Forecasting, Marzocchi et al. 2004, 2008), a sister tool which can be used to determine the probability of eruption based on real-time monitoring data in the event of volcanic unrest.

BET_VH can be used to calculate either conditional probabilities (i.e., given the event of an eruption; in other words, node 1-2-3 $P = 1$) or absolute probabilities over a user-defined time frame $\tau$ (e.g., 1 year) (Marzocchi et al. 2010). By making selections at each node, the user creates a path which represents a specific eruption scenario. A path’s resulting posterior distribution represents a logical,
quantitative synthesis of all relevant knowledge about that scenario, reflecting theoretical and modelling beliefs, how well observed data conform to beliefs and also the uncertainties associated with the beliefs (Felpeto et al. 2007, Marzocchi et al. 2010). A detailed presentation of the equations, parameters, and calculations behind each node of the tool are presented in Marzocchi et al. (2010).

A Bayesian event tree approach to volcanic hazard analysis offers multiple advantages. Aleatory and epistemic uncertainty, uncertainties associated with the natural stochastic nature of volcanic systems and our limited knowledge of volcanic processes, respectively, preclude our ability to produce precise, unequivocal information about the hazards associated with volcanic activity (Newhall and Hoblitt 2002; Marzocchi et al. 2004, 2008, 2010). The BET_VH technique treats this scientific uncertainty in a structured and rational manner, by considering probability distribution functions for every variable in the path of the event sequence (rather than a single value), as well as confidence in the data used to calculate the distributions (Marzocchi et al. 2010). Average prior probability values represent our best guesses about a distribution (aleatory uncertainty), while \( \lambda \) represents our confidence in the knowledge we used to make these guesses (epistemic uncertainty). The tool's capacity to evaluate many different event scenarios quickly through one complete user interface also increases the tool's applicability to long-term hazard management by supplying a wide array of information relevant to stakeholders with a range of different interests.

Logically synthesizing all stages of the eruption sequence and its hazards into one streamlined analysis that generates one representative output also presents advantages for communicating complex volcanic hazard data to stakeholders. Communicating one probabilistic value that considers all eight stages of the eruption hazard sequence, rather than eight different related values, may optimize communication and comprehension of probabilistic hazard data. This representative output corresponds to a homogenous assimilation of all current knowledge about the volcano (Marzocchi et al. 2008). BET_VH's ability to amalgamate many different sources of knowledge through this process also introduces a quantitative way to bring together a broad collection of diverse studies of particular volcano – from geological field investigations, historical accounts or eruptions, analytical modelling, theory, and expert opinion (Marzocchi et al. 2008, 2010).

2.3.1 Previous BET_VH studies

The framework structure of BET tools allows for the tool to be customized and applied to any volcano with ultimate user control. While a number of studies have been published on short-term forecasting tool BET_EF in terms of potential applications in quantifying volcanic unrest (e.g., Marzocchi et al. 2004, 2008; Sandri et al. 2009; Lindsay et al. 2010; Selva et al. 2012a), fewer studies have been done using the younger long-term forecasting tool BET_VH (released in 2010). Selva et al. (2010)
presented a tutorial BET_VH assessment for tephra fall hazard from the silicic caldera Campi Flegrei in Italy as a companion paper to Marzocchi et al. (2010), which introduced the tool with a fictional volcano “Mt. Donato”. Prior data used in the BET_VH for Campi Flegrei presented in Selva et al. (2010) was based on work presented by Orsi et al. (2009) for probable future eruption styles, and by Selva et al. (2012b) who explored probable future vent opening location. The tutorial illustrates how many different types of uncertainties at large volcanic calderas can be constrained and captured within the BET_VH framework. BET_VH has also been used to perform a multi-hazard PVHA for tephra fall, ballistic ejecta, pyroclastic density currents, and lahars by Sandri et al. (2014) for the El Misti stratovolcano in Peru. They illustrate that, although interactions and cascading effects of the multiple hazard are not captured, BET_VH can be used to comprehensively assess the comparative likelihood of many different hazard scenarios, with diverse potential applications, such as land-use planning and emergency management planning.

In 2008, Exercise Ruaumoko tested New Zealand’s preparedness for responding to a volcanic emergency in the Auckland Volcanic Field (AVF), New Zealand through a detailed simulation of pre-eruptive volcanic stages (Lindsay et al. 2010). During Exercise Ruaumoko, a BET_EF built for the AVF was used to track the eruption independently of a group of experts also assessing the likelihood of eruption and eruption vent location. The average probability of eruption and probability of eruption vent location calculated using BET_EF corresponded well to the likelihoods estimated by the experts (Fig 1.4, Lindsay et al. 2010). The ability of BET_EF to generate similar forecasts as a team of experts in a short processing time suggests that BET_EF could greatly improve decision-making efficiency in an emergency or crisis situation when contacting or assembling experts may not be possible, or as an aid for prioritising and guiding decision-making (Lindsay et al. 2010). Sandri et al. (2012) retrospectively investigated how BET_VH could have contributed to the decision-making in Exercise Ruaumoko by integrating the BET_EF probabilities from Exercise Ruaumoko at node 1-2-3 (probability of eruption) into a BET_VH model to help build a dynamic cost-benefit analysis framework for short-term evacuation decision-making based on the probable economic impact of lives lost from base surge in the Auckland Volcanic Field. The study found that the tool could have helped constrain where and when to make an evacuation call during the short-term exercise, as well as contribute to long-term hazard knowledge for emergency management planning (Fig 2.2).

The work done by Lindsay et al. (2010) and Sandri et al. (2012) suggests that BET tools may have potential as a tool for enhancing management of volcanic risk, and for optimizing long- and short-term decision-making regarding volcanic hazards in New Zealand. However, BET_VH is a tool still in its infancy and further research is necessary to gain a better understanding of how well it can be customized to the range of volcanism present in New Zealand, as well as its potential to support risk assessment in a variety
Chapter 2

2.3.2 Other Bayesian event tree PVHA tools

At the commencement of this work, BET_VH was the only long-term PVHA Bayesian event tree tool available to the wider research community which was free to access and which had an interface for customising the tool to new volcanoes. A similar tool, HASSET has since been introduced by Sobradelo et al. (2014), as a plug-in for the open source geographic information system Quantum GIS (QGIS). While the tools share a similar structure, HASSET combines both short- and long-term PVHA (these are presented in separate tools in the BET suite; i.e., BET_EF for short-term and BET_VH for long-term). HASSET also introduces the potential to evaluate hazards of non-magmatic events (e.g., hydrothermal explosions), while BET_EF is currently limited to hazards related to magmatic volcanic activity only. Case studies of HASSET outside of the Teide-Pico Viejo volcanic complex in the Canary Islands, Spain (Sobradelo and Martí 2010; Sobradelo et al. 2014) have not yet been published.

2.4 MODEL CAVEATS

As with all models, Bayesian event tree approaches have a number of important limitations. BET approaches aim to reduce bias in hazard analyses by considering many different potential eruption pathways and the likelihoods and uncertainties associated with them. However, there remain many epistemic and aleatory uncertainties which are not captured in this approach. Furthermore, the data which are input into BET tools and the confidence which is assigned to these datasets are both characterised by a degree of subjectivity. Accordingly, BET tools are not intended to be solely relied upon for hazard and...
risk decision-making, and the outputs should be considered in conjunction with other sources of knowledge in practice (e.g., other probabilistic models, scenario models, experience, and analogue or past activity).

2.4.1 Uncertainties

A number of uncertainties, both known and unknown, are unable to be critically accounted for in BET tools. The premise of the BET approach is that a volcanic hazard model needs to be inclusive, to consider all possibilities that an eruption pathway could potentially take (Marzocchi et al. 2010). While informed decisions about such possibilities can be made by drawing upon the volcano’s past behaviour, oral histories about the volcano, local and professional experience, and behaviour at analogous volcanoes, the user is required to make a decision about what is possible, and how it will be included in the model. For example, the user must define a limit to the extent of the volcanic area where a future vent could open (Node 4), define the size of the grid which represents individual future vent location areas (Node 4), define the eruption styles which could possibly occur (Node 5), as well as define whether the vent location and type exhibit a dependent relationship (Node 5). Such decisions implicitly exclude other possibilities, and the model’s sensitivity to each of these decisions will influence the data at subsequent nodes, as well as the final results. Such decisions should be explicit and transparent in communication of BET model results.

BET tools provide outputs at the 10th percentile, 50th percentile, 90th percentile, and average of the dataset. While expressing different levels of uncertainty in the dataset is important, and helps to define the limitations of the dataset, extreme values (e.g., 1st percentile or 99th percentile) are not calculated or provided in the most available versions of the BET tools. Similarly, very small events which are not preserved in the geological record, or very large events which did not occur in the chosen inference interval, are also extremes which will be neglected in the analyses and outputs. Excluding these data points will also have an influence on the end results, and the implications of this should be considered when assessing BET inputs and outputs.

2.4.2 Subjectivity

BET approaches are unique in that they allow many sources of knowledge (e.g., models, expert opinion, and the geological record) to be considered together within one framework. However, Bayesian approaches are rooted in the process of updating existing knowledge based on observed data, or evidence, related to that knowledge and confidence in that knowledge. From an epistemological perspective, this means that each person building a Bayesian model will have a different existing knowledge, different confidence in this knowledge, and potentially different sets of evidence with which to update this knowledge. It is essential, therefore, that users building a BET for a specific volcano widely consult others to assess and confirm what knowledge is available, used, and widely trusted. The results of a BET model, as with all models, will be dependent on the quality and types of data put into it and the weighting, or
confidence, attributed to that data.

2.4.3 BET in practice

It is important to note that the outputs of BET approaches should not be relied upon independently in decision-making. Rather, these outputs should be regarded as an additional source of information for use in decision-making, which should be considered in conjunction with the outputs of other models, deterministic analyses, experience, observations, and other important sources of knowledge. Similarly, BET tools are not intended to replace more traditional tools and datasets which aid hazard and risk decision-making. Rather, BET tools are designed to serve as an additional tool to aid decision-making. Accordingly, BET tools should be built with stakeholders in mind, and stakeholders should be consulted on the relevant eruption styles, hazards, forecast windows, and inference intervals assessed.

BET tools are not yet in practice around the world, although their potential applications to practice, such as calling an evacuation, have been proposed (Marzocchi and Woo 2007, 2009; Woo 2008; Marzocchi et al. 2010, 2012; Sandri et al. 2012; Selva et al. 2012). If BET_EF and BET_VH frameworks are consulted upon and collaboratively built in times of dormancy, they could be activated in times of crisis for live-tracking and forecasting (Lindsay et al. 2010). Long-term BET_VH forecasts could eventually be integrated into planning, such as the development of building codes. Probabilistic seismic hazard approaches for estimating peak ground acceleration are well integrated into New Zealand’s building practices (e.g., Stirling et al. 2008; New Zealand Geotechnical Society 2010), and probabilistic volcanic hazard approaches could take on a similar role in the future.
CHAPTER 3

Exploring the influence of vent location and eruption style on tephra fall hazard from the Okataina Volcanic Centre, New Zealand
Chapter 3 addresses aim 1 of the thesis, to assess BET_VH’s capacity for performing volcanic hazard analysis at one of New Zealand’s most complex and recently active volcanoes, the Okataina Volcanic Centre (OVC). Volcanic activity at the OVC over the past 26 ka has been characterised by a range of hazardous eruption styles, including both basaltic Plinian and rhyolitic Plinian eruptions, and also a range of eruption vent locations throughout the ~700 km² caldera. This chapter explores the capabilities of BET_VH to probabilistically capture the knowledge and uncertainty associated with this versatile volcanic environment through building a long-term PVHA for tephra fall hazard using geospatial analysis, expert elicitation, TEPHRA2 modelling, and BET_VH.

The chapter presents the design, justification, methods, results, and interpretation of the PVHA and discusses the implications of the findings for OVC tephra fall hazard and for the challenges and advantages of using BET_VH to model hazard in large and complex volcanic environments. The work presents the first probabilistic tephra hazard analysis for the OVC which takes into account multiple eruption vent locations and compositional eruption styles, and contributes new insight into long-term tephra fall hazard from the OVC. For example, the study reveals that the Haroharo linear vent zone (LVZ) and Tarawera LVZ have an equivalent (<1% difference) likelihood of activating in a future eruption (31.8% compared to 32.5%); that the distribution of tephra fall hazard changes significantly when different possible vent locations are considered; and that the hazard from a basaltic Plinian eruption contributes notably to the overall long-term hazard at the OVC, and should therefore be considered in assessments and analyses in addition to rhyolitic Plinian activity.

This chapter presents a manuscript which was revised and resubmitted to the Bulletin of Volcanology in November 2014.
ABSTRACT

Uncertainties in modelling volcanic hazards are often amplified in geographically large systems and in volcanoes which have a diverse eruption history that comprises variable eruption compositions and styles from different vent locations. The large ~ 700 km² Okataina Volcanic Centre (OVC) is a large silicic caldera complex in a geodynamic region of New Zealand which has displayed a range of eruption styles and compositions over its current phase of activity (26 ka – present), including one basaltic maar-forming eruption, one basaltic Plinian eruption, and nine rhyolitic Plinian eruptions. All three of these eruption styles have occurred within the past 3.5 ky, and any of these styles could occur in the event of a future eruption. The location of a future eruption is also unknown. Future vents could potentially open in one of three different possible areas of the OVC: the Tarawera linear vent zone (LVZ) (5 eruptions over the past 26 ky), the Haroharo LVZ (5 eruptions over the past 26 ky), or outside of these LVZs (1 eruption over the past 26 ky).

A future rhyolitic or basaltic Plinian eruption from the OVC is likely to generate widespread tephra fall in loads that will cause significant disruption and socio-economic impacts throughout the surrounding region. Past OVC tephra studies have focused on evaluating hazard from a rhyolitic Plinian eruption at select vent locations in the OVC’s Tarawera LVZ. Here, we expand upon these past studies by evaluating tephra hazard for all possible OVC eruption vent areas and for both rhyolitic and basaltic Plinian eruption styles, and exploring how these parameters influence tephra hazard forecasts. Probabilistic volcanic hazard model BET_VH and advection-diffusion tephra hazard model TEPHRA2 were used to assess the hazard of accumulating ≥ 10 kg m⁻² of tephra from both basaltic Plinian and rhyolitic Plinian eruption styles,
Chapter 3  BET_VH caldera case study

occurring from within the Tarawera LVZ, the Haroharo LVZ, and other potential vent areas within the caldera. We present the results of these analyses as a first-order tephra hazard assessment for the entire OVC.

Our results highlight the importance of considering all the potential vent locations of a volcanic system, in order to capture the full eruption catalogue in analyses (e.g., 11 eruptions over 26 ky for the OVC, versus only 5 eruptions over 26 ky for the Tarawera LVZ), as well as the full potential distribution of tephra hazard. Although the Tarawera LVZ has been prominently discussed in studies of OVC hazard because of its recent activity (1886 and ~1315 AD), we find that, in the event of a future eruption, the likelihood of a vent opening within the Haroharo LVZ (last eruption 5.6 ka) is equivalent (< 1% difference) to that for the Tarawera LVZ (31.8% compared to 32.5%). We also find that an eruption from within the Haroharo LVZ presents a relatively higher hazard to several localities, such as the town of Kawerau, where the average absolute probability of accumulating ≥ 10 kg m⁻² of tephra (P = 5.0E-05) is 1.3 times greater than for an eruption from within the Tarawera LVZ (P = 3.8E-05). While the absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra in the next one year from a basaltic Plinian eruption are on average 7.2 times lower than for a rhyolitic Plinian eruption throughout the surrounding region, our results suggest that the hazard posed by a basaltic Plinian eruption does contribute to the overall OVC tephra hazard, raising absolute probabilities for the entire OVC by an order of 0.14, which may have implications when considering sensitive decision-making thresholds.

Keywords

PVHA; Okataina Volcanic Centre; BET_VH; TEPHRA2; volcanic hazard

3.1 INTRODUCTION

Volcanoes are complex, non-linear systems with many degrees of freedom. Uncertainties that stem from our limited knowledge of these complicated systems (epistemic uncertainties) and their natural intrinsic variability (aleatory uncertainties) present many challenges to forecasting volcanic eruptions and their associated hazards. Modern probabilistic volcanic hazard analysis (PVHA) methodologies address these challenges by capturing and evaluating uncertainties via probability distributions, introducing a way to generate a suite of comparable and auditable quantitative data about the possible outcomes of many different events. Where traditional deterministic methods typically analyse only the best-known or worst-case scenario, PVHA methods can be used to generate information about an array of many other scenarios in addition to these events, enabling robust evaluation of potential hazards, magnitudes, and their likelihood of occurrence for use in development of hazard management strategies.

Uncertainties in modelling volcanic behaviour can be amplified in geographically large systems
such as monogenetic volcanic fields and calderas, where unknowns in eruption style and vent location must be considered over a large area (e.g., Campi Flegrei caldera, Orsi et al. 2009; Selva et al. 2012b; Auckland Volcanic Field, Bebbington and Cronin 2011; Lindsay et al. 2010; Sandri et al. 2012). Both eruption style and vent location can have a significant effect on the generation of hazardous volcanic phenomena (Selva et al. 2010, Sandri et al. 2014) and it is therefore important to consider the influence of these uncertain parameters in such environments, particularly in the context of hazard management and decision-making (Sandri et al. 2012).

The Okataina Volcanic Centre (OVC) is the most recently active caldera in the world’s most productive silicic volcanic region, the Taupo Volcanic Zone (TVZ) in New Zealand (Danišík et al. 2012) (Fig 3.1, 3.2). Eruptions over the current phase of activity at the OVC (26 ka – present) have been characterized by a range of eruption styles, including both basaltic Plinian and rhyolitic Plinian eruptions within the last 1 ky (Nairn 2002, Cole et al. 2010) (Table 3.1). The eruptions have occurred from as many as 47 discrete vents clustered in three different areas of the ~700 km² complex: the Tarawera linear vent zone (LVZ), the Haroharo LVZ, and areas outside these LVZs (Fig 3.2). Tephra was a major product of all eruptions, and a future tephra fall event from the OVC could have significant local, regional, and national-scale impacts on New Zealand’s social and economic environment. The civil defence and emergency

**Figure 3.1** Map of the Taupo Volcanic Zone (TVZ). The Okataina Volcanic Centre (OVC) sits in a dynamic area of the TVZ characterized by changes in the extensional stress regime and transitions in volcanic behavior, from rhyolite in the southwest to andesite in the northeast. Heavy dashed line outlines the modern active TVZ (45 ka – present) (Wilson et al. 1995). Figure modified from Spinks et al. (2005). Inset: Tectonic setting of the modern TVZ in the North Island of New Zealand. Box indicates enlarged area.
management group operating in the region surrounding the OVC rank local volcanic eruption as a “high priority hazard” and source of “extreme risk,” justifying a need for high quality volcanic hazard analyses which can feed into quantitative risk assessments (Bay of Plenty CDEM Group 2012).

TEPHRA2 (Bonadonna et al. 2005) is a robust semi-analytical model that forecasts tephra fallout based on wind advection, atmospheric diffusion, and eruption and particle parameters. Bonadonna et al. (2005) found that TEPHRA2 could generate reliable tephra hazard data for a range of OVC rhyolitic Plinian eruption scenarios when compared with observations from the geological record. While their study provides valuable information about the likely loads of tephra that may accumulate in the event of a multiple-phase rhyolitic Plinian eruption scenario from three possible vents in the Tarawera linear vent zone (LVZ) region of the OVC, applicability of the hazard information is limited to this eruption style and these vent locations. The analysis does not consider other potential vent location areas in the OVC, or other known hazardous styles of eruption from the OVC, such as the most recent basaltic Plinian eruption in 1886 AD (Walker et al. 1984).

Figure 3.2 Map of the OVC showing topographic caldera structures, known faults, and past vents and eruption deposits from 26 ka – present. Vents and fissures at the Haroharo and Tarawera LVZs trend NE-SW, and are inferred to be an expression of underlying faults. Map data from Leonard et al. (2010)
BET_VH (Bayesian Event Tree for Volcanic Hazards) (Marzocchi et al. 2010) is a PVHA tool that is designed to supplement data derived from individual hazard models like TEPHRA2 with additional knowledge about past volcanic behaviour, as well as additional forecasted or modelled information, such as the likelihood of a future eruption, the likelihood of different vent locations opening in a future eruption, possible eruption styles, and the hazards that may be generated, in order to create a more comprehensive hazard dataset. Selva et al. (2010) explored how BET_VH can be used to integrate different eruption sizes and locations into tephra hazard analyses for the Campi Flegrei caldera (CFc) in Italy. They found that at these large and complex caldera systems, hazard can be significantly underestimated in analyses that consider only one eruption size or vent location. The OVC is similar to the CFc in that a large source of uncertainty lies in 1) the location of a future eruption vent, and 2) the style of a future eruption (Nairn 2002, Orsi et al. 2009, Selva et al. 2010, Selva et al. 2012b).

This study investigates how BET_VH can be used to expand upon and enhance data from widely-applied hazard models, such as TEPHRA2, in order to create a more customized and more comprehensive assessment of tephra hazard from a large and complex volcanic system in New Zealand. We expand upon

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<th>LVZ</th>
<th>Eruption</th>
<th>Age (ka)</th>
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<th>Pyroclastics volume (km³)</th>
<th>Estimated Column Height (km)</th>
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<td>B</td>
<td>0.7</td>
<td>2.0</td>
<td>10 - 34</td>
<td>Nairn (2002), Walker et al. (1984), Sable et al. (2006, 2007), Carey and Sparks (1986)</td>
</tr>
<tr>
<td></td>
<td>Rotokawau</td>
<td>3.4</td>
<td>B</td>
<td>0.3</td>
<td>0.7</td>
<td>3.5 - 10</td>
<td>Kobayashi et al. (2005), Nairn (2002), Smith et al. (2006)</td>
</tr>
<tr>
<td>H</td>
<td>Mamaku</td>
<td>8.1</td>
<td>R</td>
<td>13</td>
<td>1.2</td>
<td>Plinian</td>
<td>Nairn (2002), Smith et al. (2006)</td>
</tr>
<tr>
<td>H</td>
<td>Rotoma</td>
<td>9.5</td>
<td>R</td>
<td>8</td>
<td>5.2</td>
<td>Plinian</td>
<td>Nairn (2002), Smith et al. (2006)</td>
</tr>
<tr>
<td>H</td>
<td>Rotorua</td>
<td>15.4</td>
<td>R</td>
<td>1</td>
<td>2.7</td>
<td>14-20</td>
<td>Darragh et al. (2006), Shane et al. (2007, 2008)</td>
</tr>
<tr>
<td>T</td>
<td>Rerewhakaaitu</td>
<td>17.6</td>
<td>R₆</td>
<td>5.7</td>
<td>7.6</td>
<td>15 - 25</td>
<td>Darragh et al. (2006), Shane et al. (2007, 2008)</td>
</tr>
<tr>
<td>T</td>
<td>Okareka</td>
<td>21.8</td>
<td>R₆</td>
<td>5.1</td>
<td>11.9</td>
<td>19.0</td>
<td>Nairn (2002), Darragh et al. (2006), Shane et al. (2008)</td>
</tr>
<tr>
<td>H</td>
<td>Te Rere</td>
<td>25.3</td>
<td>R</td>
<td>13</td>
<td>5.0</td>
<td>Plinian</td>
<td>Nairn (1992), Nairn (2002)</td>
</tr>
</tbody>
</table>

Ages from Lowe et al. (2008), except for Tarawera (Walker, 1984) and Rotokawau (Nairn, 2002). LVZ (linear vent zone): T = Tarawera LVZ, H = Haroharo LVZ, - = Not at one of the linear vent zones. Eruption style: B = basalt, R=rhyolitic, R₆=rhyolitic eruption with basalt components.
past studies, which are limited to rhyolitic events from a single area of the OVC (e.g., Bonadonna et al. 2005 and Jenkins et al. 2008), by evaluating tephra hazard for all likely OVC eruption vent areas and the two most explosive OVC eruption styles, A) a rhyolitic Plinian eruption (e.g., Kaharoa-style) or B) a basaltic Plinian eruption (e.g., 1886 Tarawera-style), in order to understand how these parameters influence tephra hazard forecasts, and to generate a representative first-order tephra hazard assessment for the entire OVC. We acknowledge that a maar-forming basaltic eruption is also a possible future eruption style from the OVC based on its 26 ka eruption history, but we choose to focus our analysis of tephra hazard (BET_VH Node 6, 7 and 8) on Plinian eruptions, as Plinian eruptions dominate the eruption record (10 of the 11 eruptions over the past 26 ka), and will have a much more widespread and disruptive impact than small localized explosions in the rural OVC area.

We perform an extensive review of past studies and historical records of OVC activity, carry out TEPHRA2 modelling of scenarios describing both a basaltic Plinian OVC eruption and a rhyolitic Plinian OVC eruption based on the approach of Bonadonna et al. (2005), and conduct an expert elicitation session to define any additional a priori knowledge about future eruption locations and styles at the OVC. We then use an approach based on that of Selva et al. (2010) to integrate all the data within the BET_VH framework to explore how uncertainties in future vent location and eruption style (i.e., rhyolitic or basaltic Plinian eruption) may influence forecasted OVC tephra fall and to consider what it means for volcanic hazard analysis in the region. Variation in past eruption composition and the presence of past vent location trends and anomalies in the OVC make it an ideal volcanic environment for evaluating the capabilities of BET_VH to be adapted to a unique and complex volcanic environment. The aim of this study is to synthesize new and existing information about OVC tephra fall hazard using BET_VH in order to understand the influence of eruption style and vent location on the distribution of tephra hazard so as to inform future volcanic hazard, impact, and risk assessments in the region.

3.2 GEOLOGIC SETTING

The OVC is located in a dynamic rifting zone of the TVZ which is characterized by changes in the extensional stress regime, transition in volcanic behaviour and composition (from andesitic stratovolcanoes in the NE to rhyolitic calderas in the SW), active faulting, underlying melt, and an exceptionally high heat flux (Fig 3.1) (DeMets et al. 1994, Bibby et al. 1995, Rowland and Sibson 2001, Acocella et al. 2003, Spinks et al. 2005, Heise et al. 2010, Seebeck et al. 2010). The volcanic history of the OVC includes at least three large caldera-forming rhyolitic eruptions at ~ 500 ka, ~ 325 ka, and ~ 45 ka, with episodes of explosive, dome-building rhyolitic eruptions in the intracaldera phases between these collapse events. Early deposits and structures are heavily overprinted by the youngest eruption collapse structures (~45 ka, Danišík et al. 2012), modification features (~45 ka – 31 ka, Jurado-Chicay and Walker 2000), and infill from

3.2.1 Caldera collapse and modification ~45 ka – 31 ka

The Rotoiti eruption at ~45 ka comprised a basaltic sub-Plinian eruption (~0.5 km³) followed by the violent Plinian eruption of ~100 km³ of rhyolitic magma and caldera collapse (Shane et al. 2005). A series of 12 rhyolitic Plinian eruptions followed the Rotoiti event, depositing the Mangaone Subgroup (MaSg) pyroclastic units and modifying existing collapse features (Jurado-Chichay and Walker 2000). The MaSg subgroup eruptions varied greatly in erupted mass, by up to a factor of 60 (Jurado-Chichay and Walker 2001), and represent a dynamic period of caldera modification (Nairn 2002, Smith et al. 2002). The 33 ka Kawerau Ignimbrite (unit I) is the largest of the MaSg eruptions, and was likely accompanied by further structural caldera collapse (Spinks et al. 2005, Cole et al., 2010). The MaSg caldera modification phase lasted ~ 10 – 12 ka until 31 ka (Jurado-Chichay and Walker 2000, 2001), when a period of relative quiescence commenced before post-26 ka caldera infilling and dome-building activity (Jurado-Chichay and Walker 2000, 2001; Nairn 2002; Cole et al. 2010).

3.2.2 Intracaldera activity 26 ka – present

Volcanic activity from 26 ka – present is characterized by a series of nine rhyolitic Plinian eruptions focused along two LVZs, the Haroharo LVZ (5 eruptions) and the Tarawera LVZ (4 eruptions) (Shane et al. 2008a, Cole et al. 2010) (Fig 3.2) (Table 3.1). The clustering of vents along two parallel NE-SW trending lineaments is inferred to be an expression of underlying faults (Nairn 2002, Cole et al. 2010, Seebeck et al. 2010). The eruptions, which ranged in volume from 3.6 – 13 km³ of magma typically included three stages: 1) initial phreatomagmatic, hydrothermal, or basaltic explosions, 2) multiple phase rhyolitic Plinian explosions, and 3) voluminous rhyolitic dome extrusion. Several (~ 2 – 8) vents within one LVZ were activated over different timescales during each rhyolitic eruption, which are thought to have typically lasted for a period of about several years (Nairn 2002). All eruption episodes reached Plinian eruption column heights (~ 10 – 35 km high) during the second, paroxysmal stage of eruption, depositing widespread tephra fall. The most recent rhyolitic eruption (Kaharoa) occurred just ~700 years ago (Leonard et al. 2010).

The OVC has also experienced two basaltic eruptions in the 26 ka – present intracaldera phase. The 3.7 ka Rotokawau eruption was a small E-trending basaltic fissure eruption that generated localized tephra fall and formed an alignment of four shallow maars near the northwestern margin of the OVC (Fig 3.2) (Beanland and Houghton 1991). The much larger 1886 AD Tarawera eruption was New Zealand’s largest
and most destructive historical eruption (Walker et al. 1984, Keam 1988). The 5.5-hour basaltic Plinian eruption opened multiple vents across 17 km of the Tarawera LVZ (Fig 3.2). Phreatic and hydrothermal explosions at vents located in lakes and wet sediments in the southwest generated devastating mudflows and flooding (Nairn 2002). Phreatomagmatic and magmatic eruptions at vents in the northeast generated significant tephra fall, with four vents spread over ~ 2 km contributing to a Plinian column, which reached an estimated height of ~ 34 km (Carey and Sparks 1986, Sable et al. 2006). Disruptive tephra fall impacted areas throughout the region, and lahars and flooding destroyed towns and encampments proximal to the volcano (Keam 1988).

### 3.2.3 Potential future activity and hazards

The current phase of intracaldera activity is inferred to reflect a new phase of the OVC magma system, characterized by shallower storage depths and smaller eruption volumes, and it is likely that a future eruption at the OVC will have characteristics of the known styles and hazards of the past 26 ka (Shane et al. 2005). However, outside of a state of unrest, it is unclear where the next eruption will occur, or what the style and composition the eruption will be (Marzocchi and Bebbington 2012). Unknown future vent location introduces significant spatial uncertainty for hazard modelling. A future eruption could occur from within the Tarawera LVZ, the Haroharo LVZ, or at any other location within the caldera, as demonstrated by the small 3.4 ka Rotokawau eruption. It is also unknown whether vents within the LVZ will reactivate, or whether new vents will open in a future eruption. Eruption composition and style also introduces a source of uncertainty in modelling hazards. The recent 1886 AD Tarawera basaltic Plinian eruption indicates that the basalt intrusion process in the OVC is capable of generating large basaltic eruptions with significant hazards. Properties of basaltic and rhyolitic magmas generate differences in eruption behaviour and hazard, and are important to consider in tephra fall modelling (Sable et al. 2006, Bonadonna and Costa 2013).

Lava dome formation and dome collapse, pyroclastic density currents (PDCs), debris avalanches, landslides, lahars, hydrothermal explosions, break-out floods and voluminous viscous lava flows are all hazards which are likely to occur in addition to tephra fall in the event of a future OVC rhyolitic eruption (Nairn 2002). The duration, extent, and magnitude of these types of hazards are unknown and dependent on a number of complicating factors, such as the volume and rate of dome building activity, and number of discrete Plinian phases. In the case of an OVC basaltic Plinian eruption, hydrothermal explosions, lahars, and break-out floods are likely to occur, other hazards such as lava dome-building and collapse are not.

Both a basaltic Plinian eruption and a rhyolitic Plinian eruption are, however, expected to generate substantial and widespread tephra fall. While tephra is typically less damaging than life-threatening...
hazards such as PDCs, it is capable of significant social and economic disruption, and long-term consequences when accumulations reach or exceed thresholds for various critical industries (Wilson et al. 2014a). The less destructive nature of tephra fall, however, opens the doors for potentially exposed communities to take a number informed mitigative actions to reduce social and economic risk, making it hazard that can readily benefit from hazard assessments and forecasts. Hazard forecasts for the initial Plinian phase of any eruption, in particular, would be critical in the context of risk-based decision-making and emergency response. For these reasons, we chose to focus on the tephra hazard from the initial phase of a Plinian eruption for the purposes of this study.

3.3 TEPHRA2 MODELLING

As a volcanic plume reaches the level of neutral buoyancy, it starts to spread horizontally, forming an umbrella cloud from which particles eventually fall out and deposit on the ground depending on their terminal velocity and wind transport (Sparks et al. 1997). The advection-diffusion-sedimentation model TEPHRA2 describes this physical process based on the analytical solution of the mass conservation equation in order to forecast two-dimensional tephra fallout (Bonadonna et al. 2005, Connor and Connor 2006). A Monte Carlo approach can be used to stochastically sample a defined range of values for atmospheric, particle, and eruption parameters for each run of the model. TEPHRA2 allows for multiple runs to be performed in parallel in order to execute a rapid calculation of the probable mass of tephra accumulation (kg m\(^{-2}\)) on a set of x, y points. Various approaches for the assessment of tephra hazard exist, including the analysis of: 1) one eruption scenario (OES), where a single plume height \(H\) and wind population are used to compute a scenario-based map; 2) eruption range scenario (ERS), in which a distribution of \(H\) (\(H_{\text{min}} - H_{\text{max}}\)) and a range of wind populations are stochastically sampled to compute a probabilistic map; and 3) multiple eruption scenario (MES), where cumulative ERS probability maps are computed to model long-lasting activity (Bonadonna 2006).

3.3.1 Modelling initial Plinian phase tephra hazard

Bonadonna et al. (2005) used TEPHRA2 to model the tephra fall from the c. 1315 AD Kaharoa eruption, the most recent and well-preserved rhyolitic Plinian eruption at the OVC, using both MES and ERS approaches. The Kaharoa eruption was characteristic of OVC intracaldera phase rhyolitic eruptions, with a Plinian stage, comprising 13 discrete multiple Plinian phases, followed by a stage of thick lava dome extrusion from vents within the Tarawera LVZ (Nairn et al. 2001, Leonard et al. 2002, Nairn et al. 2004). The entire eruption sequence is estimated to have lasted \(\sim 4 - 5\) years, with the Plinian stage lasting over a period of about nine days to two weeks (Sahetapy-Engel et al. 2014). The MES, which modelled a set of 10 discrete ERS episodes together, represented the entire Plinian stage of the Kaharoa-style eruption more closely than the single ERS. The MES strategy showed significantly higher tephra loads and higher
probabilities of reaching hazard thresholds because it described the accumulation associated with 10 Plinian phases. A separate MES model of OVC tephra hazard by Jenkins et al. (2008) also found that a MES approach leads to higher hazard across a broader area. Here, we acknowledge that a hazard assessment based on the ERS strategy only analyses the impact of a single Plinian phase, and that in order to evaluate the long-term impacts of the entire Plinian stage, a MES strategy would have to be used.

However, the number of Plinian phases, time gaps between Plinian phases, and duration of Plinian stages in OVC rhyolitic eruptions has been highly variable throughout the volcano’s history, which presents challenges for modelling the tephra hazard from a future rhyolitic eruption. For example, it is estimated that approximately four Plinian phases occurred over a matter of hours to days during the Waiohau rhyolitic eruption (Speed and Shane 2002), yet up to 15 Plinian phases are thought to have occurred over a period weeks to months during the Rerewhakaaitu eruption (Darragh et al. 2006) (Table 3.1). Fluctuating wind conditions over an unknown timeframe also introduce tephra hazard modelling complications. For example, early Plinian phases of the Kaharoa eruption produced tephra fall units dispersed solely to the southeast of the vent, while later Plinian phases are dispersed predominately to the north and northwest of the vent (Sahetapy-Engel et al. 2014). Based on these limiting uncertainties in future rhyolitic eruption behaviour, we restrict our study to analysis of the initial tephra hazard associated with the first individual Plinian phase of a future OVC rhyolitic eruption, and focus on exploring the influence that eruption location and composition may exert on the hazard distribution. Knowledge regarding the likely magnitude and distribution of hazard from the very first phase of explosive eruption, and the communities that are likely to be impacted at the initiation of an event, is important information for risk-based decision-making and emergency response. Tephra hazard generated by subsequent explosive phases of a rhyolitic eruption and prolonged Plinian stage activity would be dependent on the overall length of the Plinian stage and number of discrete Plinian phases. A basaltic Plinian eruption is unlikely to experience more than one Plinian explosive phase, therefore an ERS is appropriate for modelling this OVC eruption style.

This study is also limited to single vent eruptions due to uncertainties in future OVC behaviour. While more than one point-source vent is often active over the entire duration of an explosive OVC eruption stage, the number of vents, timing of vent openings, and distance between vents has been highly variable for each OVC eruption. For example, approximately two to three vents (≤ 3.5 km apart) contributed to the Plinian stage of the Kaharoa eruption (Sahetapy-Engel et al. 2014). However, as with many OVC eruptions, it is unknown whether these vents were active simultaneously or sequentially over the duration of Plinian activity. For example, the initial Plinian phases of the Kaharoa eruption are thought to have occurred from a single vent source. However, later Plinian phases are believed to have occurred from a different vent location within the Tarawera LVZ, where it is unclear if one or more vents were active at the same time (Sahetapy-Engel et al. 2014). Bonadonna et al. (2005) found that the number of vents (from one to three)
exerted negligible influence on medial and distal tephra fallout distribution for the Kaharoa eruption scenario. Indeed, the influence of multiple eruption vents in an explosive phase is likely to be restricted to proximal deposits within the OVC. Approximately four vents contributed to the Plinian phase of the 1886 AD Tarawera eruption, however, these vents were very closely spaced (≤ 2 km) and analysis of proximal deposits suggests that all four vents did not erupt in unison, but rather started and stopped at different times during the approximately 5 hour eruption (Sable et al. 2006). Accordingly, rather than choosing a random number of point-source vent locations for modelling multiple vent rhyolitic and basaltic OVC scenarios, we choose to use a single vent in TEPHRA2 ERS analyses and focus here, instead, on using BET_VH to explore how the area within the 700 km² OVC where the vent (or vents) opens (e.g., Tarawera LVZ, Haroharo LVZ) influences tephra hazard distribution and medial to distal areas impacted.

TEPHRA2 was accessed and run through TephraProb (Biass and Bonadonna 2013b), a MATLAB toolbox interface for TEPHRA2. Two series of TEPHRA2 ERS analyses were completed, based on the two most common eruption styles that have generated widespread tephra fall over the past 26 ka of activity at the OVC: 1) basaltic Plinian eruptions (VEI 4., e.g., Tarawera eruption, 1886 AD), and 2) rhyolitic Plinian eruptions (VEI 4, e.g., Kaharoa eruption, c. 1315 AD) (Table 3.2). Small basaltic eruptions (VEI 0-2) such as the ~ 3 ka Rotokawau eruption (Beanland 1981, Beanland and Houghton 1991) were not analysed here, as they produced only minor amounts (≤ 0.01 - 0.3 km³ DRE) of tephra (Beanland and Houghton 1991, Shane et al. 2008b) and the impacts of a future eruption of this style are unlikely to pose significant hazards to nearby communities and industries. It is assumed here that small basaltic explosions preceding rhyolitic activity do not significantly contribute to distal tephra fall hazard from these events. Following Bonadonna et al. (2005) and Biass and Bonadonna (2013b), sets of 1,000 runs were performed for both the rhyolitic and basaltic Plinian ERSs. Values for eruption, particle, atmospheric and fallout parameters for each ERS are defined in Table 3.2.

3.3.2 Input parameters for a rhyolitic Plinian eruption at OVC

Model parameters for the rhyolitic Plinian ERS (Table 3.2) were taken from the Bonadonna et al. (2005) TEPHRA2 study, which tested and calibrated model parameters for the Kaharoa eruption. Bonadonna et al (2005) set the minimum plume height value at the boundary between sub-Plinian and Plinian eruptions from Sparks et al. (1992) (10 km), and used a maximum plume height calculated from field data (Sahetapy-Engel 2002). These ranges for plume height and duration were used to calculate a lognormal distribution of total erupted mass \( M_0 \) using the empirical power law equation of Carey and Sigurdsson (1987). No complete grain size distribution is available for the c. 1315 Kaharoa eruption. Bonadonna et al. (2005) therefore used the result of a probabilistic analysis of the grain size distribution for three other rhyolitic Plinian eruptions from the TVZ. A series of sensitivity tests were carried out to determine best fit values for
Table 3.2 Parameters used in TEPHRA2 model simulations. Rhyolitic ERS parameters are from Bonadonna et al. (2005). Basaltic ERS parameters are from published field data and analogous eruption deposits from Cotopaxi volcano in Mexico and Mt. Etna in Italy (see text). Grain sizes are in phi

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Basaltic ERS</th>
<th>Rhyolitic ERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference OVC eruption</td>
<td>1886 AD Tarawera</td>
<td>c. 1315 Kaharoa</td>
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<td>min, max Md</td>
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<tr>
<td>min, max ϕ</td>
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<td>-7, 10</td>
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<tr>
<td>Lithic density (kg m⁻³)</td>
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<td>2350</td>
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<tr>
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<tr>
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<td>Fall Time Threshold, FTT (s)</td>
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<td>288</td>
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<td>Wind data (years)</td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>

the empirical parameters fall time threshold $FTT$ (s) and diffusion coefficient $K$ (m² s⁻¹) (for more detail on the parameters used, the reader is referred to Bonadonna et al. 2005).

3.3.3 Input parameters for a basaltic Plinian eruption at OVC

We define the basaltic Plinian ERS as an eruption of solely basaltic composition of VEI 4 (Newhall and Self 1982). Most basaltic eruptions worldwide display Hawaiian to Strombolian activity ranging from gentle effusive activity (VEI 0 – 1) to fire fountaining and weak explosions (VEI 1 – 2) (Newhall and Self 1982, Sigurdsson et al. 1999). However, the 1886 AD Tarawera basaltic eruption from the OVC was a rare, very explosive VEI 4 Plinian eruption. Few other volcanoes display analogous sub-Plinian (VEI 3) to Plinian (VEI 4) basaltic activity, but those that do, such as Mt. Etna in Italy (Walker et al. 1984; Coltelli et al. 1998, 2000), and Masaya Caldera in Nicaragua (Pérez and Freundt 2006, Costantini et al. 2009, Pérez et al. 2009), have experienced tens of these large explosive basaltic events. The frequency of large basaltic events at these volcanoes and the consistency of basalt triggering in the OVC suggest it is possible the OVC could experience another event similar to the 1886 AD Tarawera eruption, and that it is important to consider the potential hazards of a future basaltic Plinian eruption (Nairn 2002).
Minimum and maximum values for column height $H$, duration of the sustained Plinian phase $\Gamma$, and total mass erupted $M_0$ (kg) (Table 3.2), were determined based on empirical data and field studies from the 1886 AD Tarawera eruption. Some atmospheric parameters were based on available data from a calibrated TEPHRA2 analysis of the 22 July 1998 basaltic sub-Plinian eruption of Mt. Etna (Bonadonna and Costa 2013). While this event was smaller and less explosive (VEI 3) than the 1886 AD Tarawera event, the eruption parameters are well documented in a comprehensive dataset of imagery, field measurements and models (Aloisi et al. 2002), and particle dispersion parameters were comprehensively assessed by Bonadonna and Costa (2013) in a series of empirical, analytical, and numerical models, including TEPHRA2. It is assumed here that the fall time threshold $FTT$ and diffusion coefficient $K$ values for a VEI 4 basaltic eruption would be similar to a VEI 3 basaltic eruption, and that the TEPHRA2 inversion values calculated with the robust Etna dataset by Bonadonna and Costa (2013) would be more reliable than estimates made using the limited dataset of the 1886 AD Tarawera eruption.

3.3.3.1 Column height and duration

Column height distribution is based on the approximate minimum column heights observed from the 1886 AD Tarawera eruption (Walker et al. 1984) and a maximum estimated column height of 34 km for the 1886 AD Tarawera eruption calculated by Carey and Sparks (1986) based on analysis of maximum clast size dispersal. Minimum and maximum plume heights are therefore set to 10 and 34 km, respectively (Table 3.2). Duration of the paroxysmal phase of the 1886 AD Tarawera eruption was approximately 5.5 hours (Walker et al. 1984, Keam 1988, Sable et al. 2006), and a future VEI 4 event is estimated to last between 2 and 6 hours.

3.3.3.2 Erupted mass and column distribution

Values for total mass erupted $M_0$ (kg) were estimated from the minimum and maximum column heights and durations, and the density of the tephra fall deposit using the empirical power law equation of Carey and Sigurdsson (1987). Using an average deposit density of 1000 kg m$^{-3}$ for the 1886 AD Tarawera eruption calculated by Sable et al. (2009), we get an $M_0$ of 3.63+09E kg to 3.76E+12 kg. TEPHRA2 stochastically samples a logarithmic distribution of height to reflect a higher frequency of lower plumes, and a uniform distribution for eruption duration, resulting in a lognormal distribution of erupted mass in calculations (Bonadonna et al. 2005). A uniform vertical distribution of mass in the eruption column is applied with 100 integration steps in the column $i$ based on reliability of these values in Bonadonna et al. (2005).

3.3.3.3 Particle parameters

A complete grain size distribution is not available for the 1886 AD Tarawera eruption, therefore median diameter $Md_{\phi}$ and graphic standard deviation $\sigma_{\phi}$ values are taken from analyses of well-studied analogous
eruption deposits of the 1998 eruption of Mt. Etna and basaltic-andesitic Plinian eruption deposits layer 3 (c. 0.820 ka) and 5 (c. 1.18 ka) from Cotopaxi volcano in Ecuador (Barberi et al. 1995, Tsunematsu and Bonadonna 2014). Pumice density is set to 1000 kg m\(^{-3}\) based on the average density of juvenile clasts measured by Sable et al. (2006). A lithic density is set to 2700 kg m\(^{-3}\) based on particle density analyses from Sable et al. (2009). FTT value of 278 s and K value of 0.5 m\(^2\) s\(^{-1}\) are taken from a calibrated TEPHRA2 inversion analysis of the of the 1998 Mt Etna eruption by Bonadonna and Costa (2013).

3.3.4 Atmospheric parameters

In order to capture past ENSO (El Niño/Southern Oscillation) expressions and to achieve the most representative model of New Zealand wind regimes over time, archived daily wind data was retrieved for 1960 to 2011 for a central point in the OVC from the NCEP/NCAR (National Centers for Environmental Prediction/National Centre for Atmospheric Research) Reanalysis Project (Kalnay et al. 1996) using the MATLAB script dwind (Biass and Bonadonna 2010). Analysis of 10-year (2002-2012) annual climate data from at least 10 weather stations indicate that weather and wind patterns within the OVC area are spatially consistent throughout the caldera (NIWA 2012). Detailed analysis of wind by Bonadonna et al. (2005) found that seasonal variation had a minimal impact on regional tephra fall. Vent elevation was set to 614 m asl, the average elevation of past vent locations at the Haroharo and Tarawera LVZs.

3.3.5 Computational grid parameters

A two-dimensional orthogonal grid was drawn over land surrounding the OVC at 2-km resolution rendering 9,672 cells on a WGS 1984 UTM Zone 60S coordinate system. This resolution was chosen to save CPU processing time in BET_VH calculations, which are calculated on the same grid for consistency, but are performed on a single processor. Analysis of tephra hazard using 4 km\(^2\) cells is an appropriate balance between saving calculation time and maintaining applicability for hazard and risk applications.

3.4 BET_VH MODELING

The BET_VH framework is designed as a hierarchical event tree that describes eight theoretical stages (nodes) in the progression of an eruption hazard sequence (for more information, the reader is referred to Marzocchi et al. 2010). At each node, past (e.g., geological, historical) and prior (e.g., modelling, theoretical) types of data can be input and assigned a weighting in order to calculate a posterior probability distribution that reflects both sources of data and the uncertainty associated with them using Bayesian inference. The probability of a specific eruption scenario (ES) is calculated by selecting multiple nodes of the event tree. This offers multiple advantages to hazard analysis in volcanic settings with high degrees of uncertainty, such as the OVC, by treating uncertainties in a structured and rational manner, considering probability density functions and confidence in the data for every variable in the path of the event sequence.
Chapter 3  

Chapter 3  BET_VH caldera case study

(Marzocchi et al. 2008, 2010). A comprehensively populated BET_VH model reflects theoretical and modelling beliefs, how well observed data conform to beliefs, and the uncertainties associated with the beliefs (Marzocchi et al. 2010).

We set the time frame, or inference interval, for evaluation of data in the BET_VH model to the age of the OVC’s current intracaldera phase of activity, 26 ka. The time window for forecasting \( \tau \) is set to one year, a widely accepted time frame for application to long-term hazard and risk assessments (Newhall and Hoblitt 2002).

3.4.1 Defining the OVC

To establish the BET_VH grid for the OVC, a rectangle was drawn to enclose all topographic features related to the OVC (i.e., Okataina ring structure and composite caldera complex; see Figure 3.2) under the assumption that these structures reflect the geospatial boundaries of the OVC. This rectangle was then divided into 4 km² cells which aligned to the TEPHRA2 grid, resulting in a 46 × 42 km grid of 483 cells (Fig 3.3). All cells within the boundary structures and ≤ 500 m outside the outer margin of these structures were evaluated as a possible vent location, resulting in 227 OVC cells. All 256 cells that were > 500 m outside the boundary structures were not considered part of the OVC and attributed null values for Node 4 vent location in BET_VH.

The geographical boundaries of the individual LVZ areas are not well-defined in the literature as no fault traces are visible at the LVZ massifs (Rowland and Sibson 2001). For this study, a nearest neighbour analysis was performed on past vents for each LVZ in order to construct a reference boundary for the LVZs in BET_VH. Past Tarawera vents showed a nearest neighbour ratio of 0.23, a z-score of -7.0 and a p-value of <0.01, suggesting that vents of the Tarawera LVZ area are highly clustered in the OVC. Past Haroharo vents showed similar values, with a nearest neighbour ratio of 0.23, a z-score of -7.8 and a p-value of <0.01, suggesting that vents of the Haroharo LVZ are also highly clustered in the OVC. These clustering patterns quantitatively confirm the previous qualitative descriptions of the LVZs as clustered “zones” of vents.

The average distance between past Haroharo LVZ vents was calculated to be 588 m, and the average distance between past Tarawera vents was 661 m. In order to define the extent of the LVZs in the BET_VH grid cells, any cell whose centre was ≤ 500 m from the respective mean distance of a Haroharo (588 m) or Tarawera LVZ (661 m) vent was attributed to that LVZ, resulting in 47 Haroharo LVZ cells and 28 Tarawera LVZ cells (Fig 3.3). This attribution was based on the assumption that a future vent opening at an LVZ would follow a similar geospatial pattern as past activity, i.e., a future LVZ vent will open in areas near past LVZ vents. The 500 m buffer zone takes into account the uncertainties associated with the mapping of poorly-preserved or -exposed past vent locations. The resulting BET_VH LVZs (Fig 3.3) were
used to assign prior data attributed to the Haroharo and Tarawera LVZs. Remaining OVC cells are considered “other” OVC (i.e. not within an LVZ).

### 3.4.2 Node 1-2-3: Probability of eruption

Prior data for Node 1-2-3 is the probability of any eruption occurring in the next time window $\tau$. The ages of eruptions at the OVC are consistent with a random sequence, and so a Poisson model is used to estimate the probability of eruption in the next $\tau$. For the chosen time window $\tau = 1$ year and an average interval of 2,364 years between events (11 eruption episodes over 26 ka), the resulting annual prior probability of eruption at the OVC is 4.00E-04 (Stirling and Wilson 2002). This approximation is assigned a very low weight (Table 3.3), as recurrence interval estimates do not forecast future events (Bebbington 2013), and the record of events over the past 26 ka cannot be considered complete, as many smaller events may not have been preserved. Past data for Node 1-2-3 comprises the number of known eruptions over the inference interval of the model. At the OVC, there have been 11 eruption episodes (see Table 3.1) over the chosen 26,000 year catalogue.

### 3.4.3 Node 4: Vent location

While the Haroharo and Tarawera LVZs are spatially distinct complexes within the OVC (Fig 3.2), they are host to volcanic activity of the same intracaldera OVC magmatic system. Resistivity (Heise et al.

![Figure 3.3 Map illustrating data input to BET_VH Node 4. Each 4 km² BET_VH Node 4 grid cell marks a possible vent location. For past data, the number of vents that opened in each vent location over the past 26 ka is used. For prior data, the expert elicitation value for Tarawera LVZ, Haroharo LVZ, and Other-OVC are distributed across the allocated number of vent locations, respectively. Dark grey cells are considered to be locations outside of the OVC, and are not analyzed here.](image-url)
### Table 3.3 BET_VH input parameters. Symbology adopted from Marzocchi et al. (2010)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td>Forward time window of forecast</td>
<td>1 yr</td>
<td>Time window conformable to long-term hazard and risk management and annual agricultural review (see text)</td>
</tr>
<tr>
<td>PRIOR</td>
<td>( \Lambda_{1-2-3} )</td>
<td>1</td>
<td>Low weight, maximum ignorance (Marzocchi et al. 2008)</td>
</tr>
<tr>
<td>PAST</td>
<td>Inference interval (number of ( \tau ) in catalogue)</td>
<td>26,000</td>
<td>Spans current phase of activity at OVC - Nairn (2002); Shane et al. (2005)</td>
</tr>
<tr>
<td>PAST</td>
<td>Number of past eruptions in ( n_{1-2-3} )</td>
<td>11</td>
<td>Eruption episodes; see Table 3.1</td>
</tr>
<tr>
<td>Node 4: Vent location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( I_4 )</td>
<td>Total number of vent locations</td>
<td>483</td>
<td>Vent location cells are 4 km² each; see Figure 3.3, Table 3.4</td>
</tr>
<tr>
<td>PRIOR</td>
<td>( \Theta_4 )</td>
<td>Varies by ( i ); see Fig. 3.3</td>
<td>Expert elicitation session (see table 3.4) and nearest neighbour analysis</td>
</tr>
<tr>
<td>PRIOR</td>
<td>( \Lambda_4 )</td>
<td>1</td>
<td>Low weight; maximum ignorance (Marzocchi et al. 2008)</td>
</tr>
<tr>
<td>PAST</td>
<td>Number of past eruptions at vent location ( i )</td>
<td>Varies by ( i ); see Fig. 3.3</td>
<td>Eruption vents ≤ 26 ka; see Table 3.2 references</td>
</tr>
<tr>
<td>Node 5: Eruption style</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( J_5 )</td>
<td>Total number of eruption styles analysed</td>
<td>3</td>
<td>Basaltic maar-forming ( (j_1) ), basaltic Plinian ( (j_2) ), rhyolitic Plinian ( (j_3) )</td>
</tr>
<tr>
<td>PRIOR</td>
<td>( \Theta_{j_5} )</td>
<td>Null</td>
<td>Expert elicitation session (see text)</td>
</tr>
<tr>
<td>PRIOR</td>
<td>( \Lambda_{j_5} )</td>
<td>Null</td>
<td></td>
</tr>
<tr>
<td>PAST</td>
<td>Number of past eruptions of eruption style ( j ) from vent location ( i )</td>
<td>( y_{j_5}^{(1)} = 1 ), ( y_{j_5}^{(2)} = 1 ), see Table 3.2 references</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sum_{i} \sum_{j} \left( \Theta_{j_5} \right) \left( \Lambda_{j_5} \right) \left( y_{j_5}^{(i)} \right) \]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_6$</td>
<td>Node 6: Phenomenon produced</td>
<td>1</td>
<td>10 kg m$^{-2}$ tephra threshold</td>
</tr>
<tr>
<td>$\Theta_{6,j}^{(p)}$</td>
<td>Conditional probability of phenomena $p$ being produced given eruption style $j$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_{6,j}^{(p)}$</td>
<td>Equivalent number of data (node 6)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$y_{6,k}^{(p)}$</td>
<td>Number of past eruptions of eruption style $j$ to generate phenomena $p$</td>
<td>$y_{6,2}^{(\text{tephra})} = 1$</td>
<td>All basaltic Plinian ($j_2$) and rhyolitic Plinian ($j_3$) eruptions at the OVC in the past 26 ka inference interval have produced tephra $\geq 10$ kg m$^{-2}$ in some areas</td>
</tr>
<tr>
<td>$\Theta_{7,i,j,k}^{(p)}$</td>
<td>Conditional probability of tephra reaching area $k$, given eruption at vent location $i$ and eruption style $j$</td>
<td>Varies by $k$</td>
<td>Results of TEPHRA2, number of successes of tephra load $\geq 0$ kg m$^{-2}$</td>
</tr>
<tr>
<td>$\Lambda_{7,i,j,k}^{(p)}$</td>
<td>Equivalent number of data (node 7)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$y_{7,k}^{(p)}$</td>
<td>Number of past eruptions of eruption style $j$, at vent location $i$, that produced phenomenon $p$, reaching area $k$</td>
<td>$y_{7,k}^{(\text{tephra})} = 1$</td>
<td></td>
</tr>
<tr>
<td>$\Theta_{8,i,j,k}^{(p)}$</td>
<td>Conditional probability of tephra reaching area $k$ at threshold $s$, from eruption at vent location $i$, of eruption style $j$, producing phenomenon $p$</td>
<td>Varies by $k$</td>
<td>Results of TEPHRA2, number of successes of tephra load $\geq s$</td>
</tr>
<tr>
<td>$\Lambda_{8,i,j,k}^{(p)}$</td>
<td>Equivalent number of data (node 8)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$y_{8,k}^{(p)}$</td>
<td>Number of past eruptions reaching area $k$ at threshold $s$, from eruption at vent location $i$, of eruption style $j$, producing phenomenon $p$</td>
<td>$y_{8,k}^{(\text{tephra})} = 1$</td>
<td></td>
</tr>
</tbody>
</table>

*Note: we do not analyse tephra hazard for a maar-forming basaltic eruption here*
2010) and seismic velocity (Sherburn et al. 2003, Bannister et al. 2004) studies suggest the intracaldera system is driven by a single large zone of partial melt beneath the OVC. Over the past 26 ka, five eruptions have occurred at Haroharo LVZ, five have occurred at Tarawera LVZ, and one occurred outside of the LVZs (Rotokawau eruption) (Fig 3.2). Extensive NE-SW trend faulting occurs to the NE and SW of the OVC (Fig 3.2) and likely continues through the OVC area. However, the locations of potential faults are unknown due to burial by young caldera fill. The linear-nature of the LVZs and Rotokawau eruption vents demonstrate that these faults could serve as potential pathways for rising magma. While weighting must be given to the frequently active LVZ areas, the unknown nature of potential buried faults and the anomalous location of the young (3.4 ka) linear Rotokawau eruption vents suggest that the intracaldera system must be treated in its entirety, and all possible vent locations must be considered to some degree, in order for a complete assessment of hazard and to capture the full catalogue of OVC eruptions.

Past and prior data for Node 4 were input for the 227 OVC cells representing a different possible vent opening location. For the purposes of BET_VH analysis, the data input into each cell was assumed to be homogenous over the entire 4km² area. Ten of the past 11 OVC eruption episodes occurred at either the Tarawera or the Haroharo LVZ (Table 3.1). This suggests that, accordingly, there is a higher likelihood of a future eruption occurring at one of the LVZs than at another area of the OVC (e.g., Nairn 2002 and references therein). However, this widely accepted belief has not been quantified, so an expert elicitation session was held in order to quantify this a priori belief about the OVC vent location behaviour.

Expert opinion can be a useful way to quantify a priori beliefs or experiential knowledge that are not captured in other sources of data. The ability to incorporate this form of knowledge is a distinct advantage of BET tools, and the use of expert elicitation sessions for prior distribution data has been supported and integrated in previous BET studies (e.g., Lindsay et al. 2010). Many different basic to advanced methods exist for eliciting expert opinion depending on the range of expertise, experience and knowledge of a solicited group (Aspinall 2006, Kuhnert et al. 2010). Direct elicitation of a probability through group discussion and consensus was adapted in this study, due to the high level of expertise of the multiple scientists available as expert sources. Consensus among scientists is considered a powerful way to estimate subjective probabilities and define degrees of belief for scientific hypotheses (Gillies 1991, 2000). A group of 10 scientists specializing in volcanology-related fields from New Zealand’s government earth science research institute, GNS Science, participated in the session.

The experts reached consensus agreement on a probability distribution for vent location opening, conditional on the occurrence of a future eruption in the OVC based on three mutually exclusive areas: Tarawera LVZ, Haroharo LVZ, and other areas in the OVC. The experts gave a range from minimum to maximum probability for each area, reflecting epistemic uncertainty in their estimate. For Node 4 prior data,
the median value of the range given by the experts was used. Experts attributed a slightly higher likelihood to the Tarawera LVZ compared to the Haroharo LVZ, citing that it has been the most recently volcanically active of the two (Table 3.2). While the expert opinion was believed to provide valuable knowledge for informing the prior, the elicitation methodology was not elaborate, and the knowledge provided was subjective. Uncertainty is reflected in the ranges chosen by the group (see Table 3.4), and the information is at a coarser resolution than the BET_VH cell grid. For these reasons, a low weighting was assigned to the information (Table 3.3).

Past vent locations for each OVC eruption from 26 ka – present were mapped based on Nairn (2002) and other sources listed in Table 3.1 (Fig 3.3), resulting in 65 vents for past data input at Node 4 (vents activated in more than one eruption were counted for each time activated).

### 3.4.4 Node 5: Eruption style

Eruption style can be used to describe the size, magnitude, VEI, composition, or other aspects of an eruption. Here, we use a volcano-specific description of eruption style, which refers to A) an OVC rhyolitic Plinian eruption style (e.g., Kaharoa-style) or B) an OVC basaltic Plinian eruption style (e.g., 1886 Tarawera-style). For the purposes of this study, eruption style is considered independent of vent location.

Past data input at Node 5 was the number of occurrences of each style of eruption \( j \) over the time interval \( \tau \). Over the past 26 ka, there has been 1 basaltic maar-forming eruption (\( j_1 \)), 1 basaltic Plinian eruption (\( j_2 \)), and 9 rhyolitic Plinian eruptions (\( j_3 \)). It is assumed that all large events are captured in the geological record of this time frame, but we acknowledge that evidence of some smaller events may have been overprinted or lost.

The expert elicitation session group (see Node 4) was in consensus that there are no reliable prior data suggesting which of these three eruption style is more or less likely to occur in a future eruption in \( \tau \). Although rhyolitic Plinian eruptions have been much more common at the OVC in past 26 ka, the anomalous nature of the most recent basaltic Plinian eruption makes it unclear in what state the magmatic system currently is. Accordingly, we choose not to apply a prior distribution (i.e., a uniform distribution is assumed). In most cases, small eruptions are much more likely than large eruptions, and a power law distribution could be applied. However, despite basaltic Plinian eruptions being smaller events than rhyolitic

**Table 3.4 BET_VH Node 4 input data, including prior probabilities from expert elicitation session**

<table>
<thead>
<tr>
<th></th>
<th>Tarawera LVZ</th>
<th>Haroharo LVZ</th>
<th>Other-OVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>28</td>
<td>47</td>
<td>158</td>
</tr>
<tr>
<td>Prior Probability (Median)</td>
<td>0.46</td>
<td>0.41</td>
<td>0.13</td>
</tr>
<tr>
<td>Uncertainty (Range in P)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>Probability per cell</td>
<td>1.61E-02</td>
<td>8.51E-03</td>
<td>5.06E-04</td>
</tr>
</tbody>
</table>

* From expert elicitation session (see text)
Plinian eruptions, they are considered more rare (i.e., less frequent) in the global geological record and at
the OVC, so this distribution is not considered appropriate. We acknowledge that assuming maximum
ignorance (i.e., a uniform distribution of rhyolitic and basaltic Plinian events) is a conservative estimate.
We note that a higher frequency of small events is captured in analysis of tephra fallout for each eruption
style through the logarithmic distributions used in TEPHRA2 (Table 3.2).

3.4.5 Node 6: Hazards produced

For Node 6 onwards, we restrict our BET_VH analysis to consideration of tephra fall hazard generated
by a basaltic Plinian \((j_2)\) or rhyolitic Plinian eruption \((j_3)\) only. While a maar-forming basaltic eruption is also
likely to generate small volumes of tephra, Plinian eruptions and will generate a much larger volume of
tephra, with a more widespread and disruptive impact than small localized explosions in the rural OVC
area. It is assumed that all future basaltic Plinian and rhyolitic Plinian eruptions will certainly produce tephra
in a future eruption (Newhall and Self 1982) (Table 3.3). For past data at node 6, all past rhyolitic and
basaltic Plinian eruptions at the OVC produced \(\geq 10\) kg m\(^{-2}\) of tephra.

3.4.6 Node 7: Hazard reaching areas and 8: Hazard reaching threshold

Evaluation of prior probabilities for Node 7 and 8 follows the symbology and technique presented by
Selva et al. (2010) and Marzocchi et al. (2010). The data are evaluated on the same 9,672 cell grid used
in TEPHRA2 analyses, and are assumed to be homogenous. TEPHRA2 runs are modelled for a single
hypothetical vent location in the OVC. At BET_VH Node 7 and 8, those runs are virtually translated and
projected for each BET_VH Node 4 vent location \(i\) so that for each run \(r\) of eruption of size \(j\) projected for
vent \(i\) TEPHRA2 outputs a value for tephra load in kg m\(^{-2}\), \(\pi_{i,j,k,r}\) for each point \(k\).

For Node 7, the number of occurrences of any tephra \((\geq 0\) kg m\(^{-2}\)) reaching each area out of the 1,000
TEPHRA2 runs is counted to calculate a probability of tephra reaching each area. A higher weighting is
assigned to this reliable model information (Table 3.3). For Node 8, the number of occurrences of tephra
meeting or exceeding the threshold value \(s\) at each area, out of the number of occurrences of tephra
reaching the area, is counted to calculate a probability of tephra exceeding \(s\) in each area. We analyse a
tephra accumulation threshold \(s\) of 10 kg m\(^{-2}\) because this is a threshold likely to cause widespread impacts
to many different systems vulnerable to tephra fall in New Zealand, such as agriculture (Wilson and Kaye
2007), electrical power systems (Wardman et al. 2012), and water supplies (Johnston and Nairn 1993).
Using an average deposit density of 1000 kg m\(^{-3}\), 10 kg m\(^{-2}\) is equivalent to approximately 10 mm tephra
thickness. While bulk deposit densities can vary from c. 500 to 1500 kg m\(^{-3}\) (Sparks et al. 1997), 1000 kg
m\(^{-3}\) is considered an acceptable assumption for bulk deposit density for both rhyolitic and basaltic tephra
fall deposits from OVC eruptions and other Plinian eruptions worldwide (Walker et al. 1984, Smith et al.
2006).
No past data are input at Node 7 or 8. While isopach maps exist for OVC eruptions of the past 26 ka, the data are collectively at a low resolution. Isopach intervals are not consistent across maps, and it is assumed that interpolation of the limited isopach data points available to the resolution of the 4km² BET_VH grid would introduce significant uncertainty and error. Additionally, substantial changes in atmospheric behaviour over the past 26 ka mean that tephra dispersion and fallout of a future eruption will be influenced by significantly different atmospheric and wind regimes than past eruptions (Stewart and Neall 1984, Pillans et al. 1993). Therefore, past data are considered to be uninformative.

3.5 RESULTS

3.5.1 Future vent opening location

Overall, BET_VH Node 4 analyses show that in the event of a future eruption, a vent is more likely to open within either the Tarawera or Haroharo LVZ than outside of these areas. A BET_VH posterior probability distribution which considers both past and prior data at Node 4 (Fig 3.4A) shows, on average, 1.7 times higher likelihoods of a future vent opening at locations within the LVZs compared to a posterior probability distribution which considers past data alone (Fig 3.4B). The difference in spatial distribution between Figure 3.4A and 3.4B shows that inclusion of the prior data acquired through the expert elicitation sessions generates a distribution of future vent opening likelihood which reflects past OVC vent location trends (see Figure 3.2, 3.3). When compared to analyses using past data only (Fig 3.4B), analyses using both past and prior data (Fig 3.4A) show a greater range (min. – max.) of probabilities within the OVC (0.38 - 1.66% versus 0.21 – 0.77%), a higher maximum probability value (1.66% versus 0.77% for Ruawahia dome), and a 1.4 times greater standard deviation within the OVC (3.34E0-3 versus 2.31E-03) and within the LVZs (1.82E-03 versus 8.19E-04). Figure 3.4B shows a relatively uniform distribution of the average conditional probability of vent opening, while Figure 3.4A shows higher probabilities of vent opening within the LVZs, medium probabilities adjacent to the LVZs, and low probabilities in other areas of the OVC, aligning better with our understanding and observations of past OVC eruptive behaviour.

Overall, the Tarawera and Haroharo LVZs show an equivalent conditional probability of vent opening (Tarawera LVZ = 32.5% and Haroharo LVZ vents = 31.8%) (Fig 3.4A). The <1% greater probability at the Tarawera LVZ is likely due to the marginally higher prior probability values input (from expert elicitation), as well as a greater frequency of past data, i.e., a greater number of past eruption vents. The vent area with the highest probability of opening in a future eruption is located within the Tarawera LVZ at the Ruawahia Dome area (star in Figure 3.4, P=1.66%), which has had at least 6 active vents (new, or reactivated) in the past 26 ka. The overall average conditional probability of vent opening in a location outside of Tarawera LVZ or Haroharo LVZ, i.e. other-OVC, is 35.7%. However, this value is distributed over a much larger geospatial area; individual vent locations in this group have a conditional probability of
Prior probabilities were distributed uniformly throughout the respective LVZs, making the cluster of high probabilities in the centre of the LVZs a reflection of the influence of past data (Fig 3.4A). Significantly higher probabilities of vent opening are seen at vent locations where eruptions have occurred in the past, with a maximum of 1.66%, minimum of 0.78%, and standard deviation of 2.43E-03 for vent location cells within Tarawera LVZ, and a maximum of 0.93%, minimum of 0.48%, and standard deviation of 1.22E-03 for vent location cells within Haroharo LVZ (Fig 3.4A).

### 3.5.2 Tephra hazard

#### 3.5.2.1 Absolute probabilities

For all areas analysed, the average absolute probability of accumulating ≥ 10 kg m⁻² of tephra from a rhyolitic or basaltic Plinian OVC eruption from any location in the caldera in any one year is <0.02% (10th percentile < 0.015%, 90th percentile < 0.03%). Maps in Figure 3.5 show selected outputs of BET_VH Node 8 depicting the absolute probability of accumulating ≥ 10 kg m⁻² of tephra in the next one year for a number of different Plinian eruption scenarios and levels of uncertainty. Figure 3.6 shows outputs from the same dataset, depicted as a series of hazard curves for the city of Kawarau, a township to the east of the caldera.
Chapter 3  BET_VH caldera case study

Figure 3.5 BET_VH Node 8 outputs showing the average absolute probability of accumulating ≥ 10 kg m\(^{-2}\) of tephra in the next one year from a single Plinian phase resulting from A) a basaltic eruption, and B) a rhyolitic eruption, from somewhere within the Tarawera LVZ. BET_VH analyses can performed for different levels of uncertainty. For example, C shows the 10th percentile probability, and D shows the 90th percentile probability of accumulating ≥ 10 kg m\(^{-2}\) of tephra in the next one year from a rhyolitic eruption from somewhere within the Tarawera LVZ. E shows the average absolute probability of accumulating ≥ 10 kg m\(^{-2}\) in the next one year from an eruption at a single specific vent within the Tarawera LVZ, Ruawahia Dome (see star in Fig 3.4). F shows the average absolute probability of accumulating ≥ 10 kg m\(^{-2}\) of tephra in the next one year from a single Plinian phase resulting from a rhyolitic eruption form somewhere within the Haroharo LVZ. The distribution of hazard from a rhyolitic eruption and the potential areas impacted are different for a Tarawera LVZ scenario (B) and a Haroharo LVZ scenario (F). For example, the probability
of accumulating ≥ 10 kg m⁻² of tephra in Kawerau is approximately 1.3 × greater for an eruption within the Haroharo LVZ than for an eruption within the Tarawera LVZ, and the probability of accumulating ≥ 10 kg m⁻² of tephra in Murupara is approximately 1.8 × greater for an eruption within the Tarawera LVZ than for an eruption within the Haroharo LVZ. The probability of accumulating ≥ 10 kg m⁻² of tephra from a Plinian rhyolitic eruption (B, C, D, F) is on average 7.2 × greater than from a Plinian basaltic eruption (A) because of its high frequency in the past catalogue of eruptions (9 eruptions) compared to the low frequency of basaltic eruptions (1 eruption), and greater erupted mass. The higher values seen in B compared to E highlight the influence of considering all possible vent locations within the LVZ area. The probability of accumulating tephra from an eruption anywhere within the Tarawera LVZ is on average 19.75 × greater than the probability of accumulating tephra from one particular vent within the Tarawera LVZ.

The average absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra from a rhyolitic Plinian eruption at Ruawahia Dome vent, the vent cell (located within the Tarawera LVZ) with the highest probability of opening in a future eruption (Fig 3.4, conditional P=1.66%), are on average 19.75 times lower (Fig 3.5C) than for those derived from analyses considering all possible vent locations within the Tarawera LVZ (Fig 3.5B, E; 3.6A, C). Figure 3.5D, B, and E illustrate different levels of uncertainty in the estimated absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra from a rhyolitic Plinian eruption somewhere within the Tarawera LVZ. Higher estimates of hazard (higher probabilities) are associated with greater levels of uncertainty (Figs 3.5, 3.6).

The distribution of hazard from a rhyolitic Plinian eruption and the potential areas impacted are different for a Tarawera LVZ scenario (Fig 3.5B) and a Haroharo LVZ scenario (Fig 3.5F). For example, the town of Kawerau, located east of the northern part of the OVC, has on average a 1.3 times greater probability of accumulating ≥ 10 kg m⁻² of tephra from a Plinian eruption within the Haroharo LVZ (Fig 3.5F, 3.6B) compared to an eruption within the Tarawera LVZ (Fig 3.5B, F; 3.6A). In contrast, the town of Murupara, located to east of the south part of the OVC, has on average a 1.8 times greater probability of accumulating ≥ 10 kg m⁻² of tephra from a Plinian eruption within the Tarawera LVZ than for an eruption within the Haroharo LVZ (Fig 3.5B, F).

Maps in Figure 3.7 show outputs of BET_VH Node 8 depicting the average absolute probability of accumulating ≥ 10 kg m⁻² of tephra in the next one year from an eruption from anywhere within the entire northern part of the OVC (see Fig 3.5). Throughout the region surrounding the OVC, average absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra from a basaltic Plinian eruption (Fig 3.5A) are on average 7.2 times lower than the average absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra from a rhyolitic Plinian eruption (Fig 3.5B) from somewhere within the Tarawera LVZ. This can also be recognized in the hazard curves for Kawerau (Fig 3.6). This is due to the low frequency of basaltic Plinian eruptions in the catalogue of past eruptions (1 occurrence) compared to the high frequency of rhyolitic Plinian eruptions (9 occurrences), as well as the greater eruption masses (kg) modelled for a rhyolitic Plinian eruption (Table 3.2).
Chapter 3  BET_VH caldera case study

OVC. The circular shape encompassing all possible source vents in the OVC causes the shape of the hazard distribution to become more circular (Fig 3.7). The probabilities associated with accumulating \( \geq 10 \text{ kg m}^{-2} \) of tephra in the next one year from either a basaltic or rhyolitic Plinian eruption from within the OVC (Fig 3.7C) are on average 1.14 times greater than for probabilities associated with a rhyolitic Plinian

Figure 3.6 Hazard curves for the town of Kawerau (see Fig 3.5) based on the absolute probability of accumulating or exceeding certain tephra (kg m\(^{-2}\)) thresholds in the next one year from a single Plinian phase resulting from A) a basaltic or rhyolitic eruption from within the Tarawera LVZ, B) a basaltic or rhyolitic eruption from within the Haroharo LVZ, C) a basaltic or rhyolitic eruption from Ruawahia Dome vent, a single vent within the Tarawera LVZ (see star in Fig 3.4), and D) either a basaltic or rhyolitic eruption from anywhere within the OVC. The 10\(^{th}\) and 90\(^{th}\) percentiles shown with the average probability indicate the uncertainties in the modelling estimates. Hazard is underestimated if only one eruption vent and style is considered (C), compared to consideration of all possible vents and styles of eruption (D). Note: hazard curves drawn based on 0.5, 1, 10, 20, 50 and 100 kg m\(^{-2}\) intervals; curves use different vertical scales.
eruption alone (Fig 3.6D; 3.7A, B).

3.5.2.2 Conditional probabilities

BET_VH analyses show that in the event of a future eruption from within the Tarawera LVZ or Haroharo LVZ, basaltic eruptions (Fig 3.8A, D) have lower average probabilities of reaching and exceeding a 10 kg m\(^{-2}\) tephra hazard threshold than rhyolitic eruptions (Fig 3.8B, E). Tarawera LVZ eruptions (Fig 3.8A, B) have marginally higher probabilities of reaching and exceeding this hazard threshold in areas proximal and medial to the OVC compared to Haroharo LVZ (Figs 3.8D, E), while Haroharo LVZ eruptions show higher probabilities of reaching and exceeding the threshold in areas distal to the OVC (Fig 3.7B, D). Selection of eruption vent location area has a significant influence on posterior conditional probability distributions at Node 8. Differences in spatial attributes are transferred through the BET_VH framework, showing a strong

![Figure 3.7 BET_VH Node 8 maps showing the average absolute probability of accumulating ≥ 10 km m\(^{-2}\) of tephra in the next one year from a single Plinian phase resulting from (A) a basaltic eruption from within the OVC, (B) a rhyolitic eruption from within the OVC, and (C) either a basaltic or rhyolitic eruption from within the OVC. While the likelihood of being impacted by ≥ 10 km m\(^{-2}\) of tephra is on average 7.2 × lower for a basaltic eruption (A) than for a rhyolitic eruption (B), higher probabilities in C show that this low-likelihood event still contributes to the long-term hazard. The average absolute probability of accumulating ≥ 10 km m\(^{-2}\) of tephra in the next one year is on average 1.14 × greater (an increase of 0.00034%) when both basalt and rhyolitic eruptions are considered (C), compared to rhyolitic eruptions alone (B). Accordingly, tephra hazard may be underestimated if both eruption styles are not considered.](image)
influence of vent location area on the conditional probability of reaching and exceeding the 10 kg m\(^{-2}\) tephra threshold (Fig 3.8). Tarawera LVZ scenarios have on average slightly (1.0024 times) higher probabilities than Haroharo LVZ scenarios, a result of the slightly higher prior probabilities input at Node 4 for Tarawera LVZ. Analyses modelled for the single vent location with the highest probability of vent opening at Node 4, Ruawahia Dome, show that most areas have a lower average probability of reaching and exceeding 10 kg m\(^{-2}\) of tephra (Fig 3.8C) compared to average analyses modelled from the whole Tarawera LVZ (Fig 3.8B). Tephra hazard from a single vent Ruawahia Dome eruption is likely to impact a smaller area (Fig 3.8E), and while the hazard is high for areas proximal and medial to the vent, distal areas are less impacted compared to when the full LVZ hazard is modelled (Fig 3.8B). Consideration of all possible vents within an LVZ as a potential source causes a layering, or stacking, effect in fallout grid cells, resulting in the formation of a larger number of cells being potentially impacted by tephra dispersion.

Approximately 12 – 24 km separates the Haroharo and Tarawera LVZs to the north and south, respectively (Fig 3.2, 3.3). Eruptions modelled for the Haroharo LVZ show higher conditional probabilities of reaching and exceeding 10 kg m\(^{-2}\) of tephra in areas in the north than for eruptions modelled from the Tarawera LVZ, due to the relative location of the Haroharo LVZ north of the Tarawera LVZ (Fig 3.8). Similarly, eruptions modelled for the Tarawera LVZ show higher conditional probabilities of reaching and exceeding 10 kg m\(^{-2}\) of tephra in areas in the south than for eruptions modelled from the Haroharo LVZ (Fig 3.8). The longer shape of the Haroharo LVZ produces a more elongate, linear trend of tephra hazard (Figs 3.8D, E) than the shorter Tarawera LVZ (Figs 3.8B, E).

### 3.6 DISCUSSION

The goal of this study was to carry out a robust tephra hazard analysis for the OVC based on a range of new and existing information, and to evaluate how future eruption style and vent location may influence the distribution of tephra hazard from the initial Plinian phases of an OVC eruption. A BET_VH model built on TEPHRA2 analyses, expert elicitation, and an extensive review of past studies suggests that eruption location and eruption style (i.e., a rhyolitic or basaltic Plinian eruption) exert a significant influence on the distribution of tephra hazard from the OVC. Bonadonna et al. (2005) provides a comprehensive analysis of the tephra hazard from a one- to three-vent Tarawera rhyolitic eruption scenario. Our analyses expand upon their study to create a more representative picture of tephra hazard for the OVC as a whole by A) considering how the tephra hazard changes when other possible eruption locations in the OVC system are considered, B) exploring how the tephra hazard changes between an OVC rhyolitic Plinian eruption style scenario and an OVC basaltic Plinian eruption style scenario, and C) evaluating the epistemic uncertainties associated with different possible eruption scenarios (i.e., 10\(^{th}\) percentile, average, 90\(^{th}\) percentile values).
Figure 3.8 BET_VH Node 8 maps showing the average conditional probability of accumulating ≥ 10 kg m$^{-2}$ tephra given a single Plinian phase resulting from A) a basaltic eruption from within the Tarawera LVZ; B) a rhyolitic eruption from within the Tarawera LVZ; D) a basaltic eruption from within the Haroharo LVZ; E) a rhyolitic eruption from within the Haroharo LVZ; E) a basaltic eruption from Ruawahia Dome, a single vent within the Tarawera LVZ (see star in Fig 3.4); and F) a rhyolitic eruption from Ruawahia Dome. The highest probabilities of reaching and exceeding 10 kg m$^{-2}$ (reds-light yellows) are seen in areas proximal and medial to the eruption source and in distal areas to the east. In the event of a future OVC eruption, the areas most impacted by tephra fallout would depend on whether the eruption occurred at the Haroharo LVZ or Tarawera LVZ. If all possible vent locations of an LVZ are considered as potential eruption source vents (e.g., A, B), the distribution of hazard is broader compared to if only one potential vent is considered (e.g., E, F).
Most PVHA methods base tephra hazard analyses on the consideration of one eruptive source vent. However, considering only one vent location is unable to capture the full variability of hazard in caldera complexes such as the OVC. Explosive tephra-producing activity occurred from approximately 47 different vents in three different areas of the OVC over the past 26 ky (Nairn 2002). In this study, BET_VH analyses which consider all possible vent locations within a LVZ, give significantly different probabilistic distributions compared to analyses based on a single possible vent location cell (e.g., Figure 3.5, 3.6, 3.8). Analyses based on consideration of a single vent location in the Tarawera LVZ, the vent with highest probability of vent opening at Node 4, Ruawahia Dome (Fig 3.4), produced much more limited estimates of hazard distribution when compared with analyses based on the selection of all possible vent locations within the Tarawera LVZ, suggesting that single vent analyses may result in an underestimate in the distribution of hazard, and accordingly, potential areas impacted (Fig 3.5, 3.8). The spatial classification of LVZ cells using nearest neighbour analysis and the subsequent selection of LVZ cells at Node 4 allow for a more inclusive description of OVC eruption sequence behaviour and associated hazards than one possible vent source for the LVZ areas. Higher probabilities of vent opening found at those LVZ locations with past data, i.e., vents active in past eruptions, are realistic for an OVC eruption scenario. Many eruptions at the OVC have reactivated past vents or erupted within approximately 2 km from past vents (Nairn 2002).

Significant differences are also present in the spatial distributions of hazard generated by Tarawera LVZ Plinian eruptions and Haroharo LVZ Plinian eruptions due to their geographical location and extent (Fig 3.5, 3.6, 3.7). This highlights the importance of developing and including the Haroharo LVZ in hazard and risk studies for the OVC area. Although the Tarawera LVZ has been prominently discussed in studies of OVC hazard because of its recent activity (1886 and ~1315 AD), our results suggest that a Haroharo LVZ eruption (last eruption 5.6 ka) would present a relatively higher hazard to some towns, such as Kawerau, where it poses, on average, probabilities 1.3 times higher than for an eruption from within the Tarawera LVZ. Accordingly, the Haroharo LVZ should not be neglected in OVC hazard research. Approaching risk management based on the LVZ scenario which exposes an area to highest levels of hazard could promote more effective mitigation. For example, properties in the north may choose to design long-term risk management strategies based on hazard values for Haroharo LVZ scenarios because the properties are exposed to a higher volcanic hazard from Haroharo LVZ than from the Tarawera LVZ, assuming that the mitigation options based on a higher hazard would also accommodate lower hazard scenarios.

Most OVC tephra hazard studies have focused on the hazards associated with rhyolitic eruption scenarios only (e.g., Bonadonna et al. 2005, Jenkins et al. 2008, Hurst and Smith 2010). However, while basaltic events are rare and have smaller eruption masses than rhyolitic events, they can still be
catastrophic, and are capable of producing significant tephra hazard (Walker et al. 1984, Houghton et al. 2004, Barsotti and Neri 2008, Barsotti et al. 2010, Scollo et al. 2013). Deterministic scenarios depicting future basalt eruptions in the OVC estimate that tephra fall between 100 and 10 kg m\(^{-2}\) thick could cover the surrounding region with considerable associated impacts (Johnston and Nairn 1993). Our analysis of the conditional probabilities of tephra hazard reaching and exceeding 10 kg m\(^{-2}\) throughout the region in the event of a basaltic eruption are consistent with this finding, showing, on average, probabilities of accumulating \(\geq 10\) kg m\(^{-2}\) of tephra that are only 22% less than those for a rhyolitic eruption. We acknowledge that assuming a null prior (maximum ignorance) at Node 5 in BET_VH (i.e., a uniform distribution of basaltic and rhyolitic Plinian eruptions) is a grossly conservative estimate. However, because the OVC’s most recent event was an anomalous basaltic event, it is unclear in what state the magmatic system is, and what a future eruption style may be. Expert elicitation yielded consensus that whether the eruption would be basaltic maar-forming, basaltic Plinian, or rhyolitic Plinian in style could not be reliably forecasted; however, past data strongly inform the posterior absolute probabilities for this Node (Fig 3.5, 3.6).

The results of this study are limited to a single Plinian event. While this is typical of explosive basaltic Plinian eruption behaviour, a rhyolitic Plinian eruption episode at the OVC would likely consist of more than one explosive Plinian phase. Considering only one event for such a kind of eruption will lead to a significant underestimate of the total tephra hazard of the full eruption scenario. Bonadonna et al. (2005) and Jenkins et al. (2008) find that the tephra hazards associated with prolonged OVC rhyolitic events are significantly higher than a single explosive Plinian rhyolitic phase modelled here. However, tephra hazard generated by prolonged Plinian activity would be very time-dependent and eruption-specific, controlled by the overall length the Plinian stage and number of discrete Plinian phases. Further, knowing the distribution and magnitude of hazard associated with the initial Plinian phase of an OVC eruption would be very critical information in terms of planning for first response decision-making and emergency management. At the onset of unrest or eruption, existing analyses for the initial phase hazard, such as those presented here, could be applied for immediate response and communication, and new, more eruption-specific evaluations could be rapidly generated using BET_VH based on the forecasted vent locations from other tools, such as BET_EF (Bayesian Event Tree for Eruption Forecasting, Marzocchi et al. 2004), in order to adapt short-term risk management solutions to complement long-term strategies.

We note that a rhyolitic Plinian event has a much higher (on average 7.2 times greater) likelihood of impacting areas in the region in the next one year compared to a basaltic Plinian event, and this should be taken into account when managing and reducing risk. While there is low reliability in the estimations of absolute probability, these outputs could be valuable in prioritization of risk reduction relative to other hazards present in the region. However, while the absolute probability of being impacted by tephra from a
basaltic Plinian eruption is notably low for the region, analyses that consider both basaltic and rhyolitic Plinian eruptions presented here show that a 1.14 times higher hazard exists for the OVC than rhyolitic Plinian eruption hazard alone (Fig 3.5, 3.6). This difference could be critical when considering sensitive decision-making thresholds. The PVHA presented here also captures epistemic uncertainty in the tephra hazard estimates, by evaluating for the 10th percentile, average, and 90th percentile (Fig 3.5, 3.6). Expressing uncertainty in PVHA results could also be very important in a decision-making context, and for when using hazard analyses as an input into quantitative risk assessments.

The significant differences in the outcomes of various eruption scenarios underscore the need for PVHA tools to consider various unknowns, such as vent location and eruption style. BET_VH’s capacity to account for uncertainty in the eruption sequence allows for the model to better capture the complexity of the OVC volcanic history, resulting in more representative hazard assessments and accordingly, risk assessments. Outputs from reliable hazard models such as TEPHRA2 can be successfully managed with other prior data of various complexities through the BET_VH framework. Outputs of Node 4, with and without expert elicitation prior data, show the advantage of the tool’s capacity to consider more subjective forms of knowledge about volcanic areas in addition to advanced analytical tools like TEPHRA2. Important information and insight can be gained from the experiences of both scientific experts and locals to contribute to our understanding of volcanic hazard. Though inherent uncertainties exist in the quantification of subjective information, low confidence can be ascribed to the data.

As with all hazard analysis, the analysis carried out here has room for improvements. A future, more robust assessment could include additional models, other volcanic hazard types, and additional field data. Our study also highlights the difficulties of reconstructing and forecasting complex volcanic behaviour within model limitations, such as the challenges of forecasting long-term hazard for a future eruption with an unknown number of explosive phases, time gaps, and durations. However, this PVHA study highlights how BET_VH can be used to create a suite of hazard information at different levels of uncertainty, and to improve the inclusiveness of hazard assessment estimates, with manifold applications to risk assessment.

3.7 CONCLUSION

A future eruption from the OVC is likely to generate widespread tephra fall in loads that will cause significant social and economic impacts throughout the surrounding region. Previous OVC tephra hazard studies have focused on modelling tephra hazard from one to three vents at the Tarawera LVZ. However, we find that in order to achieve a more complete assessment of tephra hazard, and to capture the full frequency of events, the OVC caldera system must be treated in its entirety, and all possible vent locations considered. While the Haroharo and Tarawera LVZs are separate areas within the OVC, they are host to volcanic activity of the same magmatic system, driven by a single large zone of partial melt beneath the
OVC. A vent within either LVZ, or another area within the OVC, could serve as a potential pathway for rising magma in a future event. Our results show that the location of eruption source vents has an important influence on the spatial distribution of tephra hazard, and accordingly, potential areas impacted. Towns and cities located to the northeast of OVC, such as Kawerau (Fig 3.6), have a higher likelihood of being impacted by an event from the Haroharo LVZ, and towns and cities to the south, such as Murupara are more likely to be impacted by a Tarawera LVZ eruption.

While previous studies have explored the hazard from a future rhyolitic Plinian event, our maps showing conditional probability of accumulating ≤10 kg m⁻² in the event of a basaltic Plinian eruption highlight the importance of addressing the potential hazard from this style of event, which occurred as recently as 1886 AD. Although the absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra in the next one year from a basaltic Plinian eruption are on average 7.2 times lower than for a rhyolitic Plinian eruption, our results suggest that the hazard posed by a basaltic Plinian event does contribute to the overall tephra hazard from the OVC. Analyses that consider both basaltic and rhyolitic Plinian eruption styles show that a 1.14 times higher hazard exists than rhyolitic eruption hazard alone.

We do not present this as an exhaustive assessment of OVC tephra hazard, but rather, as a demonstration of the importance of considering the influence of uncertainties in vent location and eruption style on tephra fall for future assessments at such large complex volcanic centres. This study demonstrates the advantages of applying a probabilistic framework approach, chiefly its ability to formally merge current knowledge and understanding with observed data, and its capability to consider multiple sources of eruption variability and uncertainty. Capturing a wider spectrum of uncertainty through probabilistic evaluation of variables in the eruption sequence and hazardous phenomena facilitates a more robust and realistic assessment of hazard to inform the development of effective and appropriate risk management strategies. Our results show that the use of a synergistic probabilistic modelling approach comprising BET_VH, TEPHRA2, geospatial analysis, and expert elicitation can help work towards improving tephra hazard assessments at volcanoes with a complex eruption history. BET_VH’s ability to evaluate alternative eruption vent locations allows for a more realistic hazard analysis than single eruptive vent models. Cumulative evaluation of many different forms of prior knowledge, from advanced analytical and numerical models to past geologic data and expert opinion, enable the consideration of all present knowledge about a well-studied volcano such as the OVC to build upon and improve data from past studies.
CHAPTER 4
Integrated BET_VH-based assessment of risk to agriculture from local-source volcanic ashfall: a case study from the Bay of Plenty, New Zealand
PREFACE TO CHAPTER 4

Chapter 4 addresses aim 2 of this thesis, to develop and test a technique for integrating BET_VH data into a multi-dimensional quantitative risk assessment which considers a spectrum of both hazard and vulnerability and associated uncertainties. Through a case study which assesses the long-term risk of experiencing 90% damage to agricultural production at farms in the Bay of Plenty region (BOP), New Zealand from ashfall from the Okataina Volcanic Centre (OVC), this chapter presents a new approach for integrating complex datasets generated by BET_VH with vulnerability datasets. The resulting quantitative risk assessment illustrates how such an approach can be used to evaluate risk on a continuum of hazard and vulnerability, at multiple levels of uncertainty, and in dynamic hazard and vulnerability environments.

By integrating data from advection-diffusion-sedimentation tephra fall model TEPHRA2, long-term volcanic hazard analysis tool BET_VH (Bayesian Event Tree for Volcanic Hazards), and agricultural fragility functions with seasonal vulnerability coefficients, a robust risk assessment is developed, which considers seasonality, uncertainty, and a variety of thresholds in both hazard and vulnerability datasets to allow for a multi-dimensional and robust assessment of risk which reflects the complexity of volcanic ash impacts on agriculture. The assessment reveals that fruit farms in the BOP are at higher risk from OVC ashfall than dairy farms in the BOP, and farms to the east of the OVC are at higher risk than farms to the north of the OVC. Forecasts estimate that fruit farms in the BOP have, on average, a greater than 1 in 50 likelihood of experiencing 90% damage (loss) from OVC ashfall over the next 100 years. Detailed analysis further shows that the OVC ashfall risk at fruit farms is cyclic and fluctuates with time of year and harvest season, with the highest risk experienced during peak harvest season.

A risk uncertainty matrix is presented as a scheme to guide evaluation and communication of the level of uncertainty related with such robust quantitative risk assessments (i.e., maximum, average, or minimum estimate of risk), based on combining the different levels of uncertainty available in each of the hazard and vulnerability datasets used. The work in this chapter presents a new and structured approach for assessing volcanic risk and for expressing the uncertainties associated with such assessments, illustrating opportunities for integrating BET_VH into volcanic risk reduction aims.

This chapter presents a manuscript which is in preparation for submission to Natural Hazards and Earth Systems Sciences.
Integrated BET_VH-based assessment of risk to agriculture from local-source volcanic ashfall: a case study from the Bay of Plenty, New Zealand

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ABSTRACT

Quantitatively assessing volcanic risk is challenging due to the intrinsic uncertainties in both volcanic hazard and vulnerability estimates. This study presents a structured approach for integrating and treating uncertainty in quantitative hazard and vulnerability estimates in order to assess risk. Volcanic hazard data derived using advection-diffusion-sedimentation tephra fall model TEPHRA2 and long-term probabilistic volcanic hazard analysis tool BET_VH (Bayesian Event Tree for Volcanic Hazards) are integrated with vulnerability data available for agriculture (fragility functions and seasonal vulnerability coefficients) to quantitatively assess volcanic risk (potential for damage to agriculture) on a continuum of thresholds, at multiple levels of uncertainty, and in the context of fluctuating hazard and vulnerability environments.

This approach is illustrated through a case study which evaluates the long-term likelihood of experiencing 90% damage to agricultural production at farms in the Bay of Plenty region (BOP), New Zealand from the large and complex local volcano, the Okataina Volcanic Centre (OVC). Consideration of seasonal wind profiles, seasonal crop vulnerability, multiple eruption styles, many possible eruption vent locations, and a distribution of thresholds in both hazard and vulnerability datasets allows for a multidimensional and dynamic assessment of risk which mirrors the complexity of volcanic ash impacts on agriculture. A risk uncertainty matrix is presented as a scheme to guide evaluation and communication of the level of uncertainty related with such robust quantitative risk assessments (i.e., maximum, average, or minimum estimate of risk), based on combining the different levels of uncertainty available in each of the hazard and vulnerability datasets used.
Overall, fruit farms were found to be at higher risk from OVC ashfall than dairy farms, and farms to the east of the OVC were found to be at higher risk than farms to the north of the OVC. Forecasts based on the annual maximum estimate of risk for fruit farms show a regional average of 2.3% probability (greater than 1 in 50 likelihood) of experiencing 90% damage from a basaltic or rhyolitic Plinian eruption from anywhere within the OVC over a period of 100 years. Detailed analysis revealed that the OVC ashfall risk at fruit farms is cyclic and fluctuates with time of year and harvest season, with the highest risk experienced during peak harvest season (15 October – 14 April). The long-term ashfall hazard posed by New Zealand volcanoes, the national importance of and regional dependence on the agricultural sector, and the vulnerability of many agricultural practices to volcanic ash together emphasise the importance of considering volcanic risk in long-term management and planning at New Zealand farms. Considering uncertainty in quantitative volcanic risk assessments is an important step forward towards well-informed, applied volcanic risk reduction.

**Keywords**

Volcanic risk assessment; volcanic risk uncertainty matrix; ashfall; BET_VH; TEPHRA2

### 4.1 INTRODUCTION

Volcanic ash is the most common and widespread product of explosive volcanic eruptions. The small to microscopic sizes (≤ 2 mm) and low specific gravities of ash allow it to be transported by the wind for very long distances, with deposits sometimes reaching hundreds to thousands of kilometres from the eruption vent. The widespread nature of volcanic ash means that it can impact many different sectors of society, including critical infrastructure (Wilson et al. 2014a), health (Horwell and Baxter 2006), aviation (Durant et al. 2010), and agriculture (Neild et al. 1998).

The impacts of volcanic ashfall on agricultural land vary greatly in type, severity, and potential for mitigation depending on a number of factors, including farm type. In general, pastoral farms, such as dairy, beef, sheep, and deer farms, are relatively resilient to thin to moderate (≤ 25 mm) volcanic ashfalls. While ash coverage of grazing pasture can lead to tooth abrasion, gastrointestinal issues, eye irritation, weight loss, and distress in stock, these impacts are not typically lethal, and can often be mitigated by increased reliance on supplementary feed stores (Neild et al. 1998, Wilson et al. 2011, Wilson et al. 2007; Wilson and Kaye 2007). Deposits from eruptions that take place in acidic volcanic environments (e.g., through a crater lake) can have high concentrations of toxic soluble elements, such as fluorine (F), which can lead to health complications and fatalities of stock from ash deposits as thin as 2 mm, but instances of this are very rare (Cronin et al. 2003). Thick deposits of ash (≥ 100 mm) are likely to have the most severe impacts on pastoral farm production by rendering pasture untenable, which can lead to exhaustion of supplementary feed and clean water stores, and eventual de-stocking or evacuation of stock (Neild et al.
Thick deposits of ash will also have devastating impacts on pastoral farm assets, through loss of electrical power, abrasion of machinery, and contamination of pasture soil (Wilson and Cole 2007, Wilson and Kaye 2007). Dairy farms in particular are dependent on electricity to keep milking sheds and effluent and water pumps operating (Wilson and Cole 2007).

Horticultural farms, such as fruit, vegetable, and viticulture farms, are typically more vulnerable to the impacts of volcanic ashfall than pastoral farms. Thin volcanic ashfalls of 1 – 10 mm on plants and crops can lead to abrasion, breakage, absorption of ash, acid damage, and reduction in photosynthesis (Cook et al. 1981, Neild et al. 1998). Even if crops do not experience significant damage, cleaning ash from produce can be difficult, time-consuming, and uneconomical (Neild et al. 1998, Wilson et al. 2007, Wilson and Kaye 2007). While root vegetables have been observed to be more resilient than other types of crops (e.g., 2006 Merapi eruption, Indonesia, Wilson et al. 2007), fruiting plants are particularly vulnerable to damage from volcanic ashfall because fruit skins are delicate and often well-exposed, making them easily damaged by small amounts of ash, and difficult to wash clean.

The agriculture and forestry sectors make up more than 12% of New Zealand’s gross domestic product (GDP) and 11% of its employment (MAF 2011). Agricultural losses due to volcanic ash impacts could thus have potentially devastating effects on New Zealand. Agriculture sustains many regional economies throughout the country. For example, more than 45% of land in the Bay of Plenty (BOP) region of New Zealand is dedicated to agricultural practices (Statistics New Zealand 2012a) (Fig 4.1). Agriculture is the largest contributor to the BOP economy, comprising more than 15% of regional GDP, and the sector is the second largest employer in the region (Infometrics 2011). Horticulture makes up 8% of New Zealand’s total exports, and the BOP is a primary horticultural region of New Zealand, home to more hectares of horticultural cropland than any other region in the North Island (Statistics New Zealand 2012a). The region grows a significant amount of the country’s fruit, and is the top producer the nation’s iconic kiwifruit (78%) and avocados (50%) (Statistics New Zealand 2012b), both perennial crops susceptible to the impacts of volcanic ash.

The BOP is also an active volcanic region, with its most explosive volcano, the Okataina Volcanic Centre (OVC), located on the western border of the region (Fig 4.1). The OVC is the most recently active volcanic centre of the Taupo Volcanic Zone (TVZ), a voluminous and highly-active volcanic belt that stretches across New Zealand’s North Island (Fig 4.1), with two Plinian eruptions in the past 1 ky. Bay of Plenty farms were devastated by the OVC’s 1886 AD Tarawera eruption, when approximately 15,000 km² of land and crops were coated with millimetres to metres of tephra (Keam 1988, Poverty Bay Herald 1886, Smith 1886, Walker et al. 1984). It is likely that in the event of an eruption, today’s more extensive, high-intensity, technological farming practices may suffer even greater impacts than 128 years ago.
The particular susceptibility of agriculture, and in particular, fruit farms, to volcanic ashfall; the BOP’s dependency on these industries to sustain local economy; and the potential for receiving future ashfall from the OVC together indicate potentially high levels of volcanic risk to agriculture in the BOP, and emphasize the need for a comprehensive risk assessment. Here, we explore a new integrated approach to quantitative risk assessment using a case study of the risk to BOP dairy and fruit farms from OVC ashfall. We use the semi-analytical advection-diffusion sedimentation model TEPHRA2 (Bonadonna et al. 2005) to analyse annual and seasonal ashfall hazard for two primary ash-producing eruption types typical of the OVC, and use the probabilistic volcanic hazard analysis tool BET_VH (Bayesian Event Tree for Volcanic Hazards, Marzocchi et al. 2010) to account for variations in eruption location and eruption type in OVC ashfall hazard in the BOP. We then combine this probabilistic hazard dataset with information about seasonal agricultural vulnerability, to evaluate OVC volcanic ashfall risk to fruit farms in the BOP. Based on these evaluations, we introduce an integrated first-order quantitative assessment of risk to BOP fruit farms from local-source volcanic ashfall at different levels of uncertainty (maximum, average, minimum estimates of risk).

### 4.2 VOLCANIC RISK TO AGRICULTURE IN THE BAY OF PLENTY (BOP)

Although volcanic risk can be defined in a number of different ways, it can generally be expressed as a function of the hazards present and the existing conditions of vulnerability (potential for loss) from those hazards (CRED 2009, UNISDR 2009).

#### 4.2.1 Ashfall hazard

Multiple different aspects of volcanic ash, such as composition, acidity, and soluble chemicals
present on the surface of ash particles, can present a hazard to agriculture (Cronin et al. 2003, Neild et al. 1998). However, a consistent, simple, and common measure for forecasting the severity of impacts is the depth of the ashfall deposit (Neild et al. 1998, Wilson and Kaye 2007). Typically, thicker deposits of ash are capable of more significant and penetrating damage to farm products and assets than thinner layers, and can make rehabilitation longer and more challenging, with the potential to incur greater loss (Neild et al. 1998, Wilson and Kaye 2007). Ashfall occurs as particles fall out of an eruption plume and its umbrella cloud and deposit on the ground. Generally, larger particles fall out at proximal and medial distances from the vent, and the smallest particles fall out and deposit distally. Accordingly, ash deposits are thickest close to the eruption source, where the plume is densest and most concentrated, and thin with distance from the vent (Bonadonna et al. 1998, Carey and Sparks 1986, Sparks et al. 1997).

The thickness of ashfall deposits is dependent on eruption magnitude, intensity, duration, and wind conditions (Sparks et al. 1997). Deposit thickness will also vary according to seasonal changes in wind patterns and specific eruption parameters, such as vent location and eruption type, particularly for a large and complex volcano such as the OVC which has experienced multiple types of eruptions from multiple locations over its recent volcanic history (Cole et al. 2010, Thompson et al. in review, Chapter 3). Such variations in hazard must be captured in order to achieve a representative analysis of risk. Models for forecasting tephra fallout, such as TEPHRA2 (Bonadonna et al. 2005), and probabilistic volcanic hazard analysis tools such as BET_VH (Marzocchi et al. 2010), can be used to assess long-term volcanic ashfall hazard and identify potentially exposed farms. The high vulnerability of fruit farms, in particular, to low thresholds of volcanic ash means that it would be critical to protect crops and reduce risk from even the first thin deposits of volcanic ash from the initial explosive phase of an eruption. In the event that an eruption does not cease after one explosive phase, and instead continues, a farm’s state of vulnerability, and accordingly risk, is likely to have changed and will need to be reassessed.

4.2.2 Vulnerability

The vulnerability of farms to volcanic ash is complex and often the result of interplay among of a number of different factors. For example, a fruit farm’s vulnerability is dependent on the crop season, maturity of the crop, amount of ash, soluble content of the ash, amount of rainfall following deposition, and the dryness of plant leaves (Neild et al. 1998, Wilson et al. 2007, Wilson and Kaye 2007). Deposition of ash onto plants with wet leaves is likely to cause ash to stick more firmly, and be harder to remove. Yet rainfall which follows the deposition of ash onto dry leaves is likely to wash off ash and thus lessen the potential for acidic damage and reduced photosynthesis. Fruit farms are also likely to be more vulnerable to the impacts of ash during harvest and blooming seasons (Cook et al. 1981, Neild et al. 1998, Wilson et al. 2007). Impacts may be prolonged or exacerbated by remobilisation of dry ash in the days to months after an eruption, potentially leading to long-term issues (Wilson et al. 2011).
Agricultural fragility curves created by Wilson and Kaye (2007) give a first-order estimate of vulnerability through the relationship between thickness of the ash deposit (mm) and the probable degree of loss for fruit farms. They estimate that a dry ash deposit of 5 - 20 mm is expected to cause 90% damage (loss) to fruit farm production, potentially resulting in a very small amount of crop able to be successfully harvested and sold after intense washing and ash removal efforts. Wilson and Kaye (2007) also propose a set of seasonal vulnerability coefficients (Vc), where 0.25 represents lowest vulnerability (off season), 0.75 represents reduced vulnerability (shoulder season), and 1.0 represents highest vulnerability (peak season), which can be used to account for seasonal variation in vulnerability (Table 4.1).

4.2.3 Risk

The multidimensional nature of both volcanic ash hazard and agricultural vulnerability to ash introduces challenges to quantifying volcanic risk. However, quantifying volcanic risk can provide comparable, auditable, and practical information for evaluating the overall long-term environmental and economic risk at individual farms, and for the agricultural sector as a whole. Past work regarding volcanic ash and agriculture has primarily focused on impact assessments (e.g., Cook et al. 1981, Cronin et al. 1998, Wilson and Cole 2007), vulnerability analyses (e.g., Wilson et al. 2010), and reconnaissance evaluations (e.g., Wilson et al. 2007, 2011). Such work has provided valuable, robust, first-hand knowledge about how different types of farms are likely to be affected in the short- and long-term following an eruption. However, little previous work exists on quantifying the risk of agricultural damage. Wilson and Kaye (2007) provide an example of how agricultural production loss can be estimated using scenario-based risk analyses. However, these examples do not capture risk in a full probabilistic context. Development of a current, probabilistic risk assessment for economically-important farms in the BOP could support the implementation and prioritisation of important risk mitigation and management measures to protect both farm production (valuable commodities such as fruit) and assets (non-saleable assets such as sheds or equipment).

4.2.4 Okataina Volcanic Centre (OVC)

The Okataina Volcanic Centre (OVC) is a 700 km² dominantly silicic caldera complex located in the western BOP, in an active stress transfer zone of the Taupo Volcanic Zone (TVZ) (Acocella et al. 2003, Cole et al. 2010, Spinks et al. 2005) (Fig 4.1), the world’s most productive silicic volcanic region (Danišík et al. 2012). The volcanic history of the OVC includes at least three large caldera-forming rhyolite eruptions, at ~ 500 ka, ~ 325 ka, and ~ 45 ka, with episodes of rhyolitic eruptions in the intracaldera phases between these caldera collapse events (Cole 1973, Cole et al. 2010, Danišík et al. 2012, Leonard et al. 2002, Nairn 1992, Shane et al. 2007). Over the current phase of intracaldera activity (26 ka – present), the OVC has displayed a range of eruption styles (26 ka – present), including one basaltic maar-forming eruption, one
basaltic Plinian eruption, and nine rhyolitic Plinian eruptions. Three of these intracaldera rhyolitic Plinian eruptions, as well as the ~45 ka Rotoiti eruption, show evidence of basalt in the early stages of eruption, indicating that regional basaltic intrusion is likely a trigger for eruptions in the OVC (Cole 1973, Nairn 1992, Leonard et al. 2002, Darragh et al. 2006, Shane et al. 2005, Shane et al. 2007, Molloy et al. 2008).

The basaltic Plinian eruption and all of the rhyolitic Plinian eruptions occurred from one of two eruption vent zones, the Tarawera linear vent zone (LVZ) (5 past eruptions), or the Haroharo LVZ (5 past eruptions) (Fig 4.1). Both LVZs are characterised by broad NE-SW trending volcanic massifs built up by dome-forming activity which occurred at the final phases of each rhyolitic eruption. Although approximately 12–24 km separates the Haroharo and Tarawera LVZs to the north and south, respectively, they are interpreted to be linked to the same magmatic system. Resistivity (Heise et al. 2010) and seismic velocity (Sherburn et al. 2003, Bannister et al. 2004) studies suggest that the OVC intracaldera system is driven by a single large underlying zone of partial melt. The Tarawera and Haroharo LVZs are believed to be an expression of underlying faults that serve as pathways for rising magma (Nairn 2002). However, the locations of other potential faults within the OVC are unknown because of burial by young caldera fill. The 3.4 ka basaltic maar-forming eruption occurred outside of the LVZs, also in a series of aligned vents thought to reflect an underlying fault (Beanland and Houghton 1991). This suggests that other hidden faults may exist, and could serve as potential pathways for rising magma in a future eruption. Accordingly, a future eruption could possibly occur from anywhere within the OVC. The most recent OVC eruption, the 1886 AD Tarawera eruption, was anomalous, as it was a rare basaltic Plinian eruption, with an eruption column that reached an estimated height of ~34 km and deposited ash throughout the BOP (Carey and Sparks 1986). The event suggests that basalt intrusion in the OVC is capable of generating large basaltic Plinian eruptions with significant hazards.

Variation in eruption location (e.g., Tarawera or Haroharo LVZ) and eruption style (e.g., basaltic Plinian or rhyolitic Plinian) over the past 26 ka introduces challenges to forecasting potential ashfall. Outside of a state of unrest it is uncertain where a future eruption will occur, or what style it will be. For a comprehensive analysis of the ashfall hazard from such a volcano, all possible future scenarios should be considered and evaluated according to their likelihood. Thompson et al. (in review) (Chapter 3) used

<table>
<thead>
<tr>
<th>Season</th>
<th>Season start</th>
<th>Season finish</th>
<th>Vulnerability description</th>
<th>Vulnerability coefficient (Vc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak harvest and growth period</td>
<td>15 OCT</td>
<td>14 APR</td>
<td>Full</td>
<td>1</td>
</tr>
<tr>
<td>Planting / Shoulder season</td>
<td>15 APR</td>
<td>30 APR</td>
<td>Reduced</td>
<td>0.75</td>
</tr>
<tr>
<td>No planting or harvesting /Off season</td>
<td>01 MAY</td>
<td>14 AUG</td>
<td>Lowest</td>
<td>0.25</td>
</tr>
<tr>
<td>Planting / Shoulder season</td>
<td>15 AUG</td>
<td>14 OCT</td>
<td>Reduced</td>
<td>0.75</td>
</tr>
</tbody>
</table>
TEPHRA2 and BET_VH to construct an ashfall hazard assessment for the OVC which considered the annual hazard of accumulating certain levels of ash from either of the two Plinian eruption styles from all possible locations in order to explore how different hazard scenarios (i.e., different combinations of eruption location and style) influenced ash fallout. They found that this method offered novel insight into forecasting the shape and extent of the ash hazard distribution for different possible OVC eruptions, and for forecasting hazard at a number of different levels of epistemic uncertainty (i.e., 10th percentile, average, and 90th percentile).

### 4.3 METHODS

Our analysis of OVC ash hazard builds on the work done by Thompson et al. (in review) (Chapter 3). We used the same eruption and particle parameter settings for our TEPHRA2 analysis, but performed further analyses using seasonal wind profiles in addition to annual wind profiles, and we analyse for thresholds of ≥ 0.5, 1, 5, 10, 20, 50, and 100 kg m⁻² of ash. Considering an average deposit density of 1000 kg m⁻³, these thresholds in kg m⁻² are equivalent to approximately ≥ 0.5, 1, 5, 10, 20, 50, and 100 mm ash thicknesses, respectively. While bulk deposit densities may vary from approximately 500 to 1500 kg m⁻³ (Sparks et al. 1997), 1000 kg m⁻³ is generally considered an acceptable assumption for Plinian ash deposits worldwide (Walker et al. 1984, Smith et al. 2006). Information about other aspects of the eruption scenario data (e.g., eruption location probability distribution) were also adopted from Thompson et al. (in review) (Chapter 3) and, together with the TEPHRA2 data, were input into BET_VH using the same approach and OVC parameters established by Thompson et al. (in review) (Chapter 3). We summarise these approaches below but refer the reader to Thompson et al. (in review) (Chapter 3) for a more detailed discussion of specific TEPHRA2 and BET_VH input parameters.

#### 4.3.1 TEPHRA2

Ashfall deposits can be very widespread, depending on the magnitude, intensity, and duration of the eruption, and the ambient wind conditions. Advection-diffusion-sedimentation model TEPHRA2 forecasts the fallout and deposition (kg m⁻²) of ash particles from a spreading eruption plume based on an analytical solution of the mass conservation equation (Bonadonna et al. 2005). A Monte Carlo approach is used to stochastically sample user-defined ranges of atmospheric (e.g., wind profile), particle (e.g., grain size distribution), and eruption (e.g., column height and duration) parameters, for each run of the model, which are designed to be run in parallel for rapid calculation. We accessed and ran TEPHRA2 through the MATLAB toolbox interface TephraProb (Biass and Bonadonna 2013).

Here, we use TEPHRA2 to forecast the probable ash fallout for the two OVC eruption styles capable of generating significant and widespread ashfall, A) a basaltic Plinian eruption, and B) a rhyolitic Plinian eruption, both VEI 4. Eruption and particle parameters for this model are taken from Thompson et
Parameters choices for the basaltic Plinian eruption are based on field data from the OVC’s 1886 AD Tarawera eruption and values for well-studied basaltic sub-Plinian to Plinian eruptions at Mt. Etna volcano in Italy (Aloisi et al. 2002) calibrated by Bonadonna and Costa (2013) and Cotopaxi volcano in Ecuador (Tsunematsu and Bonadonna 2014). Parameter choices for the rhyolitic Plinian eruption are based on values calibrated for the OVC’s c. 1315 AD Kaharoa eruption by Bonadonna et al. (2005). While OVC rhyolitic Plinian eruptions often experience multiple phases of Plinian activity over durations ranging from days to months, here, we model only for the initial Plinian phase of activity, because it would prove the most critical for fruit farms due to the high vulnerability to even small deposits of ash. Once ash deposition begins, risk mitigation actions are likely to become less successful, and the vulnerability of the farm is likely to have rapidly changed. Thick, prolonged depositions of ash would result in complex and long-term manifestations of risk dependent on the interrelationship of many factors which we do not address here.

Wind profiles used in the analyses were retrieved for 1960 to 2011 for a central point in the OVC from the NCEP/NCAR (National Centers for Environmental Prediction/National Centre for Atmospheric Research) Reanalysis Project (Kalnay et al. 1996) using the MATLAB script dwind (Biass and Bonadonna 2010). A 50-year time scale is adopted in order to capture ENSO (El Niño/Southern Oscillation) fluctuations. TEPHRA2 analyses were performed with both annual wind profiles (01 January – 31 December) and wind profiles based on the four seasons important for fruit-growing farms: 1) peak harvest and growth period 15 October – 15 April (Vc = 1.0, full vulnerability); 2) planting, or shoulder season, 15 – 30 April (Vc = 0.75, reduced vulnerability); 3) no planting or harvesting, or off season, 01 May – 15 August; and 4) planting, or shoulder season, 15 August – 15 October (Vc = 0.75, reduced vulnerability) (Wilson and Kaye 2007). Wind roses in Figure 4.2 comparing annual and peak season wind patterns highlight the differences which can be captured in such analyses.

4.3.2 BET_VH

BET_VH is an event tree tool which is designed to comprehensively assess all types of knowledge about a volcano and the uncertainties associated with them using a structured Bayesian inference approach. The tool provides a framework for evaluating past (e.g., geological, historical) and prior (e.g., modelling, theoretical) data sources about different theoretical stages (nodes) in the progression of an eruption hazard sequence – Node 1, 2, 3: probability of a magmatic eruption occurring, Node 4: probability of eruption location, Node 5: probability of certain eruption style, Node 6: probability of hazard (e.g., ashfall) generation, Node 7: probability of hazard reaching certain areas, and Node 8: probability of hazard exceeding certain thresholds in particular areas (for more information, the reader is referred to Marzocchi et al. 2010). The probability of a particular hazard event can be then calculated by making selections at each node of the event tree. The 10th percentile, 50th percentile, 90th percentile, and average probability
are solved for the selected event tree path using a Bayesian approach which considers probability density functions and confidence in the data for every variable in the selected sequence (Marzocchi et al. 2008; Marzocchi et al. 2010). The variability of the tool and its ability to evaluate unknowns in a structured and rational environment offers many advantages for analysing hazard in volcanic settings with high degrees of uncertainty such as the OVC.

Here, we populate our BET_VH model with the same inputs for Nodes 1 – 5 for the OVC as Thompson et al. (in review) (Chapter 3), who present a thorough discussion and justification of the definitions and inputs used for each node. We use the same approach as Thompson et al. (in review) (Chapter 3) for Nodes 6, 7, and 8, but amend it to include the seasons and seven thresholds analysed using TEPHRA2 and described above. The approach is summarised below, but the reader is referred to Thompson et al. (in review) (Chapter 3) for more detail. Broadly, prior and past data are based on the past 26 ka of OVC activity. For node 1, 2, 3 (probability of eruption) a Poisson estimate of eruption in the next 1 year was used, based on the average OVC intracaldera eruption recurrence interval over the past 26 ka (Stirling and Wilson 2002) and the catalogue of past eruptions. For node 4 (eruption location) a nearest neighbour analysis of vents, an expert elicitation session, and the catalogue of past eruption vent locations was used. For node 5, a uniform distribution of basaltic and rhyolitic Plinian (maximum ignorance) and the frequency of past eruption types was used. We note that in most cases, a power law distribution could be applied. However, despite basaltic Plinian eruptions being moderately smaller events than rhyolitic Plinian eruptions, they are less frequent at the OVC and in the global geological record, so a power law distribution...
is not considered suitable in this case. We acknowledge that assuming maximum ignorance is a
conservative estimate.

For node 6, it is assumed that all Plinian eruptions will produce ashfall reaching the analysed
thresholds (≥ 0.5, 1, 5, 10, 20, 50, and 100 mm of ash), and that all past eruptions produced these amounts
of ash. TEPHRA2 data for seasonal wind and for the seven thresholds analysed here are used as prior
probability distribution input into Nodes 7 and 8. No past data are input for these nodes as data for past
ashfalls are not available at a high enough resolution for accurate interpolation or assessment. Past data
are also assumed to be uninformative at this node, as the wind patterns influencing past ash deposits (26
ka – 1886 AD) are likely to be substantially different than those acting today (Pillans et al. 1993; Stewart
and Neall 1984).

4.3.3 Risk assessment

Gridded results of the BET_VH analysis (10th percentile, average, and 90th percentile values) were
input into an ArcGIS platform in order to perform spatial overlay and zonal statistics for assessing exposure
to farm block polygons (AgriBase® 2011). BET_VH data for the probability of reaching thresholds of ≥10
mm, the average thickness of ash expected to cause 90% damage (loss) to fruit farm production (Wilson
and Kaye 2007), were geospatially analysed for fruit farm polygons. BET_VH data for the probability of
reaching thresholds of ≥100 mm, the minimum thickness of ash expected to cause 90% damage (loss) to
dairy farm production (Wilson and Kaye 2007), were geospatially analysed for dairy farm polygons. Where
BET_VH probabilistic hazard values overlaid a farm polygon feature, the value was attributed to the
underlying feature. Where more than one BET_VH data point existed within one farm, contained values
were averaged to create an overall mean property hazard value. Analyses were performed on a BOP
region-wide scale. Finer farm-scale analyses were also performed for one randomly selected farm to the
east of the OVC and one to the north of the OVC to explore spatial variation in risk. First-order estimates
of risk were calculated for both annual and seasonal hazard datasets based on the following equation:

\[ \text{Risk} = V_c \times |P(Dr)| \]

where \( V_c \) is the seasonal vulnerability coefficient from Wilson and Kaye (2007) and \( |P(Dr)| \) is the BET_VH
value for the absolute probability of accumulating ash in the forecasted time frame in levels reaching
exceedance thresholds expected to cause a particular proportion of damage or loss (Dr) to the farm
according to fragility functions by Wilson and Kaye (2007). Where annual risk is considered, \( V_c \) is removed
from the equation. We acknowledge that this is a basic, first-order approximation of risk, and that additional
factors such as farm size, crop value, export quantity, and income of the farm could be incorporated for a
more complete analysis.
Chapter 4  

Annual absolute probabilistic hazard curves were created based on the seven ash thresholds evaluated (≥ 0.5, 1, 5, 10, 20, 50, and 100 mm of ash) and their BET_VH probability of exceedance at the 10th, average, and 90th percentile estimates. Levels of uncertainty in the BET_VH data (10th percentile, average, and 90th percentile) and fragility function data (minimum, average, and maximum ash thicknesses expected to cause 90% damage) are used to derive minimum, average, and maximum estimates of risk. These estimates demonstrate that the level of uncertainty in the input data (i.e., hazard and vulnerability data) exerts an influence on the output data (i.e., risk data). This relationship can be summarised using a volcanic risk uncertainty matrix (Fig 4.3).

In general, maximum estimates of risk were achieved by evaluating risk using the maximum hazard estimate (e.g., 90th percentile) and the minimum vulnerability threshold estimate (in this case, the smallest amount of ash thought to be capable of incurring 90% damage). Average estimates of risk were achieved by using the average hazard estimate with the average vulnerability threshold. Minimum estimates of risk were achieved using the minimum hazard estimate (10th percentile) and the maximum vulnerability threshold (in this case, the greatest amount of ash that can be accumulated before incurring 90% damage). We multiply annual estimates of risk to forecast minimum, average, and maximum estimates of risk over six time windows (1, 10, 50, 100, 500, and 1000 years), although it is important note that these forecasts are not adjusted for changes in the probability of eruption occurring (BET_VH Node 1, 2, 3) over time, which is likely to reduce the reliability of estimates at larger time windows. Precipitation data concerning the average number of wet days per month (days with ≥ 1 mm of rain) and average rainfall per month (cm) were retrieved from NIWA (2013) in order to visualise and consider the influence of additional agricultural risk factors. In order to illustrate the comparatively higher risk posed to BOP fruit farms from the initial

**Fig 4.3 Volcanic risk uncertainty matrix.** Uncertainty in probabilistic hazard assessments can be expressed using percentile values (e.g., 10th, 50th, and 90th percentiles). Uncertainty can also be expressed in vulnerability or fragility function estimates, such as the range of thresholds (minimum, average, maximum) associated with 90% damage ratios reported by Wilson and Kaye (2007). The levels of uncertainty at which risk is assessed will affect the outcome of the risk estimate. For example, if a risk assessment is based on the upper bound of the hazard estimate (90th percentile) and the minimum or lower damage ratio threshold, the risk estimate will reflect a maximum, or more conservative estimate of the risk. The shaded area represents one specific risk assessment, and the three different zones: minimum, average, and maximum, reflect uncertainty in that one risk assessment.
phase of a Plinian OVC eruption, we also perform basic assessments for annual risk to BOP dairy farms.

4.4 RESULTS

For both dairy and fruit farms, the hazard was found to be higher in farms east of the OVC compared to farms north of the OVC (Fig 4.4, 4.5). The eastern dairy farm has a 6.6 times higher average probability of accumulating ≥ 100 mm of ash than the northern dairy farm (Fig 4.4), and the eastern fruit farm has a roughly 4.5 times higher average probability of accumulating ≥ 10 mm of ash than the northern fruit farm (Fig 4.5). These differences are likely due to the presence of predominant westerly winds in the BOP throughout most of the year (Fig 4.2). Fruit farms were found to be exposed to significantly higher annual likelihoods of damage from a future Plinian OVC eruption than dairy farms. The maximum value observed at a dairy farm for average probability of accumulating ≥ 100 mm of ash, the minimum threshold expected to be capable of incurring 90% damage to dairy farm production, was 0.0054% per year (Fig 4.4). Forecasts based on the annual maximum estimate of risk show a regional average of 0.387% probability of experiencing 90% damage from this type of event over a period of 100 years (Table 4.2). In contrast, the maximum value observed at a fruit farm for average probability of accumulating ≥ 10 mm of ash, the average threshold expected to be capable of incurring 90% damage to fruit farm production, is 0.013% in the next one year (Fig 4.5). Forecasts based on the annual maximum estimate of risk for fruit farms show a regional average of 2.3% probability of experiencing 90% damage from this type of event over a period of 100 years (Table 4.3).

**Fig 4.4** Map showing the average probability of accumulating ≥ 100 mm of ash from the initial Plinian phase of either a rhyolitic or basaltic Plinian eruption from anywhere within the OVC over the next one year at A) dairy farms throughout the BOP, B) a dairy farm north of the BOP, and C) a dairy farm east of the OVC. Probabilities for the 10th and 90th percentile are also shown for B and C, to illustrate uncertainty in the estimate. Transparent gradational scale in the key shows the average probability of accumulating ≥ 100 mm of ash throughout the BOP. Opaque binned scale shows the average probability of accumulating ≥ 100 mm of ash at each individual dairy farm, and represents the average of all of the probabilities that fall within that farm region. An ash thickness of 100 mm is the minimum threshold expected to be capable of incurring 90% damage to dairy farm production, through effects such as a reliance on supplementary feed stocks, limited milking operations, and drastic de-stocking (Wilson and Kaye 2007; Neild 1998). Farm data from AgriBase® (2011)
Fruit farm fragility functions (amount of damage expected at accumulations of different thicknesses of ash) and hazard curves (annual probability of accumulating different thicknesses of ash) combine to indicate potential risk for fruit farms east and north of the OVC (Fig 4.6). The accumulation of ash thicknesses from 5 - 20 mm, in particular, are associated with both the presence of higher levels of hazard (higher probabilities of accumulating ash) and higher damage ratios (higher damage ratios) (Fig 4.6). Higher hazard curve values for the east fruit farm and their intersection with higher damage ratios on the fragility function suggest that farms east of the OVC are also likely to have greater levels of risk than fruit farms to the north of the OVC (Fig 4.6).

Further investigation of the potential risk (likelihood of damage) at the eastern fruit farm, using hazard analyses with seasonal winds profiles and seasonal vulnerability coefficients (Vc), reveals that the risk is cyclic and fluctuates with time of year (Fig 4.7). Seasonal fluctuations in the hazard (probability of accumulating ash) at the eastern OVC fruit farm are minimal (black dashed line, Fig 4.7), despite the moderate shifts in wind patterns (Fig 4.2). However, a combined assessment of seasonal hazard and seasonal vulnerability (Vc), leads to significant seasonal fluctuations in the risk of incurring 90% damage to fruit farm production (red line and light red area, Fig 4.7), with high values of both hazard and vulnerability coinciding to contribute to high risk during the peak harvest and growth period (15 October – 14 April). Precipitation data illustrates additional factors which may influence seasonal risk, and while the data are not incorporated into risk calculations here, they indicate how other elements may contribute to the evaluation of risk. Ash deposited on wet plants is likely to become heavy, and difficult to remove, and

Fig 4.5 Map showing the average probability of accumulating ≥ 10 mm of ash from the initial Plinian phase of either a rhyolitic or basaltic Plinian eruption from anywhere within the OVC over the next one year at A) fruit farms throughout the BOP, B) a fruit farm north of the BOP, and C) a fruit farm east of the OVC. Probabilities for the 10th and 90th percentile are also shown for B and C, to illustrate uncertainty in the estimate. Transparent gradational scale in the key shows the average probability of accumulating ≥ 10 mm of ash throughout the BOP. Opaque binned scale shows the average probability of accumulating ≥ 10 m of ash at each individual fruit farm, and represents the average of all of the probabilities that fall within that farm region. An ash thickness of 10 mm is the average thickness expected to cause 90% damage to fruit farm production, through effects such as abrasion, reduction of photosynthesis, and physical damage (Wilson and Kaye 2007; Neild 1998). Farm data from AgriBase® (2011)
therefore damage plants. However, rainfall on a dry ash deposit is likely to remove ash from the plant (Neild et al. 1998). Both of these processes may have an influence in estimates of risk for the first half of December, during which peak risk coincides with a peak in the number of wet days and monthly rainfall, and also during February to mid-April, when the fruit farms in the BOP are likely to experience their lowest frequency of wet days (days with ≥ 1 mm rain) (i.e., fruit leaves are more likely to be dry), and an increasing number of rainfall events (i.e., a higher likelihood that rainfall could remove ash deposited on dry leaves).

Annual and seasonal risk analyses presented in this study are based on hazard datasets which describe probability of accumulating ash from any of the two Plinian OVC eruption styles occurring anywhere within the caldera over the next 1 year (see Methods). However, conditional BET_VH probabilities (probability of accumulating ash in the event of an eruption, i.e., Node 1, 2, 3 prior P = 1) can be used to explore how the spatial distribution of this peak season risk (probability of accumulating ≥ 10 mm of ash × a Vc of 1.0) changes depending on what type of eruption occurs from the OVC (Fig 4.8). Results show that risk from an eruption within the Haroharo LVZ is, on average, 1.9 times greater for fruit farms throughout the BOP (Fig 4.8). The differences in Figure 4.8 A-C and Figure 4.8 D-F highlight the importance of considering all possible vent locations in hazard and risk assessments. For example, a risk assessment which only considered a Tarawera LVZ eruption in risk assessment (Fig 4.8 B, C) would result, on average, in a 47% underestimate of risk if a future OVC eruption occurred at the Haroharo LVZ (Fig 4.8 E, F). Results also show that risk (probability of accumulating ≥ 10 mm of ash × a Vc of 1.0) from a rhyolitic Plinian event is 1.6 times greater than from basaltic Plinian event (Fig 4.9). These differences also emphasize that risk assessments must consider all possible eruption locations (in this case, Haroharo LVZ, ...
Tarawera LVZs, and other areas of the OVC caldera) and possible styles which are likely to generate the hazard (in this case, basaltic Plinian and rhyolitic Plinian) in order to comprehensively assess risk. A risk assessment based on a hazard analysis for the most recent event alone, a Tarawera LVZ basaltic Plinian eruption (i.e., the 1886 AD Tarawera eruption), would lead to a significant underestimation of risk.

4.5 DISCUSSION

4.5.1 OVC ashfall risk to BOP fruit and dairy farms

The BOP fruit farm risk assessments presented here highlight the multidimensional nature of volcanic ash risk to agriculture. There is a maximum estimate of a 2.3% probability, or approximately a 1 in 50 chance, that BOP fruit farms will experience 90% damage (loss) over the next 100 years from the initial phase of a Plinian eruption from anywhere within the OVC. Fruit farms experience highest risk during their peak harvest and growth period (Fig 4.6), with the example fruit farms east and north of the OVC showing that, in the event of an eruption from within Haroharo LVZ during this season, there is, on average,
a 42% and 9% probability of experiencing 90% damage to fruit farm production, respectively. Precipitation will play a role in this risk, but is difficult to quantify or accurately forecast.

Assessing and quantifying the risk from volcanic ash can help farms be aware of potential impacts, weigh the volcanic risk against other sources of risk, and inform decisions regarding risk reduction and mitigation strategies. While limited mitigation options for fruit farms exist, actions may include erection of greenhouses, or the installation and reinforcement of wind breaks, which were both found to reduce the degree of ash deposition and abrasion to crops from the 1991 eruption of Volcán Hudson in Chile (Wilson et al. 2011).
Wilson and Cole (2007) found that ≥ 150 mm of ashfall will make it very difficult for a dairy farm to have a chance at recovery. While our assessment finds that the maximum risk estimates for long-term probabilities of reaching 90% damage to dairy farms due to volcanic ashfall from the OVC is very low (0.387% over the next 100 years), this is likely a gross underestimate. Estimates here are based only on ashfall from the first initial phase of Plinian eruption. A quantitative risk assessment for dairy farms would need to be based on the full multiple-phase Plinian stage of an OVC rhyolitic eruption, which may include anywhere from four phases over matter of hours to more than fifteen over a period of weeks to months (Darragh et al. 2006, Speed and Shane 2002).
### Maximum estimate of risk

<table>
<thead>
<tr>
<th>Time window</th>
<th>P of accumulating ≥ 100 mm</th>
<th>10th Pct.</th>
<th>Avg.</th>
<th>90th Pct.</th>
</tr>
</thead>
<tbody>
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<td>0.003%</td>
<td>0.002%</td>
<td>0.004%</td>
</tr>
<tr>
<td>10 years</td>
<td></td>
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</tr>
<tr>
<td>100 years</td>
<td></td>
<td>0.286%</td>
<td>0.185%</td>
<td>0.387%</td>
</tr>
<tr>
<td>500 years*</td>
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<td>1.935%</td>
</tr>
<tr>
<td>1000 years*</td>
<td></td>
<td>2.860%</td>
<td>1.850%</td>
<td>3.870%</td>
</tr>
</tbody>
</table>

* P forecasts are not adjusted for changes in the probability of an eruption occurring over time, reducing the reliability of estimates at large time windows.

### Table 4.2 Maximum risk estimate for a dairy farm east of the OVC (see Fig 4.2) over six different time windows (1, 10, 50, 100, 500, and 1000 years), based on the average, 10th, and 90th percentile estimates of the probability of incurring 90% damage to dairy production resulting from a Plinian eruption from anywhere within the OVC, and the average, minimum, and maximum thicknesses of ash expected to cause 90% damage to production based on the fragility function of Wilson and Kaye (2007). An upper bound (90th percentile) hazard estimate (grey shaded column) and lower threshold vulnerability estimate (minimum thickness capable of 90% damage) can be used to estimate maximum, or more conservative, estimates of risk.

### Table 4.3 Three tables showing A) minimum, B) average, and C) maximum estimates of ashfall risk estimates for a fruit farm east of the OVC (see Fig 4.3) over six different time windows (1, 10, 50, 100, 500, and 1000 years), based on the average, 10th, and 90th percentile estimates of the probability of 90% damage to fruit production resulting from a Plinian eruption from anywhere within the OVC, and the average, minimum, and maximum thicknesses of ash expected to cause 90% damage to production based on the fragility function of Wilson and Kaye (2007). A shows how a lower bound (10th percentile) hazard estimate (grey shaded column) and high vulnerability threshold estimate (maximum thickness capable of 90% damage) can be used to generate minimum, or less conservative estimates of risk. B illustrates how an average hazard estimate (grey shaded column) and average vulnerability threshold estimate (average thickness capable of 90% damage) can be used to generate average, or mean, estimates of risk. C demonstrates how an upper bound (90th percentile) hazard estimate (grey shaded column) and lower vulnerability threshold estimate (minimum thickness capable of 90% damage) can be used to generate maximum (or more conservative) estimates of risk.

### Table 4.3 Three tables showing A) minimum, B) average, and C) maximum estimates of ashfall risk estimates for a fruit farm east of the OVC (see Fig 4.3) over six different time windows (1, 10, 50, 100, 500, and 1000 years), based on the average, 10th, and 90th percentile estimates of the probability of 90% damage to fruit production resulting from a Plinian eruption from anywhere within the OVC, and the average, minimum, and maximum thicknesses of ash expected to cause 90% damage to production based on the fragility function of Wilson and Kaye (2007). A shows how a lower bound (10th percentile) hazard estimate (grey shaded column) and high vulnerability threshold estimate (maximum thickness capable of 90% damage) can be used to generate minimum, or less conservative estimates of risk. B illustrates how an average hazard estimate (grey shaded column) and average vulnerability threshold estimate (average thickness capable of 90% damage) can be used to generate average, or mean, estimates of risk. C demonstrates how an upper bound (90th percentile) hazard estimate (grey shaded column) and lower vulnerability threshold estimate (minimum thickness capable of 90% damage) can be used to generate maximum (or more conservative) estimates of risk.

<table>
<thead>
<tr>
<th>Time window</th>
<th>P of accumulating ≥ 100 mm</th>
<th>10th Pct.</th>
<th>Avg.</th>
<th>90th Pct.</th>
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<tr>
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<td>0.014%</td>
</tr>
<tr>
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<tr>
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<td>0.006%</td>
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<tr>
<td>10 years</td>
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<td>0.060%</td>
<td>0.098%</td>
<td>0.142%</td>
</tr>
<tr>
<td>50 years</td>
<td></td>
<td>0.300%</td>
<td>0.490%</td>
<td>0.710%</td>
</tr>
<tr>
<td>100 years</td>
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<td>0.600%</td>
<td>0.980%</td>
<td>1.420%</td>
</tr>
<tr>
<td>500 years*</td>
<td></td>
<td>3.000%</td>
<td>4.900%</td>
<td>7.100%</td>
</tr>
<tr>
<td>1000 years*</td>
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<td>6.000%</td>
<td>9.800%</td>
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<th>90th Pct.</th>
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</tr>
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<td>0.100%</td>
<td>0.160%</td>
<td>0.230%</td>
</tr>
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<td>50 years</td>
<td></td>
<td>0.500%</td>
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<td>1.150%</td>
</tr>
<tr>
<td>100 years</td>
<td></td>
<td>1.000%</td>
<td>1.600%</td>
<td>2.300%</td>
</tr>
<tr>
<td>500 years*</td>
<td></td>
<td>5.000%</td>
<td>8.000%</td>
<td>11.50%</td>
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<td>1000 years*</td>
<td></td>
<td>10.00%</td>
<td>16.00%</td>
<td>23.00%</td>
</tr>
</tbody>
</table>

* P forecasts are not adjusted for changes in the probability of an eruption occurring over time, reducing the reliability of estimates at large time windows.
4.5.2 Capturing uncertainty in risk assessment

In order to generate a representative picture of risk for all farms, it is important to consider the inherent uncertainties in risk assessments by incorporating uncertainty in both hazard and vulnerability analyses. Calculation of fragility functions and hazard curves allows for analysis of risk on a continuum, facilitating analysis of different possible risk scenarios. The intersection of the average fragility function line and average hazard curve lines in Figure 4.6 represent average risk ($P(Dr)$) as a point. However, if uncertainties in fragility function and hazard curve analyses are considered, this intersection becomes represented as an area, rather than a point (Fig 4.6), supporting the concept of a range of potential risk, and the consideration of risk assessment based on an uncertainty matrix (Fig 4.3).

This matrix (Fig 4.3), which considers upper and lower bounds for hazard, vulnerability, and risk can also be used to characterise minimum, average, and maximum estimates of risk (Table 4.2, 4.3). Consideration of the 10th percentile probability of accumulating 20 mm of ash (maximum thickness likely to cause 90% damage), leads to a lower estimate of risk, i.e., a 0.60% probability of experiencing 90% fruit farm production loss from volcanic ashfall from the OVC in the next 100 years (Table 4.3A). In comparison, consideration of the 90th percentile probability of accumulating 5 mm of ash (minimum thickness likely to cause 90% damage), leads to a higher estimate of risk, i.e., a 2.3% probability of experiencing 90% fruit farm production loss from volcanic ashfall from the OVC in the next 100 years (Table 4.3C). Communicating the variable nature of risk and considering the upper and lower bounds can help create more realistic assessments of risk. In a case study of sheep farmers in Northern England, Wynne (1992) found that expression of uncertainty in scientific hazard information was well-accepted and favoured among farmers, who are typically very familiar with uncertainties due the many uncontrolled factors which affect their daily farming routines.

4.5.3 Challenges in quantitative risk assessment

While incorporating observations about precipitation into a quantitative risk assessment presents challenges, recognising and expressing such additional factors alongside risk assessments may help growers understand the multi-dimensional nature of volcanic risk. Analysis of the differences in hazard from the event of an eruption from within the OVC’s Tarawera LVZ compared to an eruption from within the Haroharo LVZ, highlight the importance of considering multiple dimensions of volcanic hazard, in this case uncertainty in future eruption vent location and eruption style. A risk assessment suite which considers seasonal influence, depicts multiple risk factors, and evaluates all likely eruption scenarios, such as that presented here could be used to inform decisions about important mitigation measures such as the instalment and reinforcement of wind breaks, or greenhouses (e.g., Wilson et al. 2011).

Assessments here could be expanded to evaluate risk on a finer scale. For example, the increase
in hazard (black dashed line, Fig 4.7) in the shoulder season from 15 – 30 April is likely to be a result of the smaller wind population sampled. While seasonal wind analyses give insight into broad seasonal changes, use of smaller monthly wind profiles in TEPHRA2 analyses could be used to create a more sensitive estimate of risk fluctuations. However, this would require significant additional resources and time, as it would result in a minimum of 12 eruption range scenario models (approximately 1,000 runs each) to be performed in TEPHRA2, analysed, and re-formatted for input into BET_VH.

Further, the risk analysis presented here is based on a single type of volcanic hazard from a local-source eruption at a single volcano. Long-term risk assessment which considers multiple types of hazard from multiple different volcanoes, both local and distal, would represent a more comprehensive outlook of volcanic risk. While available input data for such an assessment are currently limited, BET_VH has been recognised as a useful tool for performing integrated probabilistic multi-hazard analyses (Sandri et al. 2014). Analysis of leachate properties of basaltic and rhyolitic ashes could add further value to a risk assessment which considers hazard from both types of eruption. Information about probable grain size distribution output by TEHPRA2 could also be incorporated in such an assessment, as particular grain size characteristics can have specific effects on certain agriculture practices (Neild et al. 1998, Wilson and Kaye 2007). The customizable nature of BET_VH would allow for these deposit properties to be analysed within the existing OVC hazard analysis framework.

Although multiple studies have proposed that BET_VH could serve as a valuable input into quantitative risk analyses (Marzocchi et al. 2010, Sandri et al. 2014, Selva et al. 2010, Selva et al. 2012b), little work had been done to explore and test how BET_VH can be integrated into risk assessments. Sandri et al. (2012) used BET_VH to build a cost-benefit analysis framework for crisis evacuation decision-making based on the probable economic impact of lives lost from base surge in the Auckland Volcanic Field, assuming that exposure to base surge = all lives lost and non-exposure = no lives lost. Here, we explore long-term risk as a dynamic and fluctuating state over time, instead of as a short-term decision-making threshold. Integration of multiple datasets and methods with BET_VH analyses allows for evaluation of risk on a more continuous spectrum, which considers a broad scope of potential hazard and potential vulnerability and their associated uncertainties.

4.6 CONCLUSION

Using a case study of risk to agriculture from local-source volcanic ash in an agriculturally-dense region of New Zealand, we present a new approach for a BET_VH-based quantitative risk assessment, which explores the risk of potential damage over a continuum of hazard and vulnerability, at multiple levels of uncertainty, and in the context of fluctuating hazard and vulnerability environments. Consideration of seasonality, uncertainty, and a variety of thresholds in both hazard and fragility allow for a multi-
dimensional assessment of risk which mirrors the complexity of volcanic ash impacts.

We find that the level of risk posed to BOP farms, and BOP fruit farms in particular, from OVC volcanic ashfall is influenced by many different hazard and vulnerability factors such as:

- type of eruption (in this case, rhyolitic or basaltic Plinian);
- location of eruption (in this case, Tarawera LVZ, Haroharo LVZ, or elsewhere in the caldera);
- wind conditions present during the agricultural season in which the eruption occurs (in this case, peak-, shoulder-, or off-season wind patterns);
- thickness of volcanic ash deposited (in this case, 0.5, 1, 5, 10, 20, 50, or 100 mm); and
- the agricultural season during which the eruption occurs (in this case, peak-, shoulder-, or off-season).

Precipitation conditions (e.g., rainfall and dryness of land or crops) are also likely to factor into the overall risk, however, this is difficult to incorporate quantitatively into risk assessments or to forecast with accuracy. We present a risk uncertainty matrix for expressing uncertainty in quantitative risk assessments (i.e., maximum, average, or minimum estimate of risk) based on combining different levels of uncertainty available in the hazard and vulnerability data used, and suggest that communicating risk in this context may facilitate understanding of the inherent uncertainties present in such assessments, and that such expressions of uncertainty are likely to be well-accepted among stakeholder groups who are familiar with the degrees of uncertainty present in some of the parameters considered (e.g., among farmers familiar with variable wind conditions).
CHAPTER 5
The influence of probabilistic volcanic hazard map properties on hazard communication
Chapter 5 addresses aim 3 of this thesis, to understand how properties in the representation of BET_VH data on hazard maps and hazard curves affect the way that BET_VH data is interpreted, and to develop recommendations for communication of such data. Through a series of 14 in-person semi-structured interviews and an online survey of a group of 110 scientists and organisational stakeholders in New Zealand, this chapter identifies several design properties which influence the communication and interpretation of hazard information from probabilistic volcanic hazard maps and hazard curves designed with BET_VH-derived data, such as data classification, colour scheme, content, key expression, and map text. These properties are explored and analysed in-depth using both qualitative (thematic analysis) and quantitative (non-parametric descriptive and inferential statistics) methodologies.

The work done in this chapter provides novel and original insight into how choices in the visual representation of probabilistic hazard information on maps and other visual graphics such as hazard curves influence the way that readers interpret and understand the hazard. For example, the study revealed that the colour scheme used on a probabilistic volcanic hazard map can have strong influence on the type of hazard message taken away. Sequential colour schemes (e.g., red to yellow warm colours) were associated with a hazard distribution (high to low), whereas diverging colours (e.g., red to blue, warm to cool colours) were associated with a hazard state (present or absent). Further, 67% of respondents said that the colour scheme changed the way that they perceived the hazard. Certain styles of map data classification and hazard curve depiction were viewed as easier to read and some were associated with more accurate readings of the probabilistic data. Observations of these and other important influences are presented and critically discussed in terms of the implications for communication of probabilistic volcanic hazard data, such as data created with Bayesian event tree tools. The results of this New Zealand-based tephra fall hazard map case study are used to create the first set of advisory recommendations for the consideration of design properties when designing probabilistic volcanic hazard maps for stakeholders.

This chapter presents a manuscript which was revised and resubmitted to the Journal of Applied Volcanology in November 2014.
The influence of probabilistic volcanic hazard map properties on hazard communication

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Jan M Lindsay and JC Gaillard

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ABSTRACT

Probabilistic volcanic hazard analysis is becoming an increasingly popular component of volcanic risk reduction strategies worldwide. While probabilistic hazard analyses offer many advantages for decision-making, displaying the statistical results of these analyses on a map presents important new hazard communication challenges. Probabilistic information is complex, difficult to interpret, and associated with many uncertainties. Conveying this complicated data on a static map image without careful consideration of map user perspectives or context, may result in contrasting interpretations, misunderstandings, or aversion to using the map for decision-making. Here, we present the results of interviews and surveys conducted with organisational stakeholders and scientists in New Zealand which explored how probabilistic volcanic hazard map properties influence map interpretation, understanding, and preference. Our results suggest that choices in data classification, colour scheme, content, and key expression play important roles in how users engage with and interpret probabilistic volcanic hazard maps, and we conclude that careful attention should be paid to these selections in order to achieve effective hazard communication.

Data classification was found to influence the participants’ perceived uncertainty and data reading accuracy, with isarithmic style maps reducing uncertainty and increasing accuracy best. Colour scheme had a strong influence on the type of hazard messages interpreted, with a red-yellow scheme conveying the message of a hazard distribution (high to low), and a red-yellow-blue scheme conveying the message of hazard state (present or absent) and/or risk. Multiple types of map content were found to be useful, and hazard curves were viewed as valuable supplements. The concept of “confidence” was more easily interpreted than upper and lower percentiles when expressing uncertainty on the curves. Numerical and verbal expression in the key also had an influence on interpretation, with a combination of both a percent (e.g., 25%) and a natural frequency (e.g., 1 in 4) “probability” being the most inclusive and widely-
understood expression. The importance of these map property choices was underscored by a high portion of participants preferring to receive maps in static fixed formats, such as PDF.

This study illustrates how engaging with users in a bottom-up approach can complement and enhance top-down approaches to volcanic hazard mapping through a collaborative and integrative design process which may help to prevent miscommunications in a future crisis when maps are likely to be drafted, disseminated, and duplicated rapidly.

Keywords

Hazard communication, hazard maps, probabilistic volcanic hazard analysis, hazard curve, interviews, surveys, stakeholders

5.1 INTRODUCTION

Volcanic hazards are spatial phenomena, described and communicated globally using maps. In conventional hazard mapping practice, scientists analyse data about volcanic hazards, and then display the results on a map for a diverse audience of readers. However, this insular top-down approach to volcanic hazard communication does not necessarily translate into effective hazard awareness or informed decision-making, which are key contributors to risk reduction. These factors are dependent on how the reader interprets and understands the hazard map, a facet of volcanic hazard communication that has been relatively unexplored.

Wide variation in data types, hazard modelling techniques, cartographic styles, and subjective preference has led to a vast diversity in the ways volcanic hazard information is represented on maps (Calder et al. 2012), yet limited attention has been paid to the impact of these choices on reader response and comprehension. For example, does the use of a particular colour scheme (blues versus reds), data classification (stretched versus binned), or key expression (10% versus 1 in 10) affect the way that a user interprets hazard information from the map? Geography (e.g., Robinson 1967, Bertin 1983, MacEachren 1995, Monmonier 1996, Kunz and Hurni 2011) and communication (e.g., Fisher 1991, Hoffrage et al. 2000, Severtson and Myers 2013, Doyle et al. 2014) research literature suggests that these types of properties may play an important role in hazard information processing. As capabilities and accessibility of hazard analyses continue to advance, it is important and timely to investigate how quantitative hazard map information is interpreted by those who may refer to the maps for decision-making. Initial interpretations of maps become particularly important in the context of decision-making during high-stakes, time-pressure crisis situations when reliance on affective heuristics, or intuitive feelings about the map, is likely to be high (Finucane et al. 2000).

In this New Zealand-based study, we use qualitative and quantitative methodologies to empirically investigate how certain map properties affect the way that stakeholders and scientists respond to and
interpret information from probabilistic-style volcanic hazard maps, and aim to gain key map user perspectives on these hazard map properties. Understanding how map properties influence map legibility and accessibility can help build awareness in the scientific community about the impact of certain choices when designing hazard maps, and accordingly, help improve the consistency, clarity, and effectiveness of volcanic hazard communication.

5.2 PROPERTIES AND USERS OF PROBABILISTIC VOLCANIC HAZARD MAPS

Volcanic hazard maps are thematic maps, in which the features selected as primary map content are themed on information about the potential dangers associated with volcanoes. Probabilistic volcanic hazard maps depict, in varying ways, the likelihood of a certain dangerous volcanic phenomenon occurring in a particular area in a specific time frame. Computational advances and development of a number of probabilistic volcanic hazard analysis methodologies over the past decade (e.g., Mader et al. 2006) have led to a marked increase in the amount of probabilistic volcanic hazard maps being created today. There are many advantages of using a probabilistic approach to analyse volcanic hazards. Volcanoes are inherently complex systems associated with many degrees of uncertainty. Probabilistic methods allow scientists to evaluate the unknowns and to quantify and compare the likelihood of a broad range of different possible hazard scenarios, introducing more practical applications to risk assessment than traditional methods which typically analyse only one scenario (Newhall and Hoblitt 2002, Marzocchi et al. 2012). However, using probabilistic volcanic hazard data to build hazard maps also presents new challenges. Probabilities are inherently difficult to communicate and understand among experts and non-experts alike (Hoffrage et al. 2000, Spiegelhalter et al. 2011), and are interpreted and contextualised differently by different types of map users (Reyna and Brainerd 2008, Doyle et al. 2014). Conveying uncertain data using concrete map images may also introduce communication obstacles (Severtson and Myers 2013).

Many methods exist for both generalising (simplifying) and representing (depicting) thematic content on maps (Slocum 1999, Dent et al. 2009). Extensive options mean that strikingly different maps can be created from a single set of data. Such choices for representing the data may have important impacts on how the map is perceived and interpreted (Monmonier 1996). While a map may be designed to convey a single dataset of interest, it does not convey a single universal message. Each user constructs their own individual knowledge from interpreting the different symbols, colours, and expressions on the map (Bertin 1983, MacEachren 1995). Some key thematic map properties for which it is important to consider the choice of representational style are: data classification, map content, and colour scheme (Monmonier 1996, Dent et al. 2009).

Data classification refers to the characterisation and categorisation of a dataset into a particular
visual symbology (Dent et al. 2009, Slocum 1999). For example, for a dataset which comprises 1,000 numerical values that range from 1 to 100, e.g., probabilistic hazard values, those values can be stretched gradationally over a gradual ramp of colours, where each value responds to a unique shade of colour on the ramp (e.g., white = 0 to black = 100 for a greyscale ramp). Isopleths or isarithms (lines connecting points of equal value) can be applied on top of the shaded classification to provide points of reference for the reader. Alternatively, the numerical values can be classed into exclusive bins which contain a specific range of values (e.g., 1 – 9, 10 – 19, and 20 – 29) and are represented by a unique colour. All values that fall together within a certain bin, or colour, are equally representative of that category. Applying different data classifications can yield markedly different patterns on the map, and can also influence how readers interpret the data (Robinson et al. 1995, Monmonier 1996, Brewer and Pickle 2002).

Map content is another important property which can influence interpretation of thematic maps (Monmonier 1996, Dent et al. 2009). Background content, such as boundaries, rivers, and landforms, are provided as points of reference for the reader, and are essential for users to be able to orient themselves with the data. Haynes et al. (2007) and Nave et al. (2010) found that selection of background content can have a significant influence on how well readers understand volcanic hazard maps, particularly among local populations living proximal to the volcano. The representation of thematic feature content also has an impact on how readers interpret the map. Probabilistic hazard datasets are typically quite robust in that they often include a range of data types (e.g. volcanic ash thickness, ash grain size) at multiple levels of uncertainty (e.g., 90th percentile, average) over a number of different time frames (e.g., in the event of an eruption, in the next 10 years). For example, some probabilistic volcanic hazard map toolsets are currently being designed to output two types of mappable content: a distribution of the probabilities of reaching and exceeding a fixed hazard intensity threshold (e.g., 10 mm of ash), or a distribution of hazard intensities expected at a fixed probability threshold (e.g., 25%) over any user-defined timeframe (Tonini et al. in review) (Appendix C). Certain types of hazard information may have different meanings and salience to different types of map users.

Influencing more than just aesthetics, colour is a map property that has the power to provide visual contrast, unify elements, and guide attention of the map reader (Robinson 1967, Wolfe and Horowitz 2004). Blends of colour hue, saturation, and lightness can be manipulated to create a broad range of appropriate and logical colour schemes for maps. However, colour schemes also have a high margin for confusion (Brewer 1994, Robinson et al. 1995, Olson and Brewer 1997). Colours are inherently imbued with meanings for the map reader (Robinson 1967, Bertin 1983, Brewer 1994, Dent et al. 2009). While many volcanic hazard maps employ a Western green – yellow – red “stoplight” colour scheme, or a blue – yellow – red “cold to hot” colour scheme, these may have certain unintended meanings for the map reader (Monmonier 1996). For example, red may be associated with “hot” or “bad” and green with “vegetation” or
“good.” A green – red diverging colour scheme is also likely to be very difficult to perceive for a colour blind user (Olson and Brewer 1997, Jenny and Kelso 2007, Brewer et al. 2013). Approximately 8% of males and 0.5% of females have some form of colour-vision deficiency (AOA 2014) and this can cause complications if not taken into consideration in map colour scheme design (Olson and Brewer 1997, Jenny and Kelso 2007). Although map makers strive for the highest degree of objectivity in designing probabilistic hazard maps, these fundamental choices for colour scheme, content type, and data classification are largely driven by the subjective preference. Currently, there are few recommendations available for choosing appropriate styles, as the impact of these choices has not previously been tested with volcanic hazard map users.

Volcanic hazard maps have a wide range of applications and uses, and accordingly, they have many different types of users. In New Zealand, some important hazard map stakeholders are in local and regional government, health, education, agriculture, aviation, communications, emergency management, and other groups which may use volcanic hazard information to make decisions regarding national, institutional, or local risk reduction. The detailed quantitative nature of probabilistic volcanic hazard information is well suited for organisational stakeholder decision-making, and could enhance the structure, performance, and reliability of decision-making strategies (Woo 2008, 2009; Marzocchi et al. 2012). Although each stakeholder will have different perspectives and informational needs, resource and time constraints make it impractical to develop unique hazard maps for each user group, particularly in a time of volcanic crisis (Leonard et al. 2014). It is therefore important to investigate how hazards maps can be designed to maintain a wide degree of relevance, legibility, and applicability among a diverse group of organisational stakeholders. In order to do this, stakeholder perspectives and opinions must be taken into account, as studies show that differences exist in the way that scientists (typically the hazard map makers) and other stakeholders, such as emergency managers, understand and use probabilistic volcanic hazard information (Doyle et al. 2011, 2014). Emergency managers are a particularly important group of hazard map users in New Zealand, as they are responsible for managing many short- and long-term natural hazard and risk reduction decisions which directly affect populations at risk (MCDEM 2002).

We emphasise that people at risk are also very important stakeholders in probabilistic volcanic hazard maps and in the decisions made using the maps, but acknowledge that a survey of those at risk is outside of the scope of this study. We also acknowledge that the New Zealand stakeholder community is a generally well-educated populace, and typically has a good grasp of the concept of volcanic hazard due to regular engagement with the science community. Exploring probabilistic volcanic hazard map perception in other cultural, volcanic, and socio-economic settings both within in New Zealand and internationally, is an important area for further research.
5.3 METHODS

A pragmatic mixed-methods approach was adopted (Morgan 2007), where qualitative semi-structured in-person interviews were implemented as a pilot study to test ideas and questions which informed the development of a qualitative and quantitative online survey exploring the influence of probabilistic volcanic hazard map design properties on understanding and communicating hazard. Inductive thematic analysis of semi-structured interviews was used to identify themes regarding how scientists and stakeholders felt about certain map design properties and how they engaged with the hazard maps. Design properties which emerged as themes which have a sensitive or powerful impact on interpretation of the hazard maps were explored further in the survey among a broader sample group. Both methodological components of this study were individually approved by a human participation ethics committee (see Appendix A).

It was emphasised to participants that the data on the maps was hypothetical, and all participants were reminded that the maps seen were not to be referred to for any type of decision-making. The datasets used were in raster format and represented the probability of accumulating a certain thickness of volcanic ash in the event of a rhyolite eruption from Tarawera volcano in New Zealand’s North Island. Datasets were based on actual ash hazard analyses done by Thompson et al. (in review) (Chapter 3). Tarawera volcano is a well-known active volcanic complex in New Zealand, and has had two very large explosive eruptions in the past 1ka (Walker et al. 1984, Nairn et al. 2001). Ash fall hazard was chosen because it is one of the most common products of volcanic activity worldwide, and it is a widespread, disruptive hazard that can impact society on many different spatial, temporal, and socio-economic scales (Blong 1984). Ash fall is also a volcanic hazard that is commonly analysed using a probabilistic approach because of the need to consider variable atmospheric conditions (e.g., Scollo et al. 2008, Folch 2012). New Zealand regularly experiences small scale (~1 – 2 mm) volcanic ash fall from its most frequently active volcanoes, with the most recent incidence of minor ash fall occurring in 2013 (Scott and Potter 2014).

5.3.1 Interviews

A one-on-one semi-structured interview format was used, in which a flexible framework of questions was built around discussion of six maps which were designed to foster discussion of the participant’s views on map data classification, colour scheme, content, key expression, and usefulness (Fig 5.1). Interviews lasted an average duration of 40 minutes. The same probabilistic hazard dataset, showing the probability of accumulating ≥10 mm of ash, was used for all maps (except one), so that only changing map design properties, and not changing data, influenced responses. All maps depicted hazard only for the administrative region in which Tarawera volcano is located, and were viewed at 315 × 275 mm size.
Figure 5.1 Maps used in the in-person interviews. Maps A – D were presented for discussion of data classification types: A) gradational shaded (minimum-maximum stretch), B) isarithmic with solid isopleths (5% labelled intervals), C) isarithmic with dashed isopleths (5% labelled intervals), and D) binned (10% intervals). Map E shows probabilistic hazard data displayed in a blue-yellow-red diverging colour scheme, and map F showed a deterministic scenario hazard map (the only map to use a different dataset). Data were cut to a geopolitical regional boundary. Maps were viewed at 315 × 275 mm size.

Four of the maps showed the hazard data displayed using different data classification styles: gradational shaded (minimum-maximum stretch), isarithmic with solid isopleths (5% labelled intervals), isarithmic with dashed isopleths (5% labelled intervals), and binned (10% intervals). These maps were displayed using a red-yellow multi-hue sequential colour scheme similar to that used commonly in volcanic hazard maps worldwide. The fifth map displayed the data using a blue-yellow-red multi-hue diverging colour scheme similar to that used in other types of hazard maps worldwide (e.g., flooding), and the sixth map showed a deterministic scenario hazard map based on a single pre-determined eruption scenario (i.e., one wind condition and one set of eruptive parameters). A series of cards depicting numerical expressions of percent (10%), natural frequency (1 in 10), and decimal probability (0.1) and verbal expressions of “probability,” “likelihood,” and “chance” were also presented for discussion.

Participants were recruited by e-mailing informational flyers to regional and district councils near Tarawera volcano and to the national geological research institute (GNS Science), with encouragement to circulate the information among colleagues, affiliates, and peers who would be interested in participating. Initial contact was made by interested persons contacting the researchers with an expression of interest. A total of 14 people participated in the interviews, including four volcano scientists with specialties in
Figure 5.2 Map images used in the survey (Table 5.1, Questions 6-13) showing three different probabilistic hazard data classification styles: A) gradational shaded, B) binned, and C) isarithmic. Blue outline shows the urban area of Whakatane for reference purposes here only. In the survey, Whakatane and other areas appeared outlined in grey with grey striped fill underneath the transparent hazard overlay (not clearly visible at reduced size printed here). Seventeen urban areas, main highways, large lakes, and a greyscale digital elevation model underlie the transparent hazard layer as background features. Black triangle shows area of Tarawera volcano. Maps were viewed at 800 × 710 pixels.
volcano geophysics, monitoring, and hazard analysis, and ten stakeholders with specialties in emergency management, planning, infrastructure and resource management, and public health.

Full transcripts of the semi-structured interviews were analysed using inductive thematic analysis at the semantic level, based on the framework outlined by Braun and Clarke (2006). The transcripts were analysed in order to identify emergent themes regarding how map properties such as data classification, colour scheme, key expression, and content influenced the way the participant thought about or interpreted...
Figure 5.5 Maps used in the survey (Table 5.1, Questions 23-25) showing three different map colour schemes: A) red-yellow sequential, B) blue-yellow sequential, and C) blue-yellow-red diverging. Maps were presented in both gradational shaded (left) and binned (right) data classification format simultaneously so that participants could visualize the colour schemes on different styles of map. Maps were viewed at 584 × 518 pixels.
the map and its usefulness.

5.3.2 Survey

The online survey comprised 16 pages of 31 questions designed to measure participant views on data classification (Fig 5.2), map content (Fig 5.3), key expression, hazard curves (Fig 5.4), map colour scheme (Fig 5.5), explanatory text (Fig 5.6), and map format. These topics were chosen based on their assumed relevance from results of the interviews, literature review, and the prominence of these properties recognised in existing natural hazard maps. The survey is summarised in Table 5.1. The survey was based on participants viewing eight different hazard maps styles (Fig 5.2, 5.3, 5.5) and two hazard curve styles (Fig 5.4), and responding to questions about them. The results of the interviews informed some of the design features used in the survey maps. Seven of the maps showed the exact same probabilistic hazard data, the probability of accumulating ≥1 mm of ash, so that only changing map design properties, and not changing data, influenced responses. The remaining map used the same dataset, but showed a probability threshold (i.e., 25% probability), instead of an ash threshold (i.e., ≥1 mm ash). All maps were displayed at 150 ppi with a size of 800×710 pixels (except for colour scheme maps, shown at 584×518 pixels) and were designed with colour blind-safe 8-bit RGB colour schemes retrieved from the Color Brewer tool (www.colorbrewer2.org, Brewer et al. 2013). Color Brewer is a free, online, research-backed (Brewer 1994, 1996; Harrower and Brewer 2003) tool which provides many colour schemes specifically designed to suit a variety of display environments (e.g., screen or print) and be colour blind accessible. Participants accessed the free online survey using a custom one-time-use URL. The survey was open for participation for 41 days. Average time for completion was 25 minutes. A copy of the survey can be found in Appendix B.

Participants were recruited using a standard snowball sampling methodology. E-mails were sent by the researchers to approximately 50 organisations with a request that the information advertising the survey be circulated to any persons who may use, be interested in, or be involved in the production and

**Volcanic Ash Hazard**

*Based on the event of an eruption at Tarawera*

**Tarawera volcano**

Tarawera volcano has experienced at least five large, explosive rhyolite eruptions over its 25,000 year history, with the last one occurring just 700 years ago. A rhyolite eruption could occur at Tarawera again some time in the future. One of the most widespread hazards of rhyolite eruptions is ash fall. Ash fall is considered a very disruptive hazard, but is unlikely to threaten lives.

**Probabilistic hazard**

This map shows the average probability of accumulating 1 mm of ash if a rhyolite eruption were to occur. The values are based on 1,000 computerised simulations of possible eruption scenarios. In the event of an eruption, actual ash fall out would be dependent on wind conditions present at the time of the eruption.

**Figure 5.6** Explanatory text provided at the top of one of the maps in the survey (Table 5.1, Questions 26-27)
editing of, volcanic hazard maps in New Zealand. The e-mail encouraged interested persons to share the survey link with colleagues or associates that they thought may also be interested. All interview participants were also directly invited to participate in the survey. The survey drew 110 participants from a variety of different occupational disciplines, with 29.1% of respondents in the scientist group, and 70.9% in the stakeholder group (including 26.4% in emergency management and planning) (Table 5.2). The majority of participants (88.1%) ranged between 25 and 64 years of age, and 88.2% held an undergraduate or postgraduate/graduate degree (Table 5.3).

Descriptive and inferential statistical analyses of survey results were performed using IBM SPSS predictive analytics software. Responses to this survey generated primarily non-parametric nominal (i.e., categorical) data, and chi-square tests were used to identify the existence of significant differences within and among samples. Text responses to open-ended survey questions were qualitatively analysed using inductive thematic analysis at the semantic level to identify key patterns and themes.

5.4 RESULTS

5.4.1 Interviews

5.4.1.1 Map data classification

Clarity/ease of reading, precision/uncertainty, and aesthetics emerged as the three primary themes in participants’ discussion of map data classification. The ease with which participants were personally able to read data from the map was a motivator for map preference, but participants also expressed consideration of how easy it would be to use the map to communicate with peers and the public:

> It’s more than just communicating it [the map] to fellow scientists, or fellow emergency managers, or engineers, or whatever. It’s also how do you communicate that further down to, to members of the public. – Stakeholder 5

The isarithmic maps (Fig 5.1B, C) were well-liked and were viewed as accurately portraying the realistic nature of the volcanic ash hazard, while also being easy to read with a high degree of precision:

> The advantage is you can still quite easily see the gradational nature of the probability, but at the same time you can read off the actual percentage if you feel you need to read that off. – Scientist 4

No relationship was observed between dashed (Fig 5.1C) and solid isopleths (Fig 5.1B) and interpretation of hazard information. However, the black isopleths and labels across the map were viewed as busy and distracting, detracting from the aesthetic appeal of the map. Participants overall recommended smoothing of the isopleths, citing that straight lines and right angles resulting from the square grid used in the model were visually unappealing and could falsely imply certainty. Participants also viewed the 5% intervals on the isopleths (Fig 5.1B, C) as misleadingly precise, and instead preferred the 10% intervals used in the binned map (Fig 5.1D).
### Table 5.1 Summary of questions asked in online survey. See Appendix B for full survey.

<table>
<thead>
<tr>
<th>Question</th>
<th>Topic</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Understanding of voluntary consent</td>
<td>MC</td>
</tr>
<tr>
<td>2</td>
<td>Understanding of access to summary of study findings</td>
<td>MC</td>
</tr>
<tr>
<td>3</td>
<td>Primary field of work</td>
<td>MC*</td>
</tr>
<tr>
<td>4</td>
<td>Experience/memories of volcanoes</td>
<td>MC*</td>
</tr>
<tr>
<td>5</td>
<td>Importance of volcanic hazard maps</td>
<td>MCL</td>
</tr>
<tr>
<td>6</td>
<td>Read hazard from gradational shaded map</td>
<td>Txt</td>
</tr>
<tr>
<td>7</td>
<td>Qualitative hazard from gradational shaded map</td>
<td>MCL</td>
</tr>
<tr>
<td>8</td>
<td>Read hazard from binned map</td>
<td>Txt</td>
</tr>
<tr>
<td>9</td>
<td>Qualitative hazard from binned map</td>
<td>MCL</td>
</tr>
<tr>
<td>10</td>
<td>Read hazard from isarithmic map</td>
<td>Txt</td>
</tr>
<tr>
<td>11</td>
<td>Qualitative hazard from isarithmic map</td>
<td>MCL</td>
</tr>
<tr>
<td>12</td>
<td>Order data classification style maps preference</td>
<td>DD</td>
</tr>
<tr>
<td>13</td>
<td>Explain data classification style maps preference</td>
<td>Txt</td>
</tr>
<tr>
<td>14</td>
<td>Helpfulness of fixed ash/probability threshold maps</td>
<td>MCL</td>
</tr>
<tr>
<td>15</td>
<td>Preferred map to receive of fixed ash/probability threshold maps</td>
<td>MC</td>
</tr>
<tr>
<td>16</td>
<td>Preferred key text</td>
<td>MC</td>
</tr>
<tr>
<td>17</td>
<td>Influence of key text on perceived level of hazard</td>
<td>MC*</td>
</tr>
<tr>
<td>18</td>
<td>Read hazard curve with percentile lines</td>
<td>MC</td>
</tr>
<tr>
<td>19</td>
<td>Ease/difficulty of reading hazard curve with percentile lines</td>
<td>MCL</td>
</tr>
<tr>
<td>20</td>
<td>Read hazard curve with confidence interval area</td>
<td>MC</td>
</tr>
<tr>
<td>21</td>
<td>Ease/difficulty of reading hazard curve with confidence area</td>
<td>MCL</td>
</tr>
<tr>
<td>22</td>
<td>Rank helpfulness of hazard curves being available with map</td>
<td>MCL</td>
</tr>
<tr>
<td>23</td>
<td>Preferred colour scheme set of maps</td>
<td>MC</td>
</tr>
<tr>
<td>24</td>
<td>Explain reason for colour scheme preference</td>
<td>Txt</td>
</tr>
<tr>
<td>25</td>
<td>Influence of colour scheme on hazard perception</td>
<td>MCL*</td>
</tr>
<tr>
<td>26</td>
<td>Helpfulness of explanatory text to understanding map</td>
<td>MCL*</td>
</tr>
<tr>
<td>27</td>
<td>Importance of explanatory text on map</td>
<td>MCL*</td>
</tr>
<tr>
<td>28</td>
<td>Desired format for receiving volcanic hazard maps</td>
<td>MC*</td>
</tr>
<tr>
<td>29</td>
<td>Age bracket</td>
<td>MC</td>
</tr>
<tr>
<td>30</td>
<td>Ethnicity</td>
<td>MC</td>
</tr>
<tr>
<td>31</td>
<td>Highest level of education</td>
<td>MC</td>
</tr>
</tbody>
</table>

* Optional comments text box provided
* Can select more than one answer
MC Multiple choice
MCL Multiple choice Likert scale
Txt Text
DD Drag-and-drop
The binned map was also well-liked among participants, who viewed it as easy to read and visually appealing. Stakeholder participants also expressed that the binned map allowed for interpreting the map with more certainty, viewing binned zones as "more definitive." Stakeholders also expressed the bins as a useful tool for visualising zones:

Although there’s defined areas between them [bins], it’s kind of useful in terms of a planning aspect that you’ve got some boundaries to work on. – Stakeholder 6

However, both scientists and stakeholders expressed that the boundaries between classes on the binned map (Fig 5.1D) could present a disadvantage if they were interpreted as non-gradational or "step-wise":

Except, when you put a boundary on it, then people probably think if they’re on one side of the boundary or the other there’s a huge difference in probability when there isn’t. – Scientist 3

The background content was generally well liked, and viewed as helpful for orientation and location tasks, without cluttering the map. In contrast, geopolitical boundary limits on the data were not liked. Participants suggested that the boundary made the hazard appear to “stop” artificially. Participants also emphasized that managing and responding to hazards is a collaborative process that crosses boundaries, and that uncertainties or unknowns for the hazard in the surrounding regions introduced potential issues for interpretation and application.

### 5.4.1.2 Map colour scheme

Colour associations, zoning, and response emerged as the three primary themes in participants’
dialogue concerning map colour scheme. Overall, participants associated red hues with a presence of hazard and blue hues with an absence of hazard. This became particularly important in low probability areas, which would be considered as “safe” if seen in the blue-yellow-red diverging map (Fig 5.1E), but would still be considered as having a potential to be impacted on the red-yellow sequential map (Fig 5.1A-D):

My first impression of that [diverging map] is, blue would be safe. Whereas, where this [blue area] is yellow in the other maps, it implies there is some sort of risk that we need to consider. – Stakeholder 2

These associations were described by participants as “subliminal,” “genetic,” and “psychological.” The contrast between hues in the diverging map (Fig 5.1E) was seen as making the hazard appear smaller, as a localised zone, and was discussed as facilitating distinction between impacted zones in the context of targeting response attention:

It makes it very clear, ‘that’s the area we’re worried about. We’re not worried about anything else around the district’. – Stakeholder 7

Stakeholders also observed that the diverging colour scheme appeared very similar to other natural hazard maps that they had experience with:

Automatically [I] relate that to weather maps… and just to complicate matters worse, we’re also doing flooding maps, and the models that we use are based very much on the same colour format. So I would look at that straight away and think, ‘Oh, it’s a flood map.’…because you see the blue. – Stakeholder 8

This was the only significant difference observed between scientists and stakeholders in the interviews. The potential difficulty in reading maps due to colour blindness was raised as an issue by several participants.

5.4.1.3 Map key expression

Trust and familiarity emerged as two themes in discussion of key expression. Overall, participants viewed the verbal expressions “probability” and “likelihood” as very similar. However, “probability” was considered by stakeholders to sound more reliable, scientific, and trustworthy, and in that context, it was also interpreted as a more definitive way of expressing the hazard:

Depends on how accurate you want to be. Probability means yes, definitely it is 10% probable. Whereas 10% likelihood [means] well it might, it might not. – Stakeholder 9

“Chance” was perceived as untrustworthy, and akin to “slang,” invoking associations with gambling and horse-racing. Percentages (e.g., 10%) were overall the most preferred numerical expression, with participants explaining that they are a commonly used format in many different walks of life. However, some participants noted that natural frequencies (e.g., 1 in 10) were easier for people to get a “feeling” or gist for the value. Decimal values (e.g., 0.1) were universally considered as unfamiliar and too difficult for
most people to understand. Many participants also commented that the gradational shaded key symbology was difficult to read with only three percent values marked (min., med., and max.).

5.4.1.4 Map content

Participants viewed the probabilistic maps (Fig 5.1A-E) as long-term planning and reference tools, and as preparedness tools to use in the event of an impending crises before more detailed deterministic-style maps (e.g., Figure 5.1F or an ash advisory bulletin) were available. Participants also expressed that 10 mm was a high threshold in terms of useful application of the map. Most participants expressed that their primary concern would be the possibility of acquiring any ash at all, explaining that a hazard threshold even as low as 1 to 2 mm thickness would have very important impacts that they would need to consider:

Any ash to me is the worst case scenario. - Stakeholder 3

Similarly, some participants expressed that probabilistic data for low ash thresholds was helpful supportive content:

I think the probability is more important than the thickness because [of] the way people work. It’s, ‘Will I get ash?’ Not, ‘How much will I get?’ …They’re not sort of thinking ‘We can do this with 10 millimetres, we can’t do this with 100.’ It’s kind of ‘Oh, ok, we have to deal with volcanic ash.’ Saying that there’s a 30 or 40 percent chance…drives home a pretty strong message that they’ve got to deal with it. – Scientist 2

Many participants also suggested that addition of text explaining the possible impacts of the ash thickness would make the map more relevant and useful. It was advised that the text be placed directly onto the map face, explaining that it could easily be misplaced, truncated, or disregarded if supplied separately.

5.4.1.5 Revisions to maps for survey

The results of the pilot study interviews which were based on the six maps in Figure 5.1 informed some revisions to the maps in order to better meet user preferences and needs, resulting in the eight map styles explored in the survey (Fig 5.2, 5.3, 5.5):

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**Table 5.3 Participant demographics**

<table>
<thead>
<tr>
<th>Age bracket Group</th>
<th>Percent (%)</th>
<th>Ethnicity Group</th>
<th>Percent (%)</th>
<th>Highest level of education Group</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-24</td>
<td>4.0</td>
<td>NZ European</td>
<td>60.4</td>
<td>Did not complete high school</td>
<td>0.0</td>
</tr>
<tr>
<td>25-44</td>
<td>51.5</td>
<td>NZ Maori</td>
<td>3.0</td>
<td>High School/GED</td>
<td>4.0</td>
</tr>
<tr>
<td>45-64</td>
<td>36.6</td>
<td>Other European</td>
<td>27.7</td>
<td>Vocational/Trade qualification</td>
<td>6.9</td>
</tr>
<tr>
<td>65+</td>
<td>5.0</td>
<td>Asian</td>
<td>0.0</td>
<td>Tertiary/University degree</td>
<td>22.8</td>
</tr>
<tr>
<td>Prefer not to answer</td>
<td>3.0</td>
<td>Pacific</td>
<td>0.0</td>
<td>Postgraduate/Graduate degree</td>
<td>65.4</td>
</tr>
<tr>
<td>Other</td>
<td>6.9</td>
<td>Prefer not to answer</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefer not to answer</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Geopolitical boundary constraint on hazard data removed (Fig 5.2)
• Colour blind accessible colours were adopted
• 10% bins and isopleth intervals were adopted (instead of 5%)
• More intervals were labelled on the gradational stretch symbology in the key
• White contour lines were used instead of black (to reduce map noise)
• Isopleths were smoothed to remove the jagged artefact of the modelling grid
• ≥1 mm of ash was displayed instead of ≥10 mm of ash.

5.4.2 Survey

Out of the 110 respondents, seven participants did not fully complete the survey. Results for questions with missing values were measured using only the number of completed responses (min. 103). Results are reported for the 5% significance level (95% confidence), where \( \chi^2 \) is the chi-square value for a goodness-of-fit chi-square test (one sample), Pearson \( \chi^2 \) is the chi-square value for a Pearson chi-square test of independence (two or more samples), df is the degrees of freedom, and \( \alpha \) is the level of significance.

In response to a question about whether they had ever experienced volcanic activity or had any memories associated with volcanic activity (Table 5.1, Question 4), 68.8% of participants responded “yes.” Of those, 64.0% described specific volcanic activity in New Zealand. When asked to rank their opinion about how important it is to have a volcanic hazard map for the potentially active volcanoes in New Zealand on a 5-point Likert scale (Table 5.1, Question 5), 99.1% of respondents expressed that it was important to some degree, with 73.4% ranking it “very important.”

5.4.2.1 Map data classification

Results for questions about data classification (Table 5.1, Question 6-13, Fig 5.2) are shown in Figure 5.7A-D. When reading probabilistic hazard for the 78 km\(^2\) urban area of Whakatane, respondents were more likely to give a range of values (e.g., 40-45%) as opposed to a single value (e.g., 40%) when using the binned data classification map (Fig 5.2B) \( (\chi^2=114.919, \text{df} = 1, \alpha<0.001) \) or the isarithmic map (Fig 5.2C) \( (\chi^2=117.237, \text{df} = 1, \alpha<0.001) \) (Fig 5.7A). In contrast, respondents were equally likely to give either a range of values or a single value when using the gradational shaded map (Fig 5.2A) \( (\chi^2=0.092, \text{df} = 1, \alpha=0.762) \) (Fig 5.7A). Of those who responded with a range, more participants (17.9%) reported a 5% interval range when using the isarithmic map (Fig 5.2C) than for any other data classification map style. Ten percent ranges were the most commonly estimated range interval for all data classification types. The actual hazard values for Whakatane ranged between approximately 40 – 45%. When reading hazard from
the isarithmic map (Fig 5.2C), respondents were more likely to estimate a single or range of values within 40 – 45% (very accurate) or 35 – 45% (generally accurate) than when using the other two maps (Fig 5.7B). When using the gradational shaded map (Fig 5.2A), respondents were more likely to under- or over-estimate the hazard value (Fig 5.7B).

More than half of respondents interpreted the qualitative level of hazard as “medium” regardless of map data classification style used (Fig 5.7C). The level of qualitative hazard interpreted from each map did not change for 71.8% of respondents who chose only one hazard level for all three maps. Scientists were more likely to show a change in the level of qualitative hazard interpreted from the different maps
than stakeholders (Pearson $\chi^2 = 7.987$, df = 2, $\alpha = 0.018$), with 40.0% of scientists choosing two hazard levels among the three maps, and 3.3% choosing three, and 25.0%, and 0.0% of stakeholders choosing two and three levels of hazard, respectively.

The isarithmic data classification map (Fig 5.2C) was ranked as the most preferred map choice, and the gradational shaded map (Fig 5.2A) was ranked the least preferred (Fig 5.7D). There was no difference in the preferences of scientists and stakeholders, with 37.5% of both scientists and stakeholders preferring the binned data classification map (Fig 5.2B), and 62.5% preferring the isarithmic (Fig 5.2C) (Pearson $\chi^2 = 0.000$, df = 1, $\alpha = 1.000$). Respondents wrote an average of 30 words in response to an open-ended text question about map data classification style preference. Three main themes emerged concerning the influence of map data classification style on respondent’s interpretation of the hazard map: clarity/ease of reading, precision/uncertainty, and realistic hazard representation. Many respondents stated that the presence of gradational shading (Fig 5.2A, C) was favourable because it represented the gradational nature of ash fall hazard more realistically:

* Clearest because it shows that the hazard is gradational, steadily decreasing away from the source. – Scientist 30

Similarly, the binned map (Fig 5.2B) was seen by many users to be an unrealistic portrayal of ash hazard:

* The [actual] change is gradational, so [the binned map] is too stepwise. Gives the wrong impression. – Stakeholder 54

However, using gradational shading only (i.e., without isopleths) (Fig 5.2A) was overall seen as requiring too much effort to read with any degree of precision. When labelled probability isopleths were included on the gradational shaded map, many participants found the resulting isarithmic map (Fig 5.2C) much easier to read with a higher degree of precision:

* [It is] instantly obvious which range of values an area falls within, plus you can see where in the range it falls, so you can get quite a precise value just by quickly looking at the map. – Stakeholder 87

Less reliance on the key symbology was also seen as increasing precision:

* The labels indicating the probability band removes any confusion associated with the colour symbology. – Scientist 104

### 5.4.2.2 Map content

Results for questions about map content (Table 5.1, Question 14-15, Figure 5.3) are shown in Figure 5.8A-B. Both types of map content investigated (Fig 5.3) were viewed as helpful to some degree by the majority of respondents, with 95.2% of respondents ranking the fixed ash threshold map (Fig 5.3A), and 89.4% ranking fixed probability threshold map (Fig 5.3B), as very helpful, helpful, or somewhat helpful (Fig 5.8). Among the 97.2% of respondents who chose a preference, no statistically significant difference exists between preference for receiving a map with content describing a fixed ash threshold, a fixed...
probability threshold, or one of each \( (\chi^2=1.529, \text{df} = 2, \alpha=0.465) \). There was no statistically significant difference in the preferences of scientists and stakeholders \( (\text{Pearson } \chi^2=2.111, \text{df} = 2, \alpha=0.348) \).

5.4.2.3 Map key expression

Results for questions about key expression (Table 5.1, Question 16-17) are shown in Figure 5.9. When presented with three different combinations of verbal and numerical phrases of probabilistic hazard in the map key, 73.4% of respondents said the phrases used did not change the level of hazard they

![Map content helpfulness](image)

**Figure 5.8** Respondents’ preference and perceived helpfulness of two different types of map content: maps depicting a distribution of probabilities of reaching and exceeding a fixed ash threshold, such as 10 mm (fixed ash threshold), and maps depicting a distribution of ash thicknesses expected at a fixed probability threshold, such as 25% (fixed probability threshold) (see Figure 5.3). Both types of content were viewed as helpful to some degree, and no statistically significant difference exists for preference between receiving a fixed ash threshold map, fixed probability threshold map, or one of each (see text for Pearson’s chi-square test values).

![Preferred map content](image)

**Figure 5.9** Map key expression preference. More than half of respondents preferred the map key which expressed the hazard as both a percent (25%) “probability,” as well as a natural frequency (1 in 4) “likelihood.”
interpreted from the map. However 14.6% of respondents thought that the natural frequency expression (1 in 4) made the hazard seem greater than the percentage (25%). Despite the majority of respondents saying that the key had no influence on hazard perception, 93.2% of respondents chose a preferred key expression (Fig 5.9). More than half of respondents preferred having both a percent “probability” and natural frequency “likelihood” expressed in the key. The second most preferred key expression was a percent probability. Of the 22.3% of respondents who entered text as optional commentary, many described the key with a natural frequency “likelihood” expression only as “amateurish,” “subjective,” and “awkward,” with one respondent citing that “likelihood” has a different and specific meaning in their field of work. Percent probability was generally described as a common, familiar expression that was readily understood by both professionals and the public. Some respondents suggested that providing the natural frequency likelihood alongside a percent probability may help the message be received by a larger audience. No significant difference existed in the key expression preference of scientists and stakeholders (Pearson $\chi^2=0.892, \text{df} = 3, \alpha=0.892$).

5.4.2.4 Hazard curves

Results for questions about hazard curves (Table 5.1, Question 18-22, Figure 5.4) are shown in Figure 5.10A-B. When ranking how helpful it would be to be provided with hazard curves for chosen locations on the map, 55.4% of respondents said the curves were very helpful, helpful, or somewhat helpful. However, scientists found the hazard curves significantly more helpful than stakeholders, with 73.3% of scientists ranking the curves as helpful to some degree, but only 48.1% of stakeholders (Pearson $\chi^2=0.892, \text{df} = 3, \alpha=0.892$).

![Graph A: Response variation in reading hazard curves](image)

![Graph B: Ease/Difficulty of reading hazard curves](image)

**Figure 5.10** Responses based on separate questions in which respondents used a hazard curve for a point in the urban area of Whakatane drawn with average probability, 10th, and 90th percentile lines, and then with average probability and an 80% confidence area (see Figure 5.4). Graph A shows the frequency at which six possible responses were chosen using each hazard curve for a question which required the respondent to read information from the curve and choose which statement was the most true. Response option four is the most correct answer. Graph B shows the level of ease/difficulty respondents reported for reading information from each hazard curve.
\( \chi^2 = 6.324, df = 2, \alpha = 0.042 \). Nine percent of stakeholders were not sure about the helpfulness. Performance in reading a hazard curve for Whakatane improved significantly when respondents used the hazard curve with the 80% confidence area (Fig 5.4B), with 70.3% of respondents choosing the most correct answer, compared to 12.6% when using the hazard curve with 10th and 90th percentile lines (Fig 5.4A, Fig 5.10A). More than 46% of respondents chose a response option in which the 10th percentile was incorrectly described as 10% confidence when using the hazard curve with 10th and 90th percentile lines (Fig 5.4A), compared to just 7.9% when using the hazard curve with 80% confidence area (Fig 5.4B) (response option 2, Figure 5.10A). In describing the ease/difficulty of reading the two hazard curves, 71.9% of respondents found the curve with 10th and 90th percentiles difficult or very difficult to read, and 26.2% found it average, easy, or very easy, compared to 41.6% and 57.4% of respondents for the 80% confidence area curve, respectively (Fig 5.10B).

5.4.2.5 Map colour scheme

Results for questions about colour scheme (Table 5.1, Question 23-25, Figure 5.5) are shown in Figure 5.11A-B and Figure 5.12A-C. For more than 67% of respondents, colour scheme had an effect on how they perceived the level of hazard (\( \chi^2 = 14.957, df = 2, \alpha = 0.001 \)) (Fig 5.11A). The blue-yellow-red diverging colour scheme (“diverging”) (Fig 5.5C) and red-yellow sequential colour scheme (“red”) (Fig 5.5A) were the most preferred colour schemes (Fig 5.5, 5.11B). Among the top two preferred colour schemes, chosen by 89.1% of respondents, the red map (Fig 5.5A) was preferred by a majority 59.3% of scientists, and the diverging map (Fig 5.5C) was preferred by a majority 64.3% of stakeholders (Pearson \( \chi^2 = 5.072, df = 1, \alpha = 0.024 \)).

Figure 5.11

Responses pertaining to A) the degree to which map colour scheme influences hazard perception, and B) preference between blue-yellow sequential (blue), red-yellow sequential (red) and blue-yellow-red diverging (diverging) colour schemes on probabilistic volcanic hazard maps (see Figure 5.5). The majority of respondents (67.3%) agreed that colour scheme influenced their perception of hazard, with diverging and red being the two most preferred colour schemes.
Respondents wrote an average of 16 words when explaining their map colour scheme preference. Four main themes emerged concerning the influence of colour scheme: colour associations, cultural/social/mental connotations, zoning, and risk and response. Figure 5.12 highlights the words most frequently used by respondents in discussion of each colour scheme. Red hues were associated with concepts of danger, the presence of hazard, and volcanoes (Fig 5.12A). In contrast, blue hues were associated with concepts of safety, the absence of hazard, and water (Fig 5.12B):

- Red always denotes hazard to me. – Stakeholder 89
- The blue looks negative rather than low. The colour blue is usually associated with water. – Stakeholder 57

Many respondents remarked that the colour associations were evoked by cultural, social, or psychological connotations. Respondents used words such as “intuitively,” “universally,” “subliminal,” “socialised,” “logical,” and “used worldwide,” to describe the reasons for their strong associations with the colours red and blue. The associations with red and blue colours were consistent for both diverging and sequential colour schemes:

- [The divergent map] give the impression of safety [in the blue areas] and emphasizes danger in the red areas. [The red map] gives the impression of
increasing danger closer to the volcano. – Scientist 99

Red-blue seems to imply hazard and non-hazard, instead of hazard and less hazard. – Stakeholder 58

When describing the diverging colour scheme map, many respondents explained that they liked that the contrast made it much easier to “distinguish” and “delineate” the map into discrete “zones” (Fig 5.12C). However, the zones of colour had different context for different users. While responses describing the red map primarily focused on describing the map in the context of hazard, there was a marked increase in discussion of “risk” with the diverging colour scheme map among stakeholders (Fig 5.2B, C):

The blue de-emphasises lower likelihood areas allowing for a more risk-based focus. – Stakeholder 46

In some cases, the area of transition for the divergent colours was explicitly linked to response action:

The transition between hot and cold colours should be carefully set at a standard point, as anywhere in cold colours is unlikely to receive attention when planning in government departments is carried out. – Stakeholder 91

5.4.2.6 Map explanatory text and map format

In responding to questions about explanatory text (Table 5.1, Question 26-27, Figure 5.6), 94.1% of respondents said that providing informative text about the volcano, probabilistic hazard, and possible volcanic ash impacts on the map was helpful to some degree. The same proportion of respondents also viewed explanatory text on the map as important to some degree, with 50.5% ranking it “very important.” Results for questions about map format (Table 5.1, Question 28) are shown in Figure 13. The most popular format for receiving volcanic hazard maps was PDF, followed by GIS layer and JPEG (Fig 5.13). More than three-quarters of respondents (75.3%) chose more than one of the five format options provided.

5.5 DISCUSSION

5.5.1 Data classification and uncertainty

Regardless of map data classification style viewed (Fig 5.2), more than half of survey participants considered the probability of accumulating ≥1 mm of ash in Whakatane as a medium level of hazard. Few participants, and particularly few stakeholders, changed the qualitative descriptor used, even when their estimates of numerical value varied between maps, highlighting that qualitative descriptors of hazard may have less sensitivity for reflecting subtle perceived changes in hazard data. This demonstrates possible issues with relying on a broad verbal probability translation table for volcanic uncertainty, and emphasises the importance of including numerical values along with qualitative descriptors of probability as suggested by Doyle et al. (2011) and Budescu et al. (2009).

Estimates of hazard read from a probabilistic hazard map displaying only a gradational shaded
stretch of values (Fig 5.2A) were less consistent than for other data classification types (Fig 5.7A, B), which suggests that there is low reliability in the way users may read and interpret information from this style of map. The vast majority of participants also ranked the map as least preferred (Fig 5.7D) or expressed dislike, which could manifest in practice as an aversion to using and applying maps with data presented in this style. However, the addition of probability isopleths dramatically improved the favourableness and readability of gradational shaded data classification. The isarithmic map (Fig 5.2C) was the most preferred (Fig 5.7D) and most accurately-read data classification style (Fig 5.7B). Presence of isopleths also increased the frequency of reading hazard as a range of values instead of a single value (Fig 5.7C), which is a more accurate estimation of hazard for the 78 km² area of Whakatane (actual hazard ~40 – 45%, Figure 5.2). Expressing a range of values may have positive implications for practice, as Dieckmann et al. (2010) found that using a range of probabilities to express uncertain information is likely to be considered more credible and responsible in a decision-making context than use of a single value probability.

The isarithmic data classification (Fig 5.2C) also appeared to enhance the level of map engagement, by encouraging participants to critically assess the map and estimate a more precise range of probabilities. Reading the gradational shaded map (Fig 5.2A) required participants to spend increased effort, only to achieve a broad variation in accuracy and a low level of consistency in responses. Reading the binned map (Fig 5.2B) facilitated quick perception of a range of hazard with little effort, but the majority of respondents read this as “definitive” and did not elaborate beyond the 10% accuracy conveyed in the map key. When reading the isarithmic map (Fig 5.2C), participants were able to quickly and easily estimate a 10% range of hazard, and more participants opted to critically assess the shading within the 10% interval to increase the precision of their estimate to within 5% accuracy (Fig 5.7B). The non-discrete “fuzzy” appearance of gradational shading is considered an appropriate strategy to depict uncertain hazard and

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**Figure 5.13** Desired formats for receiving volcanic hazard maps. Participants could choose one or more of the five formats, GIS layer, JPEG, KML, Paper, or PDF, or write in an alternative one. More than one option was chosen by 75.3% of respondents. The format preferred most by respondents was PDF (78.2%)
risk information (MacEachren 1992, Slocum 1999), and our results suggest that adding isopleths to this style effectively improves reader ability to interpolate shading for those who seek to reduce uncertainty.

Concern about precision and uncertainty in the modelled data was a primary theme regarding data classification in both the interviews and the surveys. For example, most participants found 5% interval isopleths (Fig 5.1B, C) unfavourable because they appeared to depict “unwarranted” precision or certainty. The prominence of uncertainty and precision in discussion of the maps suggests that it is recognised as an important component of probabilistic volcanic hazard data by both scientists and stakeholders. Donovan et al. (2012) found that effective communication and acknowledgement of uncertainty among both groups was critical for achieving useful application of probabilistic volcanic hazard and risk data in decision-making during volcanic crises at Montserrat. However, uncertainty in volcanic hazard maps is not always recognised or accepted, and it is important to explore how users perceive and approach uncertainty in maps. In the context of map properties, our results indicate that depicting 10% intervals in probability may be perceived as appropriate, adequate, and accessible for visualising and processing hazard information among a diverse group of users.

As a whole, participants expressed a general understanding that there are uncertainties associated with modelled probabilistic volcanic hazard data. However, more specific concepts of uncertainty related to the nature of the probabilistic data were less clear. The concept and meanings of lower and upper percentile values were not consistently or easily understood by the majority of participants when reading from a hazard curve (Fig 5.10). A hazard curve displaying the concept of confidence (Fig 5.4B) was better understood, with more participants also finding it easier to read than the curve with percentiles (Fig 5.4A). These differences have important implications for the language and graphics we use to communicate probabilistic hazard. As probabilistic tools such as volcanic hazard curves become more integrated in volcanic hazard and risk management (e.g. Tonini et al, in review) (Appendix C) it is important to understand the contextual measures which can be implemented to improve the presentation of results and achieve clearer communication, particularly because statistical interpretation is a common challenge for many people (Reyna and Brainerd 2008).

5.5.2 Colour scheme and messages of hazard

The emergence of “risk and response” as a theme associated with the diverging colour scheme showed that the concept of hazard was also ambiguous in some cases. Volcanic hazard refers to the possible occurrence of a dangerous or destructive volcanic phenomenon, and can vary in frequency, magnitude, and spatial extent. In contrast, volcanic risk implies consideration of both the hazard and the vulnerabilities and capacities of people and communities in the areas exposed to the hazard (Fournier d’Albe 1979, UNISDR 2009). While the volcanology community agrees that scientists are responsible for
analysing and communicating hazard, the role of scientists regarding volcanic risk and response advice is more controversial, as risk-based decision-making must take into account many social, political, and economic factors (Marzocchi et al. 2012). The diverging colour scheme (Fig 5.5C) was preferred by a significantly greater proportion of stakeholders than scientists, as this group may have a greater propensity for seeking risk-related information. Our results suggest that unintended messages or connotations of risk and risk-based response may be avoided by using sequential, rather than diverging, colour schemes to illustrate hazard. Diverging hues convey messages of a changing state or phenomena (Slocum 1999), such as a safe state and a dangerous state. In contrast, adjusting lightness and saturation of incremental hues on a sequential scale conveys a message of changing intensity or degree (Slocum 1999), recognised in the participants’ perception of low, but not absent, hazard in light yellow-coloured areas on the red colour scheme map (Fig 5.5A). Sequential hue colour schemes have also been found to convey changing intensity in health risk maps (Severtson and Vatovec 2012, Severtson and Myers 2013).

The stakeholder participants’ tendency to observe “confusing” similarities between the diverging colour scheme volcanic hazard map (Fig 5.5C) and hydrological-type hazard maps highlights the fact that many stakeholders are often responsible for dealing with many different types of hazard and risk. Despite volcanic ash not being a high-temperature phenomenon, the associations of “hot” volcanoes with the red map (Fig 5.12A) suggests that using warm colour schemes may make volcanic hazard maps distinguishable for users who frequently encounter hazard and risk maps for other phenomena. Improvement in the colour contrast of the maps from the interviews to the surveys emphasizes the importance of selecting colour blind accessible colour schemes. Color Brewer (Brewer et al. 2013) was an effective and simple tool for choosing colour blind accessible map colour schemes, and filters which show how the map is likely to appear to a colour blind reader, such as those offered in Adobe Photoshop, or in the free online tool Color Oracle (www.colororacle.org, Jenny and Kelso 2007), can be helpful tools for testing preliminary colour selections on maps (Fig 5.14). Depicting value labels on the map face, instead of only in the key, may also assist participants with vision deficiencies.

5.5.3 Key expression and map trust

The verbal expression “probability” was associated with greater levels of trust than “likelihood.” This suggests that verbal expression in the key can play a role in interpretation of hazard map data, as trust is a critical factor in stakeholder engagement with uncertain hazard map data (Frewer and Salter 2007, Wachinger et al. 2013). For numerical expression, preference of percentages over natural frequencies may reflect a high level of numeracy in the sampled stakeholder group which reported high education levels. While many studies suggest natural frequencies are the most widely- and well-understood numerical expression of probabilistic information (e.g., Hoffrage et al. 2000, Lipkus 2007), others (Reyna and Brainerd 2008, Keller and Siegrist 2009, Severtson and Myers 2013) advise that the
effect of expression is dependent on reader numeracy skills. Using a combination of both percentages and natural frequencies on the key was the most favoured option by more than half of participants (Fig 5.9), and also may be the most inclusive option for reaching trust and understanding among audiences with different numeracy skills. Including natural frequency expressions may also have additional importance in the context of low probability hazard values, as users may be more likely to interpret very low probabilities as “very low hazard” when reading natural frequencies, as opposed to interpreting very low probabilities as “no hazard” when reading percentage values (Kahneman and Tversky 1979, Reyna and Brainerd 1991, Stone et al. 1994). This trend may be indicated by the ~15% of respondents who viewed the hazard as greater when presented with a natural frequency compared to a percentage.

5.5.4 Map content and map usefulness

Overall, participants showed an understanding for the gradational nature of volcanic ash hazard, acknowledging the “realistic” appearance of gradational shading, and dismissing a geopolitical constraint on hazard. These positive indications of understanding of volcanic ash hazard may be due to the high proportion of participants with memories or experiences of volcanoes. Equal preference of fixed ash threshold and fixed probability threshold maps indicates that there are audiences for both types of probabilistic volcanic hazard map content, and that offering different types of outputs is a valuable aspect of probabilistic volcanic hazard analysis tools. Outputs at a number of different threshold levels are likely to be useful, with results of this study suggesting even thresholds as low as 1 mm of ash can be useful.
information for many stakeholders. However, many participants drew upon experiences from New Zealand’s past minor ash fall events to express the perceived value in information for 1 mm of ash, and this is likely to be different in other regions, where decision-makers and communities are more frequently exposed to greater thicknesses of volcanic ash.

5.5.5 Map format and the importance of map-maker choices

The high preference to receive PDF, JPEG, and paper formats (Fig 5.13), suggest that many hazard map users do not expect to alter any of the properties on the original map (via GIS or other digital tools). Accordingly, the many representation choices for map properties made by the map makers (often volcanic hazard scientists) are important because they are likely to be carried through decision-making processes. Participants also expressed intentions to use the maps as tools for communicating with others during decision-making processes, stressing the importance of being able to clearly understand the map themselves in order to be capable of clearly and consistently explaining the hazard map to others, as recommended in a collective communication strategy by key national stakeholders (MCDEM 2010). Considering that maps are likely to be used “as is,” it is important that makers of volcanic hazard maps are aware of how choices in map properties can influence communication and understanding.

5.5.6 Methodological remarks

Semi-structured interviews served as a valuable pilot study methodology for acquiring rich contextual thematic data and for recognising important topics and issues, and the surveys were a successful method for exploring and testing these topics among a broader sample group. Overall, no major discords or contrasts were recognised between the results of the two methodologies. Inclusion of open-ended text questions in the survey enhanced the richness of the survey data collected and delivered insight into motivations behind key trends. Limitations in the survey methods include possible sampling bias, question order bias, and internet access. The survey was also limited to investigation of the selective map properties and topics addressed in the questions, and other important factors or issues may exist that are not covered here. In snowball sampling, the sample is affected by the network of relationships that exist. Accordingly, more well-connected populations are more likely to be included in the sample (Patton 2002). However, we assume that the proportion of stakeholders (70%) to scientists (30%) sampled is an appropriate representation of the target population. We found this purposive sampling method was suitable for achieving a high level of participation among those who met the specific criteria related to volcanic hazard maps and decision-making, but acknowledge that potential biases could exist within the sample. For example, no statistically significant differences were recognised among age groups for all parameters. However, the 18 – 24 and 65+ year age categories may have been underrepresented for this spread of occupational disciplines (Table 5.3). Findings may also contrast significantly among groups with a lower
rate of tertiary and postgraduate education (Table 5.3). This study focused on a New Zealand population sample, and important cultural differences may exist for other regions. For example, although red is globally considered a potent, emotional, active colour (Adams and Osgood 1973), it has connotations of danger in many Western cultures, but is a colour of joy in some Eastern ones, and a colour of life in New Zealand Māori culture (e.g., Jackson 1972), and these types of cultural meanings could influence the way users interpret hazard depicted in red colours (Edsall 2007).

Ash fall hazard was investigated in this study because probabilistic hazard analysis approaches are widely available and commonly employed for this type of volcanic hazard (e.g., Scollo et al. 2008, Folch 2012). Other important volcanic hazards, such as lahars (volcanic mudflows) and lava flows are becoming closer to having widely applied probabilistic analysis toolsets, but a probabilistic approach is not yet as common for mapping these gravity- and topography- driven volcanic hazards. Some of the results and findings presented here may be different for volcanic hazard maps depicting these and other hazards.

5.5.7 Implications for volcanic hazard map design

Results presented here indicate that stakeholders hold strong views about certain hazard map properties, and highlight the importance of considering user perspectives in hazard map development. Opening the map design process to user contemplation, criticism, and testing in times of volcanic dormancy can help build stronger, more reliable maps and can prevent miscommunications and mistrust during a crisis, when maps are likely to be drafted, disseminated, and duplicated rapidly. The quality of visual graphics and maps presented for decision-making can play a vital and significant role in the outcomes of a crisis (Tufte 1997). A collaborative and iterative design process which considers diverse user perspectives can help identify key issues, and may help contribute to the development of a more valuable end product.

Our findings suggest that the representation of data classification, colour scheme, key expression, and content, and map presentation format all have an influence on interpretation and communication of probabilistic volcanic hazard map information. These properties have varying influence on map preference, understanding, trust, and application, which could have important effects for hazard management decision-making and incorporation into risk reduction strategies, particularly if a reader relies on intuitive gist or feeling for the information presented to some degree (Reyna and Brainerd 1991, Finucane et al. 2000). Accordingly, while research into user preference is important, as readers are more likely to use a map which appeals to them, complementary empirical measurements of map interpretation are also important because the subjectively preferred map may not always be the most effective map for decision-making (Mendonça and Delazari 2011). For example, our results show that although stakeholders preferred the diverging colour scheme (Fig 5.5C), a diverging colour scheme may convey unintended or false messages.
of risk (Fig 5.12C).

Our results also emphasise that there is no one-size-fits-all map presentation. One map cannot comprehensively meet the precise needs of a diverse audience of stakeholders. For example, different ash thresholds may be of concern to different stakeholder groups, and each group may use the map for different modes of communication with different audiences and communities. However, giving a voice to different stakeholder groups in an inclusive approach to hazard mapping can help map makers strive for the most integrative map possible to mediate this issue. Empirical investigation into the interplay of different map properties and how they cumulatively affect the appeal and interpretations of a map with different stakeholder groups can help map makers work towards achieving the most collaborative and effective map possible. A more consentient map can facilitate consistent messaging among stakeholder communities and stakeholder audiences, and reduce the circulation of potentially conflicting information.

Although it is important to communicate a consistent message, it may often be appropriate to create a set of maps instead of a single map, for example, a map set comprising a fixed ash threshold map (Fig 5.3A) and a fixed probability threshold map (Fig 5.3B) supplemented with available hazard curves (Fig 5.4). It is also important to consider that probabilistic volcanic hazard maps are built on the results of a particular input model, which uses a particular set of parameters, assumptions, and limitations. In some circumstances, it may be appropriate to present the results of more than one model. In all cases, explanatory text should be provided on the visual itself to ensure the information is contextually supported.

We further note that the challenges of displaying uncertain information on a map is not unique to volcanic hazards, but has also been discussed in fields such as hurricane hazards (Broad et al. 2007), seismic hazard (Newman et al. 2001), and health hazards (Severtson and Myers 2013). Although the target audiences and messages vary for each discipline, many of these visualisation and communication challenges are analogous or shared, and research undertaken in one field can serve as a valuable resource for guiding enquiries and applications in other hazard-related fields.

5.5.7.1 Future work

Few significant differences were recognised between stakeholder and scientist participants in this study, which may be due to limitations in sample size of the study and design of the survey questionnaire (Table 5.2). Recommendations for future work in this area would be to focus on identifying any key differences affecting hazard map perception among various stakeholder groups (e.g., scientists, emergency managers, and the public). People living in areas potentially exposed to volcanic hazard are very important stakeholders in hazard map information, and are a primary audience for hazard maps in the event of volcanic unrest. However, in many cases, these people are likely to be less familiar with visualisations of volcanic hazard and probabilistic data. As such, future research exploring how volcanic
Chapter 5

hazard map design influences hazard communication and understanding among these people should be undertaken in order to improve the successful transfer of important hazard information to the wider at-risk community. Further work also needs to be undertaken to identify any further properties which may influence hazard map communication and interpretation, in addition to a more probing investigation of the parameters explored here, such as testing more colour schemes and map content types. We propose that future studies in other volcanic regions or on other natural hazards could adopt a similar methodology to that presented here, and refer the reader Appendix B for a full copy of the online survey.

5.6 CONCLUSION

It is impossible to achieve a wholly objective representation of complex reality on a map. However, empirically-informed representation choices can help volcanic hazard maps be designed with an enhanced level of ethical intersubjectivity and transparency which may help reduce miscommunication and misunderstanding. There are few existing guidelines available for how to choose appropriate representations of volcanic hazard data on a map, as no previous studies have assessed the impact of such choices on hazard communication. Here, we do not propose a universal standardisation for probabilistic volcanic hazard map properties. We do, however, suggest ten important considerations, in the context of the results of this New Zealand- and volcanic ash-based study, for map makers to take into account when creating maps to be used by stakeholders, such as emergency managers, for high-stakes decision-making:

- Using an isarithmic map comprised of gradational shaded stretched data classification with smoothed and labelled 10% interval probability isopleths is an ideal format for conveying the gradual nature of the hazard and for encouraging critical analysis of the data with a high level of accuracy.
- Red-yellow sequential colour schemes are commonly associated with volcanoes and hazard, and reduce the potential for confusion with hydrological hazard map types. The colour scheme can effectively convey the message that areas depicted as low hazard areas still have some level of hazard present.
- Diverging colour schemes may facilitate unwanted associations with volcanic risk concepts, and may enable use of the map as a reference tool for risk-based response decisions based on the transition area between hues. The colour scheme may convey messages of hazard absence in low hazard areas, and, depending on colour, may also be confused with other hazard map types (e.g. flooding hazard map). However, this scheme may be helpful for facilitating the interpretation of a high hazard “zone”.
- Color Brewer (www.colorbrewer.org, Brewer et al. 2013) is a helpful free online tool for selecting colour blind safe, appropriately balanced map colour schemes. Any colour scheme should be
tested using a colour blind filter tool, such as those offered through Color Oracle (Jenny and Kelso 2007) or Adobe® Photoshop, before dissemination. Including labels of probability on the map face also assists vision deficient users.

- When expressing uncertainty in a dataset, the concept of “confidence” is grasped more easily and more clearly by stakeholders than lower and upper percentile data ranks, particularly in hazard curve graphics.

- A percent (e.g., 25%) “probability” is a trusted numerical-verbal expression of probabilistic volcanic hazard, which is considered familiar and reliable. Including a natural frequency (e.g., 1 in 4) in addition is likely to help to increase understanding of the expression among a broader audience and may reduce the tendency to interpret very low hazard as “no hazard”.

- Qualitative hazard descriptors (e.g., “low,” “medium,” and “high”) are less sensitive than numerical hazard values (e.g., 30%, 45-50%), and may not accurately reflect users’ perceived change in hazard probability.

- Both fixed probability and fixed ash threshold maps are valuable probabilistic volcanic hazard map content types for organisational stakeholder groups.

- Static PDF format is a convenient, popular, and preferred format for receiving and sharing volcanic hazard maps, emphasising the importance of map property representation choices.

- Some differences exist in probabilistic volcanic hazard map interpretation between scientists and stakeholders, suggesting that engaging with users in a multi-perspective bottom-up approach to hazard mapping can complement and enhance traditional top-down approaches.
CHAPTER 6
Synthesis and discussion
Synthesis and discussion

6.1 INTRODUCTION

This chapter comprises a brief synthesis of the findings from Chapters 3, 4, and 5, and explores the implications of these findings in the context of the potential of probabilistic Bayesian event tree tools such as BET_VH to contribute to volcanic hazard analysis, risk assessment, and volcanic hazard and risk communication in New Zealand. The chapter also addresses additional insight which emerges from assimilating the collective outcomes of the interdisciplinary work presented in these chapters.

6.2 SYNTHESIS

The overall aim of this thesis is to explore the potential for probabilistic Bayesian event tree tools in New Zealand through a BET_VH probabilistic volcanic hazard analysis (PVHA) (Chapter 3), a BET_VH-based quantitative volcanic risk assessment (Chapter 4), and a study on how different aspects of communication influence the way that users interpret BET_VH-derived maps and graphics (Chapter 5). Together, these chapters bring several new contributions to the existing body of knowledge on Bayesian event tree tools, PVHA, and communication of probabilistic hazard data and uncertainties.

Chapter 3 presents the first tephra hazard analysis for the Okataina Volcanic Centre (OVC) which considers multiple different possible vent locations and both basaltic and rhyolitic Plinian eruption styles, and quantitatively describes the OVC’s linear vent zones (LVZs), areas which have been prominently recognised and discussed in the OVC literature, but have not previously been probabilistically investigated. The work also presents the first integration of popular advection-diffusion-sedimentation model TEPHRA2 (Bonadonna et al. 2005) and Bayesian event tree tool BET_VH (Marzocchi et al. 2010). The long-term PVHA presented in this chapter exemplifies BET_VH’s capability to include multiple different types of data in analyses. Nearest neighbour geospatial analysis, an expert elicitation session, and TEPHRA2 modelling of two of the most explosive OVC eruption styles (basaltic Plinian and rhyolitic Plinian) were performed and used as prior data input into the BET_VH tool, and an extensive review of the OVC’s past eruption catalogue was performed to define past data input. The PVHA reveals that the annual average absolute probability of accumulating ≥ 10 kg m⁻² of tephra from the initial Plinian phase of rhyolitic or basaltic OVC eruption from any location in the caldera in any one year is <0.02% (10th percentile < 0.015%, 90th percentile < 0.03%). It also reveals that in the event of a future eruption, the likelihood of a vent opening within the Haroharo LVZ (5 of the past 10 Plinian OVC eruptions) is equivalent (< 1% difference) to that
for the Tarawera LVZ (also 5 of the past 10 Plinian OVC eruptions) (31.8% compared to 32.5%). The chapter presents the first tephra fall hazard analysis for a Haroharo LVZ eruption scenario from the OVC. The PVHA reveals that the average absolute probability of accumulating $\geq 10$ kg m$^{-2}$ of tephra in the city of Kawerau is 1.3 times higher for an eruption from within the Haroharo LVZ compared to an eruption from within the Tarawera LVZ. The many different hazard analyses, (i.e., different combinations of eruption style, eruption location, and levels of uncertainty) which were able to be generated from one BET_VH assessment demonstrates the value of the tool for capturing and evaluating uncertainty. While past OVC tephra fall hazard studies (e.g., Bonadonna et al. 2005, Jenkins et al. 2008) have only considered rhyolitic events, results presented in this chapter suggest that a basaltic Plinian eruption also poses significant hazard to the region surrounding the OVC, and that analyses which only consider rhyolitic Plinian eruptions could underestimate absolute hazard probabilities. Overall, the research presented in this chapter demonstrates and emphasises the importance of considering all potential vent locations of a volcanic system, and all eruption styles relevant to the hazard analysis purpose, in order to develop a more comprehensive and representative analysis of volcanic hazard, and provides an example of how such an analysis can be achieved using BET_VH.

Chapter 4 presents a new approach for developing BET_VH-based quantitative risk assessments. The case study, which explores OVC ashfall risk to farms in the agriculturally-dense Bay of Plenty (BOP) region, quantifies the risk of potential damage over a continuum of hazard and vulnerability, at multiple levels of uncertainty, and in the context of fluctuating hazard and vulnerability environments. The results illustrate how consideration of seasonality, uncertainty, and a variety of thresholds in both hazard and vulnerability allows for a multi-dimensional assessment of risk which mirrors the complexity of volcanic ash impacts. A risk uncertainty matrix is presented for expressing uncertainty in quantitative risk assessments (i.e., maximum, average, or minimum estimate of risk), based on combining different levels of uncertainty available in the hazard and vulnerability data used. The risk assessment revealed that fruit farms in the BOP have higher levels of OVC ashfall risk than dairy farms in the BOP, and that farms to the east of the OVC experience higher levels of risk than farms to the north of the OVC. Forecasts based on the annual maximum estimate of risk for fruit farms show a regional average of 2.3% probability (greater than 1 in 50 likelihood) of experiencing 90% damage from this type of event over a period of 100 years. Detailed analysis revealed that the volcanic ashfall risk at fruit farms is cyclic and fluctuates with time of year and harvest season, with the highest risk experienced during peak harvest season (15 October – 14 April). Overall, the research presented in this chapter illustrates the complexity of volcanic risk which arises from dynamic hazard and vulnerability conditions, and demonstrates the advantage of being able to quantify these conditions in risk assessment through coupling BET_VH datasets with vulnerability datasets.

Chapter 5 presents the first set of empirically-based recommendations for consideration in the
design of probabilistic volcanic hazard maps. Through a series of 14 in-person semi-structured interviews and an online survey of 110 scientists and organisational stakeholders in New Zealand, this chapter identified several design properties which influence the communication and interpretation of hazard information from probabilistic volcanic hazard maps and hazard curves designed with BET_VH-derived data. The classification used to represent probabilistic volcanic hazard data on the map was found to influence perceived uncertainty and data reading accuracy, with isarithmic style maps most effective in reducing uncertainty and increasing accuracy (more estimates falling within 5% of the actual hazard displayed for the area on the map). Colour scheme influenced the type of hazard messages taken away from the map, with red-yellow sequential colour schemes conveying messages of a hazard distribution (high to low) and a red-blue diverging colour scheme conveying messages of a hazard state (present or absent) and/or risk. Volcanic ashfall (or tephra fall) maps which showed data based on a hazard exceedance threshold (e.g., 10 mm thickness) and those which showed data based on a probability exceedance threshold (e.g., 25%) were both viewed as helpful, with no statistical difference between preference for receiving one or the other, or both. Absolute probability hazard curves were viewed as potentially valuable supplements to the map by more than half of all participants. However, scientists viewed the hazard curves more helpful than the stakeholders, of which nearly 10% responded that they were unsure about the curves’ helpfulness. The concept of a “confidence” interval in the probability estimate (i.e., area between the 10th and 90th percentiles) was better understood than depictions of different percentile probability estimates among all participants. Numerical and verbal expressions of probability also had an influence in interpretation of the map, with a percent (e.g., 25%) or natural frequency (e.g., 1 in 4) “probability” being the most favoured expression. Overall, the research presented in this chapter identifies the important role that visual representation properties play in the interpretation of visual PVHA and BET outputs such as maps and hazard curves.

6.3 CAPTURING UNCERTAINTY IN VOLCANIC HAZARD AND RISK ASSESSMENTS

Addressing uncertainties brings a greater level of comprehensiveness to volcanic hazard analyses and the risk assessments that are based on them. For highly variable volcanic environments such as the OVC, the potential hazards of future activity are unable to be captured through one or two scenario-based deterministic scenarios. A scenario-based assessment of the OVC would mean choosing one, or at most a few, vent location points within the entire ~700 km² caldera or extensive LVZs. A hazard analysis based on this type of approach could be misleading, considering that a vent could open in an unknown or new location anywhere throughout the OVC (Nairn 2002). The ability to consider multiple vent location areas is a distinct advantage of BET_VH, and the results in Chapter 3 illustrate the important influence of vent location on hazard distribution. The ability to evaluate the likelihoods associated with vent locations can
also reveal important information about long-term hazard. For example, evaluation of past vent location data and expert elicitation data together gave new insight into the likelihoods associated with future activity at the LVZs. Results in Chapter 3 show that a future eruption is equivalently (<1% difference in probability) likely to occur within the Haroharo LVZ or within the Tarawera LVZ, which may have important implications for land-use planning and focusing future research into volcanic hazard and vulnerability.

The ability to consider the absolute, in this case annual, hazard posed by all possible vent locations and relevant hazardous eruption styles together can also help to recognise important long-term hazard trends. The OVC BET_VH PVHA considering both basaltic and rhyolitic Plinian eruption styles shows that a higher hazard exists than for rhyolitic Plinian eruption hazard alone. Although the absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra in the next one year from a basaltic Plinian eruption are on average 7.2 times lower than for a rhyolitic Plinian eruption, the hazard posed by a basaltic Plinian eruption does contribute to the overall OVC tephra hazard, raising absolute probabilities for the entire OVC by an order of 0.14, and this could have important implications for future work and planning. Through a similar BET_VH approach, Selva et al. (2012a) identified that the Campi Flegrei caldera potentially poses an overall higher hazard to the Italian city of Naples than the more prominently studied and discussed Mt Vesuvius. Such findings can guide and inform preparedness and reduction actions, and illustrate the advantages of performing long-term PVHA studies during periods of volcanic dormancy.

A BET_VH hazard framework conceptually represents all possible knowledge and uncertainty about a volcano and the hazard being investigated (Newhall and Hoblitt 2002; Marzocchi et al. 2004, 2008). Developing a BET_VH framework is a time consuming and challenging process which involves collaboration and collation of knowledge from many different sources (e.g., past eruption history, expert knowledge, hazard modelling). However, once developed, the framework introduces many advantages for performing robust risk analyses. Chapter 4 illustrates the valuable knowledge that can be learned through BET_VH-based risk analysis approaches, in this case an assessment of risk to agriculture, in particular fruit farms, in the BOP. For example, the assessment revealed that although the hazard (absolute probability of accumulating ash thicknesses likely to be capable of 90% damage) was highest during the shoulder season from 15 – 30 April, the highest risk (absolute probability of accumulating ash thicknesses likely to be capable of 90% damage times the seasonal vulnerability coefficient, Vc) is experienced during the peak harvest and growth season (15 October – 14 April). Combining the upper (90th) and lower (10th) percentile hazard estimates of hazard and minimum and maximum bounds for fragility function estimates which quantify vulnerability (amount of damage, or loss, from a certain ash thickness accumulation) (Fig 4.5) allowed for a detailed assessment of the uncertainty in the values behind these findings. This type of volcanic risk assessments could be used to inform plans for proactive risk reduction measures at fruit farms in the OVC. However, these measures could be associated with a substantial cost (e.g., a greenhouse
installation to protect at-risk crops), so it is important to be fully informed about the uncertainties in the risk estimates guiding such decisions.

The volcanic risk uncertainty matrix provides a visual schematic for communicating how these estimates can be made and also what they represent. Risk is multidimensional, and the work in Chapter 4 illustrates how incorporating probabilistic methods such as TEPHRA2 and BET_VH into risk assessment enables analysis to be refined to a very detailed level. However, it will be imperative to understand the needs of the stakeholder in order to perform a relevant and applicable volcanic risk assessment.

6.4 COMMUNICATING PROBABILISTIC DATA AND UNCERTAINTIES

The ability to capture and assess aleatory and epistemic uncertainties in estimates of volcanic hazard and risk is one of the key underlying advantages of the BET_VH tool. The hazard analysis developed in Chapter 3 and risk assessment generated in Chapter 4 are founded in the evaluation of uncertainties in volcanic activity, wind conditions, and crop fragility, and both give substantial insight into the different dimensions of tephra fall hazard and risk from the OVC. These datasets, which address many different possible scenarios, the likelihoods associated with different scenarios, and overall likelihoods resulting from any and all possible scenarios at multiple different levels of uncertainty allow for a very thorough treatment of volcanic hazard and risk variables. However, they also result in an almost overwhelming amount of information to communicate to potential users. This gives rise to three main questions: What is the most essential information to communicate? How much information should be communicated? And, in what styles and formats should the information be communicated?

The first two questions will be primarily answered according to the needs of the audience for whom the data is being generated or provided. This will differ greatly based on the specific map purpose, as well as the characteristics, demands, and needs of the audience (e.g., Rosenbaum and Culshaw 2003). For example, the quantity and detail of information needed by land-use planners or structural engineers is likely to be very different than the quantity and detail of information need by a local government interested in developing an informational resource for its local community. As an example, Leonard et al. (2014) outline some of the different types of considerations which need to be taken into account when designing volcanic hazard information for different audiences. BET tools offer the ability to meet the information needs of a wide variety of stakeholder audiences, and stakeholders should be consulted on these first two questions to ensure that the information provided is appropriate and relevant. The latter question, of communication format, will also be guided by audience needs, but is less straightforward. PVHA, and Bayesian event trees in particular, are young tools in applied volcanology. Accordingly, many audiences are likely to be unfamiliar with this type of information, and many scientists developing PVHA tools are likely to have little experience in communicating this type of information. The work done in Chapters 4 and 5 of this thesis...
gives insight into this question, and raises several points about engaging with the concept of uncertainty in the communication of probabilistic volcanic hazard and risk.

6.4.1 Attitudes towards uncertainty

The volcanic hazard information output by BET tools is fundamentally rooted in uncertainty. Expressions of uncertainty concerning either our knowledge of the volcano (epistemic uncertainty) or the natural variability of the system (aleatory uncertainty) have not been prominently discussed in traditional approaches to (and applications of) volcanic hazard analysis (e.g., Volcanic hazards information series, e.g., Neall et al. 1993) (Fig 1.2). Accordingly, many volcano scientists are apprehensive about discussing uncertainties regarding volcanic hazard (Sparks et al. 2013). However, communication research, such as the landmark study by Wynne (1992) on perception of scientific information regarding hazard and risk among farmers, suggests that expressions of uncertainty about hazards are likely to be accepted well, as many people are used to the daily uncertainties of life. Wynne (1992) notes, however, that farmers in the study did not recognise or readily accept traditional scientific expressions of uncertainty (e.g., percentiles). Accordingly, the study proposes that this communication aspect is one of the seven key criteria used for lay judgement of science: “Criterion iv: Is the form of knowledge as well as the content recognisable?” (Wynne 1992, p. 298). The study suggests that expressing uncertainty in hazard or risk in more familiar terms is likely to have better communication success.

The risk uncertainty matrix proposed in Chapter 4 (Fig 4.3) is an example of how scientific concepts of uncertainty in volcanic risk may be translated for non-scientific audiences. Rather than citing a “90th percentile hazard estimate and a minimum vulnerability threshold” or a “10th percentile hazard estimate and a maximum vulnerability threshold”, a range could be given, spanning the minimum to maximum estimates of risk. This may also present a distinct advantage for communication with governmental stakeholders, as expressing a range of probabilities, such as the range between minimum, average, and maximum estimates of risk, was found to be considered more reliable and credible by participants in a study by Dieckmann et al. (2010). Accordingly, adopting the concept and simplified terminology of a risk uncertainty matrix may help constructively communicate the uncertainty in a risk estimate to a variety of audiences. The same concept could be applied to communicating uncertainties in hazard estimates. For example, Fig. 3.5 shows how hazard estimates at the 10th percentile, average, and 90th percentile uncertainty levels vary. When communicating such information to stakeholders, a range from “minimum” (10th percentile) to “maximum” (90th percentile) estimates of hazard could help communicate the uncertainty in an accessible way. Investigation into hazard curve graphics with stakeholders in Chapter 5 found that the concept of a certain level of “confidence” in a probabilistic hazard estimate (Fig. 5.4) was much more readily understood than the concept of percentiles (Fig. 5.10), further suggesting that percentiles may not be an optimal way to communicate with more general audiences. The matrix scheme
Chapter 6

**Synthesis and discussion**

introduces options for scientists who are considering how to communicate robust PVHA hazard and uncertainty datasets. For example, the hazard curves depicted in Fig. 1.5 and 3.6 could be adjusted to this presentation format for certain stakeholder audiences. Many of the PVHA communication findings are also relevant for risk assessments based on PVHA data. See, for example, the confidence interval shown in Fig. 4.7 to communicate the uncertainty in the average estimate of risk.

Findings in Chapter 5 also suggest that organisational stakeholders in New Zealand are generally comfortable with the broad concept of uncertainty in scientific hazard assessments. In fact, it played a primary role in the way participants approached interpretation of the probabilistic volcanic ash hazard maps in the study. For example, interview participants overwhelmingly suggested that the maps should show 10% intervals of probability, because anything more precise (e.g., 5%) was interpreted as showing “misleading” accuracy in the data. This is in accordance with the observations made by Wynne (1992) and Deickmann et al. (2010), who both suggested that uncertainty can play a constructive role in hazard and risk communication. While this has positive implications for the integration of PVHA in applied volcanological practice, it is of critical importance that the uncertainty is expressed in a clear, accessible, and relatable manner, as unclear or confusing expressions and ambiguity could lead people to actions such as decision avoidance or a weakening of trust, among others (e.g., Curley et al. 1984, Johnson and Slovic 1998, Politi et al. 2007). Based on findings in Chapter 5, one way to achieve clearer communication of such uncertainties is to communicate numerical values alongside qualitative expressions such as “maximum” and “minimum”. Descriptions of probabilistic volcanic hazard using verbal, or qualitative, expressions were much less sensitive to perceived changes in hazard than participants’ descriptions using numerical expressions. For example, although participants were likely to change their numerical estimate of hazard (e.g., 40%) when looking at different probabilistic volcanic hazard maps, they were far less likely to change their verbal estimate (e.g., “medium”). The participant group as a whole also interpreted many different probability values as “medium” hazard. This agrees with findings from Budescu et al (2009) and Doyle et al. (2011) that verbal expressions are interpreted inconsistently among different people. Describing estimates using both verbal and numerical expressions may have an important influence on perceived validity of the uncertain/probabilistic data as well, as Johnson and Slovic (1998) found that people were less likely to feel trust or confidence in the competency of scientists when only verbal expressions were used, without numerical values.

### 6.4.2 Visual representations of probabilistic data

The work in Chapter 5 also presents empirical evidence that the format and styles used to visually represent PVHA data on maps has a substantial influence on the way stakeholders interpret the hazard information and the uncertainty associated with it. Communication properties such as colour scheme, key expression, and data classification affected the way people understood BET_VH data. This has important implications for the use of long-term PVHA tools such as BET_VH in operational practice. Namely, that the
initial outputs of the tool may be not always be suitable for direct transfer into communication exchanges. Rather, this work suggests that consideration and attention should first be given to how the data is represented, in order to ensure that the correct messages are transferred, and they are received easily and clearly. For example, if the goal were to communicate that the entire area is potentially exposed to hazard, a red sequential colour scheme may be most appropriate (Fig. 5.5A). If the goal were to communicate that there is one primary zone which should be focused on, a diverging colour scheme may be most appropriate (Fig. 5.5C). Being aware of the influence that such properties have on the communication exchange and dialogue is important.

As more and more scientists adopt the use of probabilistic tools, and as the volcanologist’s role continues to undergo a shift and expansion into the realm of decision-making and communication surrounding events (Sparks et al. 2013), it is imperative to empirically identify and investigate the factors which play an important role in communication and interpretation of probabilistic information. A review of risk communication by Bostrom and Löfstedt (2003) conclude that while there have been growing advances in some fields (e.g., health), hazard and risk communication still largely relies on subjective judgement and intuition rather than well-researched principles. Tufte (1997) and Spiegelhalter et al. (2011) explore how visual communication graphics and the way in which they show uncertainty have played a pivotal roles in both the successes and shortcomings of past events, but they similarly conclude that there has been little progress in this area in terms of empirical research. Further, Politi et al. (2007) note that particularly little is known about how to visually communicate uncertainty in probabilistic hazard and risk with different audiences. The work in Chapter 5 presents an important first step towards developing empirically-based advice for probabilistic volcanic hazard and risk communication maps and graphics, and also makes significant contributions to knowledge in the broader field of probabilistic hazard and risk communication. However, many important challenges still need to be explored.

6.4.3 Challenges in communicating probabilistic hazard, risk, and uncertainty

6.4.3.1 “The L'Aquila 7”: an embodiment of the challenges facing applied PVHA

The recent trial of “the L'Aquila 7" in Italy highlighted both the ongoing evolution of the role of natural hazard scientists in decision-making, and also the importance of clearly communicating probabilistic and uncertain hazard information. On October 22, 2012, six scientists and one government official, deemed the “L’Aquila 7” in media reports, were convicted of manslaughter for failing to adequately assess and warn of the risk of an earthquake before of a tragic earthquake in 2009 which caused more than 300 deaths (Cartlidge 2013, Rosen 2014a). The trial broke headlines around the world (e.g., Economist 2011, Fountain 2011, Hall 2011, Bardin 2012, Johnston 2012, Moloney and Wang 2012) and raised outcry among the scientific community (e.g., AAS 2010, AGU 2010, Nature 2012). On the 31st of
March, 2009, the seven experts had attended a Major Risk Committee meeting following a sequence of earthquakes in the seismically active region of L’Aquila. They concluded that a future earthquake was not predictable in a deterministic sense, and that the probability of occurrence of a large earthquake in the short-term remained significantly low (Marzocchi 2012, 2013). On 6 April, 2009, a 6.3-magnitude earthquake devastated the region.

The trial and conviction was a complex and criticised case, influenced by many complicating factors. However, a core area of discussion within and around the trial centred on the communication of low-probability, high-consequence natural hazard events, and the challenges of communicating probabilistic hazard and risk assessment information about these events (e.g., Fountain 2011, Hall 2011). The scientists successfully appealed their conviction in 2014 (Abbot and Nosengo 2014, Rosen 2014b). However, the case raised global attention to the importance of understanding how the outputs and uncertainties associated with probabilistic hazard and risk analysis tools should be applied, considered, and communicated, especially as scientists become more integrated in the decision-making process (e.g., the Major Risk Committee) (Marzocchi 2012). This type of knowledge is important to acquire before an impending crisis, when existing networks, structures, and knowledge bases are relied upon (Leonard et al. 2014). In order for tools such as BET_VH to be adopted into such processes, it is important that the people involved in such decision-making environments are integrated in the design of BET_VH outputs in order for them to best serve their purpose.

The suite of datasets that PVHA analyses offer is exemplified by the many outputs and figures presented in Chapters 3 and 4. In order to fully capture uncertainty in communication, it likely that more than one map or visual will need to be produced in a short- or long-term context, and more research needs to be done into the best methods for communicating a suite of information. However, results of the work done in Chapter 5 highlight that stakeholders are open to getting more than one type of output. For example, a third of participants preferred to receive both a probability threshold tephra hazard map and an exceedance threshold tephra hazard map if given the opportunity (Fig 5.8B). This illustrates that it is important to engage with stakeholders in order to assess their wants and needs for communication. Integrating stakeholders into dialogue and research surrounding PVHA tools such as BET_VH can help ensure that development of such tools and their outputs advances in the appropriate and relevant directions for applied practice.

6.5 BET_VH AS AN EVOLVING TOOL

The customisable nature of Bayesian event trees tools and their ability to consider many different types and sources of knowledge means that scientists are able to get closer to a realistic representation of hazard than ever before. For example, the maps of OVC tephra hazard in Chapter 3 produce a
significantly more detailed assessment of tephra fall hazard compared to the map presented in Fig 1.2A. Developing a BET_VH framework which includes assessment of multiple different hazards (e.g., flow hazards and ballistic projectile hazards in addition to tephra fall hazard) such as in Sandri et al. (2014), would allow for an even more robust picture of long term hazard. However, Sandri et al. (2014) focused their multi-hazard analysis on a stratovolcano (El Misti, Peru) with a primary central vent which was assigned a 90% likelihood of opening in a future eruption in the prior data. In comparison, Ruawahia Dome vent, the vent cell (located within the Tarawera LVZ) with the highest probability of opening in a future OVC eruption identified in Chapter 3, had an average conditional posterior probability of vent opening of only 1.66%. The significantly greater spatial uncertainty in vent location at calderas such as the OVC and possible prolonged multi-phase behaviour at the OVC would introduce significant uncertainty into multi-hazard estimates which aim to capture the entire sequence of the activity, which could last for months to years.

While the tool was able to provide robust insight about the initial phase of eruption from the OVC (Chapter 3), which proved valuable for risk assessment (Chapter 4), challenges remain in terms of incorporating the many epistemic and aleatory uncertainties associated with such large calderas capable of prolonged, multi-phase eruptions. For example, for many eruptions at the OVC over the past 26 ka (time frame of the model), burial has made it difficult to constrain the exact number, timing, and behaviour of different vents activated. This introduces significant challenges to defining TEPHRA2 and BET_VH Node 4 input parameters to forecast future hazard. Similarly, in later degassed phases of OVC eruptions, dome-building activity may occur at a different vent location than the Plinian activity (Nairn 2002), and this would introduce challenges into building a long-term OVC multi-hazard assessment which considered both tephra fall and block-and-ash flow hazard. However, many of these limitations will be addressed through ongoing advances in hazard-specific modelling capabilities (e.g., TEPHRA2) and in continued geological field work and research to constrain and define past activity.

As with all models, the principal logic underlying PVHA methods is that the outputs will only be as good as the inputs. Accordingly, Bayesian event tree tools are only able to significantly contribute to volcanic hazard and risk management if valuable data and models exist for a certain volcano and its associated hazards. For example, this BET_VH analysis for OVC tephra fall hazard could not have been performed without a probabilistic tephra hazard model such as TEPHRA2. The development of a Bayesian event tree framework requires time-consuming, rigorous scientific exploration of all existing knowledge about a volcano before it can be built. Further, all of the data must be quantifiable, formatted into the specific file format for input into the tool, and assigned a weighting. This may require a specific and robust set of skills. For example, the TEPHRA2 output format and BET_VH input format are not optimally designed for efficient transfer of data. Coding software skills are required to manipulate the very large
datasets into the appropriate formats. This can prove a computation challenge as well, as probabilistic
datasets, derived from many repeated runs and sampling of multiple parameters, are inherently large.
TEPHRA2, for example, is optimally run on a super-computer cluster in order to perform hundreds to
thousands of parallel runs of the model (Bonadonna et al. 2005). As technological and computational power
advances, PVHA methods and tools such as BET_VH will continue to evolve and improve and ultimately
become more accessible to a wider domain of users and operational settings.

6.5.1 PyBetVH

The version of BET_VH used in this work (BET_VH, Marzocchi et al. 2010) has already evolved
into a new and enhanced version of the tool over the course of this thesis. The new implementation of
BET_VH, called PyBetVH, was released in December 2014 (Tonini et al. in review) (Appendix C) and is
now available online from the collaborative volcanological research and resource website Vhub at
https://vhub.org/resources/betvh. The new Python code version of the tool offers a more robust and
interactive graphical user interface (GUI). The new GUI enables the user to create several new kinds of
graphical outputs, which were verified to be potentially helpful ways of communicating BET_VH information
through the work done in Chapter 5 of this thesis. The new outputs offered in addition to the existing
hazard exceedance threshold maps are: 1) absolute hazard curves, 2) conditional hazard curves, and 3),
probability exceedance threshold hazard maps. While the BET_VH GUI can only be used to visualise maps
which show a hazard exceedance threshold map, i.e., a map which shows the distribution of probability of
exceeding a certain hazard threshold (e.g., 10 mm of ash), the PyBetVH GUI allows the user to output
maps based on a hazard threshold or a probability threshold. The work done in Chapter 5 of this thesis
illustrated that stakeholders are likely to find both types of map helpful (e.g., Fig 5.3, 5.8). Further, the work
in Chapter 5 also found that probabilistic Bayesian event tree-derived hazard curves (Fig 5.4) had potential
to be valuable graphical tools in PVHA communication (e.g., Fig 5.10). The new output capabilities
introduced by PyBetVH are presented in Tonini et al. (in review) (Appendix C) through examples using
the data presented in Chapter 3 of this thesis. BET_EF (Marzocchi et al. 2004) is also currently being
revised to a new version BET_UNREST which will extend the short-term forecasting to include non-
magmatic volcanic unrest (e.g., hydrothermal-induced monitoring anomalies) (Rouwet et al. 2014, in press;
Tonini et al. in review) (Appendix C).

6.6 THE POTENTIAL FOR PROBABILISTIC BAYESIAN EVENT TREE TOOLS IN NEW
ZEALAND

This thesis brings empirical rigour to evaluation of the potential for Bayesian event tree tools such
as BET_VH (or PyBetVH) for volcanic hazard analysis, risk assessment, and hazard and risk
communication in New Zealand. The review of existing work and interpretations based on the original
research presented in this methodological study, suggest that these tools could in fact play an important role in New Zealand in the future, although more work needs to be done to investigate different aspects of the tools before they could be operational. For example, the L’Aquila case illustrates the benefit of having collaboratively-established protocols for how such tools should be used and implemented (Marzocchi 2012), and this has not yet been done in New Zealand. Further work also needs to be done in the area of communication of probabilistic volcanic hazard and risk information, based on the gaps and future directions recognised in Chapters 5 and 6 of this thesis. However, the incentive and demand for such tools is growing in New Zealand, making further development and research in this area likely.

New Zealand leads the world in adopting probabilistic methods into applied volcanic hazard analysis and volcanic risk management. For example, in the recent 2012 Te Maari eruption crisis in New Zealand, the PVHA model ASHFALL (Hurst 1994, Hurst and Smith 2004) was used to forecast tephra hazard and the PVHA tool Titan2D (Patra et al. 2005, Sheridan et al. 2005) was used to forecast mass-flow hazards and both were incorporated into the building of crisis hazard maps (Leonard et al. 2014). Early investigations into the idea of a national PVHA for New Zealand based on the concept and methods of the New Zealand Probabilistic Seismic Hazard Model (Stirling and Cole 2002) show that there has been interest expressed in the potential for developing long-term probabilistic volcanic hazard data in New Zealand for over a decade. Based on tests of BET_EF in Exercise Ruaumoko, the Auckland Civil Defence and Emergency Management Group explicitly advocate the use of Bayesian event trees for assisting decision-making in a future volcanic crisis (CDEM 2013).

There is also a need for the information provided by such tools. In their review of the current state of land-use planning in New Zealand, Glavovic et al. (2010) conclude that improving our understanding of natural hazards and prioritising associated risk reduction measures are two “burning issues” which need attention. Developing robust probabilistic assessments of volcanic hazard and risk using BET_VH could help address these needs. Further, as the Regional RiskScape (Schmidt et al. 2011) software continues to develop, there will be an ever increasing demand for probabilistic inputs on natural hazard and risk. However, in volcanic areas affected by great economic and social hardship, such as around Mt. Pinatubo in the Philippines, volcanic hazard and risk must be balanced within the wider context of people’s daily risks (Gaillard 2008) and the amount of resources and governmental support which can be dedicated to integrating such sophisticated computation techniques in such areas are likely to be sufficiently less or lacking completely when compared to countries such as Italy and New Zealand (Sparks et al. 2013).

Integrating Bayesian event tree tools into applied volcanological practice is not intended to replace scientific advisory groups, or classical geological approaches to hazard analysis. In fact, the tools depend on valuable input from such sources. However, they could provide a powerful statistical tool for guiding
priorities, informing decisions, and rapidly evaluating scenarios of interest in an objective manner. In this respect, the quantitative forecasts output by tools developed prior to a crisis are less likely to be influenced by external pressures (e.g., social, economic, political) during a crisis. Long-term PVHA could lead to proactive management of volcanic hazard and risk, and an event tree framework allows for certain parameters to be easily updated to incorporate new sources of data or meet changing understandings of a volcano. Through the application and continued investigation of such tools, New Zealand and other volcanically active regions can work towards a comprehensive, collaborative, structured, and integrative approach to volcanic risk reduction based on robust evaluations of knowledge from many sources.
CHAPTER 7
Conclusions and future work
7.1 CONCLUSIONS

Through three interdisciplinary case studies based on the tool BET_VH (*Bayesian Event Tree for Volcanic Hazards*, Marzocchi et al. 2010), this thesis finds that Bayesian event tree probabilistic volcanic hazard analysis (PVHA) tools have encouraging potential to contribute to applied volcanological practices in New Zealand. The tools demonstrate an ability to enhance hazard analyses, to deliver robust and detailed risk assessments, and to communicate volcanic hazard and risk messages through carefully and collaboratively-designed visual and verbal media such as maps, curves, and matrices.

7.1.1 Volcanic hazard analysis

Results of the BET_VH PVHA for the Okataina Volcanic Centre (OVC) revealed that in order to estimate the full potential distribution and magnitude of hazard, all possible vent locations and both basaltic and rhyolitic Plinian eruption styles should be considered in tephra hazard analyses. While the absolute probabilities of accumulating ≥ 10 kg m⁻² of tephra in the next one year from a basaltic Plinian eruption are on average 7.2 times lower than for a rhyolitic Plinian eruption, the hazard posed by a basaltic Plinian eruption does contribute to the overall OVC tephra hazard, raising absolute probabilities by an order of 0.14 when both styles are considered. This may have implications when considering sensitive decision-making thresholds. The distribution and magnitude of hazard throughout the OVC is highly sensitive to eruption vent location, with areas to the north exposed to higher hazard from an eruption within the Haroharo LVZ and areas to the south exposed to a higher hazard from an eruption within the Tarawera LVZ. The ability to take into account all vent location areas when considering hazard distribution is a distinct advantage of using BET_VH for long-term hazard analysis.

7.1.2 Volcanic risk assessment

BET_VH outputs enabled a robust multi-dimensional assessment of ashfall risk to farms in the Bay of Plenty region when combined with agricultural fragility functions and seasonal vulnerability coefficients. Fruit farms were found to be more at risk of OVC ashfall than dairy farms, and farms east of the OVC were found to be more at risk than farms north of the OVC, based on the forecasted annual probabilities of experiencing 90% damage (loss) to production. Detailed analysis revealed that the volcanic ashfall risk at fruit farms is cyclic and fluctuates with time of year and harvest season, with the highest risk experienced during peak harvest season (15 October – 14 April). A risk uncertainty matrix based on combining different
levels of uncertainty available in the hazard and vulnerability datasets, can serve as a guide for evaluating and expressing the level of uncertainty in quantitative risk assessments.

7.1.3 Volcanic hazard and risk communication

The way that probabilistic volcanic hazard information is represented on hazard maps and hazard curves influences the way that a reader understands and interprets the hazard information. A study of more than 110 scientists and stakeholders in New Zealand revealed that properties such as data classification, colour scheme, key expression, and type of probabilistic content, have an influence on map preference, understanding, trust, and the level of hazard perceived, which could have important implications for hazard management decision-making and incorporation into risk reduction strategies, particularly as studies have shown that readers often rely on intuitive gist or feeling for decision-making information to some degree (Reyna and Brainerd 1991, Finucane et al. 2000). Giving a voice to stakeholder groups in an inclusive co-creation approach to the design of hazard maps and other graphics can help scientists strive for the most integrative and effective communication possible.

7.1.4 Bayesian event tree tools and New Zealand

The ability of BET_VH to be customised to the highly complex OVC suggests that the tool has potential for accommodating the many volcanoes in New Zealand which have similarly complicated eruption histories or lesser degrees of complexity. New Zealand has also demonstrated an interest and demand for probabilistic volcanic hazard and risk resources in areas such as land-use planning (Glavovic et al. 2010), emergency management (CDEM 2002, Auckland Council and CDEM 2013), and damage and loss modelling (Regional RiskScape, Schmidt et al. 2011). In addition, some probabilistic volcanic techniques are already being utilised in volcanic crisis response (e.g., Leonard et al. 2014). This suggests that there are significant opportunities for Bayesian event tree tools and their outputs to be received and integrated into volcanic risk reduction in New Zealand. Engaging with stakeholders in all applications can ensure that the outputs of such quantitative assessments are presented in the clearest, most relevant, and effective way.

7.2 FUTURE WORK

The work in this thesis has identified several important areas for future research in volcanic hazard analysis, risk assessment, and volcanic hazard and risk communication both in New Zealand, and worldwide, as outlined below:

1 While the recommendations for consideration in the design of probabilistic volcanic hazard maps presented in Chapter 5 have potential to serve as a valuable resource and starting point for people who aim to communicate probabilistic volcanic hazard information, further work needs to be done
with different stakeholder groups and different map properties. People at risk, for example, are one of the most important stakeholders of volcanic hazard information, and therefore should be incorporated into such social science studies regarding volcanic hazard communication in future work.

2 The work in Chapter 5 demonstrated the important and often powerful role of visual representation choices in probabilistic volcanic hazard map communication. It is likely that similar influences (e.g., colour scheme) act in the interpretation of non-probabilistic volcanic hazard maps, as well as hazard maps for other natural hazards, and future work in this area could help recognise important properties and establish recommendations relevant to this large domain.

3 The risk uncertainty matrix presented in Chapter 4 is a concise visual guide to evaluating and expressing uncertainty in probabilistic volcanic risk assessments. While it has been suggested here that the simplified terminology presented in this matrix is likely to help communicate the results of quantitative risk assessments based on tools such as BET_VH, this should be tested with stakeholders in future studies.

4 Methods for modelling multiple phase eruptions exist within some hazard specific models (e.g., Bonadonna et al. 2005, Jenkins et al. 2008). However there are many challenges to long-term forecasting of these multi-phase events at volcanoes such as the OVC due to unknown timing between phases, likelihood of different vents opening between phases, and overall duration of the multiple phase activity. Development of a way to statistically treat the uncertainties through stochastic sampling of probability distributions could allow for such variables to be captured in tools such as BET_VH. This would become particularly relevant for modelling multi-hazard activity at the OVC (Chapter 3), as hazards are likely to occur in a certain progression over time, e.g., block-and-ash flows are more likely to occur at the end of an OVC eruption, and tephra fall is more likely to occur at the beginning (Nairn 2002).

5 The quantitative risk assessment presented in Chapter 4 for fruit farms in the Bay of Plenty revealed valuable information about the long-term risk from local-source volcanic ashfall. However, this assessment is based on a relatively basic calculation of risk. Further work could establish a more robust and multivariable equation for the calculation of risk in order to achieve even more detailed assessments (e.g., crop export value, recovery costs).

6 In many cases it will be necessary to consider more than one volcano in hazard and risk analyses in order to achieve a fully representative long-term and comprehensive volcanic hazard and risk analyses in New Zealand. For example, for farms in the Bay of Plenty, ashfall from volcanoes such as Taupo, Ruapehu, and White Island are likely to contribute to ashfall risk in addition to the OVC (Fig 3.1). Although there are currently few approaches in this area (e.g., Stirling and Cole 2002,
Hurst and Smith 2010, Jenkins et al. 2012a, b), a suggested long-term goal for Bayesian event tree tools is to include a node for “volcano” at the beginning of the sequence, so that more than one volcano can be analysed within one framework, and fully comprehensive datasets for all volcanoes could be considered together. This would require a wealth of knowledge about each volcano and a large computational capacity, but could result in a nationally shared resource and the ability to perform comprehensive evaluations of local-, regional-, and distal-source volcanic hazard. Such analyses would also be very beneficial for integration into other national objectives such as Regional RiskScape (Schmidt et al. 2011).

In order to understand the full potential for probabilistic Bayesian event tree tools for volcanic hazard analysis, risk assessment, and hazard and risk communication in New Zealand, social science investigations of the wants, needs, and demands of stakeholders in New Zealand should be conducted. This thesis identifies that the tools have encouraging potential to enhance hazard analyses, deliver in-depth risk assessments, and be communicated in a consistent and clear manner. A natural next step would be to investigate how stakeholders view the potential of the tools in regards to helping meet their own volcanic risk reduction goals.


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Index to appendices

Appendix A: Human Participant Ethics Documents ................................................................................................. 183
   i. Guide to human participant ethics documents ................................................................................................. 185
   ii. CEO information sheet (interviews) .................................................................................................................. 187
   iii. CEO consent form (interviews) ....................................................................................................................... 193
   iv. Participant information sheet (interviews) ........................................................................................................ 195
   v. Participant consent form (interviews) .................................................................................................................. 199
   vi. Interview study flyer A ....................................................................................................................................... 201
   vii. Interview study flyer B ..................................................................................................................................... 203
   viii. Participant information sheet (online survey) ................................................................................................. 205

Appendix B: Copy of online survey .......................................................................................................................... 207

Appendix C: PyBetVH manuscript (in review in Computers and Geosciences) ...................................................... 223
APPENDIX A

Human Participant Ethics Documents
GUIDE TO HUMAN PARTICIPANT ETHICS DOCUMENTS

The research performed in Chapter 5 of this thesis was approved by the University of Auckland Human Participant Ethics Committee (UAHPEC). The interview study was approved on 04 June 2013 (Reference No. 9623), and the survey study was approved on 15 April 2014 (Reference No. 011505). The related documents present in Appendix A are explained below:

The CEO information sheet (interviews) is a document explaining the purpose and format of the interview study which was presented to chief executive officers (CEOs) at organisations where study participants were recruited. The CEO was required to sign a CEO consent form (interviews) in order to recruit participants at that organisation.

The Participant information sheet (interviews) is a document explaining the purpose and format of the interview study which was presented to potential participants at organisation where CEO consent was received. The information in this sheet was reviewed with in person with each participant, and each participant was required to sign a Participant consent form (interviews) before participating in the study.

The Interview study flyer A and B are informational flyers about the study which were circulated at organisations where it was approved by CEOs.

The Participant information sheet (online survey) is a document explaining the purpose and format of the survey study which was provided at the start of the online survey (Appendix B). The home page of the online survey stated that: “completing and submitting the survey is implied as consent.”

Based on the conditions outlined by the UAHPEC approvals (Reference Nos. 9623 and 011505), the identity of all participants is confidential, all consent forms are confidential, and all participants’ audio-records, transcripts, and responses are confidential and will be securely and privately kept by the researchers for 6 years, after which it will be destroyed.
REQUEST FOR PERMISSION FOR EMPLOYEE PARTICIPATION IN RESEARCH STUDY
CEO Bay of Plenty stakeholder group

Your organisation has been selected as a group to participate in a research study entitled *Exchange of probabilistic volcanic hazard information between scientists and stakeholders: insights on the influence of communication format* being conducted by Mary Anne Thompson under the supervision of Jan Lindsay and JC Gaillard. This research study on volcanic hazard maps is being done as part of Thompson’s PhD thesis at the School of Environment at the University of Auckland. Your organisation was selected to participate because it is considered a stakeholder in the Bay of Plenty that may be affected by volcanic hazards, and because your organisation may use volcanic hazard maps in a decision-making context.

Recent changes in volcano sciences have seen a shift from traditional qualitative hazard maps that show broad “high,” “medium,” and “low” hazard areas, to modern quantitative maps that show distributions of the probability or likelihood that a specific volcanic hazard will occur in a certain area. These new maps show more complex and detailed volcanic hazard data than ever before. However, little work has been done to understand how these new maps translate into stakeholder decision-making and how effectively they are understood by the stakeholders who use them, such as members in your organisation.

The goal of this research study is to improve the communication of probabilistic volcanic hazard information between scientists and regional- and district-level stakeholders in the Bay of Plenty by investigating how probabilistic volcanic hazard maps are understood and used by stakeholders for decision-making. It aims to create guidelines that help scientists build volcanic hazard maps that better meet stakeholders’ needs for practical and informed decision-making.

The researchers would like to request your permission to recruit select members of your organisation who have a lead role in decision-making related to geologic hazards, or who may use a volcanic hazard map provided by scientists, to participate in this study. The study consists of approximately 45 minute to one hour audio-recorded interviews by the student researcher, Mary Anne Thompson, in which participants will discuss their organisational experience and interest in volcanic hazard maps, as well as interactively discuss several probabilistic maps shown during the interview. All participants’ identities and responses will remain confidential to all persons other than the researchers. Data and transcripts from the project will be published as part of Thompson’s PhD thesis and will be published in peer-reviewed publications authored by Thompson, Lindsay, and Gaillard. The identity of your organisation and identity of participants will remain confidential and will not be disclosed in any of the works authored by the researchers. You may request a summary of findings that will be available after completion of the project. This request can be made on the CEO Consent Form. Interview data will be confidentially stored with the researchers on the University of Auckland campus and destroyed after six years.
After reading this Request for Permission for Employee Participation in Research Study, please read the following Participant Information Sheet (PIS). The PIS explains the basis and procedures for the research study, the selection of participants, the potential benefit to participants, how the interview data will be stored and later destroyed, how confidentially of participants will be preserved, and provides contact details for the study. A copy of the PIS will be given to each participant to thoroughly read and discuss with the student researcher before a participant consents to participate. Participation is completely voluntary, and selected members of your group are under no obligation to participate.

After you have read through this Request for Permission for Employee Participation in Research Study and the Participant Information Sheet please ask the PhD student researcher, Mary Anne Thompson, about any questions or concerns that you may have about your employee’s participation in this research study. Once these questions and concerns are addressed to your satisfaction, please sign the Consent Form for CEO of Bay of Plenty stakeholder group sheet if you give permission for the researchers to use members of your organisation as participants in this research study. In addition, I seek assurance that participation or non-participation will not affect the participant’s relationship and employment with the organisation. This assurance can be given by signing the Consent Form.

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142; Telephone: 09 373-7599 extn. 87830/83761; Email: humanethics@auckland.ac.nz. You may also contact the principle investigator, Jan Lindsay, School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142; Telephone: 09 373-7599 extn. 86678; Email: j.lindsay@auckland.ac.nz; or you may contact Paul Kench, Head of the School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142; Telephone 09 373-7599 extn. 88440; Email: p.kench@auckland.ac.nz.

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 04 JUNE 2013 FOR (3) YEARS REFERENCE NUMBER 9623.
A.ii CEO information sheet (interviews)

PARTICIPANT INFORMATION SHEET
Bay of Plenty stakeholder group member

1. What is the title of this research project?

Exchange of probabilistic volcanic hazard information between scientists and stakeholders:
insights on the influence of communication format

2. What is this project about?

Entering a new era in volcanic hazard mapping

Destructive phenomena generated by volcanic activity, such as ash fall, can have lasting impacts on communities living near a volcano. Volcanic hazard maps created by scientists help community stakeholders manage hazards by showing where, and to what degree, destructive phenomena may occur. Traditional hazard maps are created using general qualitative expressions such as “high,” “medium,” and “low” to describe the destructive potential of a volcano in an area. You may have seen this style of map before.

However, today there is a growing trend in the use of probabilities to describe volcanic hazards. These modern probabilistic methods allow scientists to generate detailed numerical distributions that express the likelihood of a specific volcanic hazard occurring in an area. As probabilistic methods for hazard analysis grow and evolve, and become more popular among scientists, the way in which volcanic hazards are communicated through maps is changing commensurately.

Designing new volcanic hazard maps to suit you

The outputs of probabilistic tools have higher resolution and complexity than traditional qualitative hazard data, and can be expressed in many ways (for example, different colour scales or number formats). Yet while scientists are now creating and distributing more probabilistic hazard maps than ever before, little work has been done to explore the effectiveness and clarity of these maps with the people who will use them – stakeholders like you. This study investigates how probabilistic hazard maps are understood and applied by the people who use them, and explores what kinds of design components and content make probabilistic volcanic hazard maps easiest to understand, interpret, and utilise for the stakeholders who will use them to make decisions.

3. What does my participation in this study involve?

What will I do?

If you choose to participate in this study, you will discuss volcanic hazard maps with the PhD student researcher, Mary Anne Thompson, in a conversational-style interview. You will
discuss your experience with volcanic hazards and volcanic hazard maps, and how you might encounter them in your organisational role. You will look at several new probabilistic volcanic hazard maps of the Bay of Plenty region and will discuss the content and usefulness of the information depicted. The interview will be a casual, relaxed, and open discussion. The researchers encourage you to share your opinions and views.

Should I be concerned or worried about the hazards on the maps?
Hazard maps shown in this study are for interview purposes only. Maps will show levels of hazard in the Bay of Plenty from volcanic ash fall associated with different types of eruptions that could occur from the Okataina Volcanic Centre, the large volcanic complex in the Bay of Plenty to which Tarawera volcano belongs. They do not suggest any real or coming events. Ash fall hazards presented on the maps are non-life-threatening hazards. Maps presented in this study have not been peer-reviewed or published and should not be used to make decisions. If you are uncomfortable discussing volcanic hazards and volcanic eruptions, you should not consent to participate in this study.

Will I benefit from this study?
As a member of a stakeholder group in the Bay of Plenty who may use volcanic hazard maps in your role, this study provides you with the opportunity to shape the information you will receive from future maps so that it better meets your groups needs for management and mitigation of volcanic hazard and risk. Better volcanic hazard maps could lead to less stakeholder loss in the event of future volcanic activity.

4. What are the objectives of this project?
From the interviews, the researchers hope to learn information to achieve the following objectives:

**Objective 1:**
Improve the communication of probabilistic volcanic hazard information between scientists and regional and district level stakeholders by investigating how probabilistic volcanic hazard maps are understood and used by stakeholders for decision-making, and

**Objective 2:**
Create guidelines that help scientists build volcanic hazard maps that better meet stakeholders’ needs for practical and informed decision-making.

5. Who is performing this research?
The study is being conducted by Mary Anne Thompson as part of her research for a Doctorate of Philosophy (PhD) degree in Geology at the University of Auckland’s School of Environment under the supervision of Jan Lindsay and JC Gaillard.

6. Do I have permission from my employer to participate in this research?
Your employer has given assurance that your participation or non-participation will not affect your relationship and employment with the organisation.

7. Procedures

**Before the interview**
After reading this Participant Information Sheet, please discuss any questions or concerns you have with the PhD student researcher, Mary Anne Thompson, until they are answered to your satisfaction. After you have read and discussed the Participant Information Sheet and signed the Consent Form, the interview will begin.
During the interview

You and the PhD student researcher, Mary Anne Thompson, will be the only persons present for your interview, which will be held in a closed room to preserve your anonymity and the confidentiality of your responses. The interview will be audio-recorded to ensure research accuracy. The interview is expected to take approximately 45 minutes to one hour of your time. The PhD student researcher will have a personal list of topics to guide discussion, and may be taking research notes during the interview, but the environment will be casual, relaxed, and flexible to any ideas and comments. During the interview you will see several probabilistic volcanic hazard maps to prompt discussion.

After the interview

After the interview, you are encouraged to ask any questions about the project that you may have. The researchers will use your anonymous interview results, along with other anonymous interviews, to draw interpretations about the effectiveness of probabilistic hazard maps and the objectives of this study. Remarks made during the interview that are interesting or relevant to the research objectives will be transcribed by the PhD student researcher. Audio-recording ensures the accuracy of these transcriptions. You may request to review and edit a copy of any transcripts from your interview. This request can be made on the Consent Form. Your confidentiality is of high importance and you will never be individually identified with your responses to persons other than the student researcher, principle investigator, and co-investigator.

8. Data storage, retention, destruction and future use

Your interview audio records and partial transcripts will be stored for six years in a confidential and secure location on the University of Auckland campus with the student researcher, Mary Anne Thompson. Data will be published as part of Mary Anne Thompson’s PhD thesis and will be used in peer-reviewed publications authored by Thompson, Jan Lindsay and JC Gaillard. Transcripts from your interview (which you will have the opportunity to review and edit) may be used in these works; however, your identity will not be disclosed with the transcription and will remain confidential. On the Consent Form, you may request to receive a summary of findings, which will be available to you after completion of the project. After six years, the audio records and audio record transcripts will be deleted and destroyed.

9. Right to withdraw from participation

Do I have to consent to participate in this study?

Participating in this study is completely voluntary, and you are under no obligation to consent to this interview. It is your choice whether or not you choose to participate in this study.

What if I decide I don’t want to finish after I already consent and begin the interview?

You can elect to withdraw from the study at any time prior to completion of your interview. Simply state to the PhD student researcher that you no longer wish to continue and that you would like to withdraw your participation. If you withdraw, all of your audio-records and responses will be destroyed and will not be used in the study. Once you have completed the interview, your responses may only be withdrawn by notifying the researchers within 7 days from the date of the interview.
10. Confidentiality

Your individual identity will be known only to the student researcher, Mary Anne Thompson, the principle investigator, Jan Lindsay, and the co-investigator JC Gaillard. The research discussions that take place between you and the student researcher during the interview should not be discussed with persons other than the student researcher, principle investigator, or co-investigator.

11. Contact details

Who can I contact about the research project?

When you have read this information, the PhD student researcher, Mary Anne Thompson, will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact Mary Anne Thompson by e-mail at m.thompson@auckland.ac.nz or by telephone at +64 9 373 7599 ext. 88403. Alternatively, you can e-mail the principle investigator, Jan Lindsay, at j.lindsay@auckland.ac.nz or you can e-mail the co-investigator, JC Gaillard, at j.c.gaillard@auckland.ac.nz.

Who can I contact if I have a concern or complaint about the study?

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142; Telephone: 09 373-7599 extn. 87830/83761; Email: humanethics@auckland.ac.nz. You may also contact Paul Kench, Head of the School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142; Telephone 09 373-7599 extn. 86440; Email: p.kench@auckland.ac.nz.

12. Approval

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 04 JUNE 2013 FOR (3) YEARS REFERENCE NUMBER 0623.
CONSENT FORM
CEO Bay of Plenty stakeholder organisation

"This form will be held for six years."

I ________________________________ [PRINT NAME] have read the Request for Permission for Employee Participation in Research Study and the Participant Information Sheet for the study entitled Exchange of probabilistic volcanic hazard information between scientists and stakeholders: insights on the influence of communication format being conducted by Mary Anne Thompson under the supervision of Jan Lindsay and JC Gaillard. I have understood the nature of the research, and why members of my organisation have been selected to participate. I have had the opportunity to ask questions and have had them answered to my satisfaction.

- I give permission for members of my organisation to take part as participants in this project and agree to them being interviewed by the student researcher, Mary Anne Thompson.
- I understand that participation will take approximately 45 minutes to one hour of time.
- I understand that individual participants and/or my organisation are free to withdraw participation at any time before completing an interview, and that after completion of the interview responses may only be withdrawn by the individual participant notifying the researchers within 7 days from the date of the interview. I understand that my organisation does not have the right to withdraw data given by individual participants.
- I understand that the participants will be audio recorded, that the records will be partially transcribed by the student researcher, and that participants may request to review and edit their transcripts.
- I agree not to discuss the project with the persons other than the student researcher, principle investigator, or co-investigator.
- I understand that the participants' audio-records, transcripts, and responses are confidential and will be securely kept by the researchers for 6 years, after which it will be destroyed.
- I understand that the participants' identity will only be known by the student researcher, principle investigator, and co-investigator.
- I understand that the hazard maps used in this interview are not peer-reviewed or published and are not to be used for decision-making.
- I give assurance that participation or non-participation will not affect the participant's relationship and employment with the organisation.
- I □ wish / □ do not wish to receive a summary of findings after completion of the project (please check one).

E-mail for summary: ________________________________

Signature ________________________________ Date ________________

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 04 JUNE 2013 FOR (3) YEARS REFERENCE NUMBER 93263.
PARTICIPANT INFORMATION SHEET
Bay of Plenty stakeholder group member

1. What is the title of this research project?

*Exchange of probabilistic volcanic hazard information between scientists and stakeholders: insights on the influence of communication format*

2. What is this project about?

**Entering a new era in volcanic hazard mapping**

Destructive phenomena generated by volcanic activity, such as ash fall, can have lasting impacts on communities living near a volcano. Volcanic hazard maps created by scientists help community stakeholders manage hazards by showing where, and to what degree, destructive phenomena may occur. Traditional hazard maps are created using general qualitative expressions such as "high," "medium," and "low" to describe the destructive potential of a volcano in an area. You may have seen this style of map before.

However, today there is a growing trend in the use of probabilities to describe volcanic hazards. These modern probabilistic methods allow scientists to generate detailed numerical distributions that express the likelihood of a specific volcanic hazard occurring in an area. As probabilistic methods for hazard analysis grow and evolve, and become more popular among scientists, the way in which volcanic hazards are communicated through maps is changing commensurately.

**Designing new volcanic hazard maps to suit you**

The outputs of probabilistic tools have higher resolution and complexity than traditional qualitative hazard data, and can be expressed in many ways (for example, different colour scales or number formats). Yet while scientists are now creating and distributing more probabilistic hazard maps than ever before, little work has been done to explore the effectiveness and clarity of these maps with the people who will use them – stakeholders like you. This study investigates how probabilistic hazard maps are understood and applied by the people who use them, and explores what kinds of design components and content make probabilistic volcanic hazard maps easiest to understand, interpret, and utilise for the stakeholders who will use them to make decisions.

3. What does my participation in this study involve?

**What will I do?**

If you choose to participate in this study, you will discuss volcanic hazard maps with the PhD student researcher, Mary Anne Thompson, in a conversational-style interview. You will
discuss your experience with volcanic hazards and volcanic hazard maps, and how you might encounter them in your organisational role. You will look at several new probabilistic volcanic hazard maps of the Bay of Plenty region and will discuss the content and usefulness of the information depicted. The interview will be a casual, relaxed, and open discussion. The researchers encourage you to share your opinions and views.

Should I be concerned or worried about the hazards on the maps?

Hazard maps shown in this study are for interview purposes only. Maps will show levels of hazard in the Bay of Plenty from volcanic ash fall associated with different types of eruptions that could occur from the Okataina Volcanic Centre, the large volcanic complex in the Bay of Plenty to which Tarawera volcano belongs. They do not suggest any real or coming events. Ash fall hazards presented on the maps are non-life-threatening hazards. Maps presented in this study have not been peer-reviewed or published and should not be used to make decisions. If you are uncomfortable discussing volcanic hazards and volcanic eruptions, you should not consent to participate in this study.

Will I benefit from this study?

As a member of a stakeholder group in the Bay of Plenty who may use volcanic hazard maps in your role, this study provides you with the opportunity to shape the information you will receive from future maps so that it better meets your groups needs for management and mitigation of volcanic hazard and risk. Better volcanic hazard maps could lead to less stakeholder loss in the event of future volcanic activity.

4. What are the objectives of this project?
From the interviews, the researchers hope to learn information to achieve the following objectives:

**Objective 1:**
Improve the communication of probabilistic volcanic hazard information between scientists and regional and district level stakeholders by investigating how probabilistic volcanic hazard maps are understood and used by stakeholders for decision-making, and

**Objective 2:**
Create guidelines that help scientists build volcanic hazard maps that better meet stakeholders’ needs for practical and informed decision-making.

5. Who is performing this research?
The study is being conducted by Mary Anne Thompson as part of her research for a Doctorate of Philosophy (PhD) degree in Geology at the University of Auckland’s School of Environment under the supervision of Jan Lindsay and JC Gaillard.

6. Do I have permission from my employer to participate in this research?
Your employer has given assurance that your participation or non-participation will not affect your relationship and employment with the organisation.

7. Procedures

**Before the interview**

After reading this Participant Information Sheet, please discuss any questions or concerns you have with the PhD student researcher, Mary Anne Thompson, until they are answered to your satisfaction. After you have read and discussed the Participant Information Sheet and signed the Consent Form, the interview will begin.
During the interview

You and the PhD student researcher, Mary Anne Thompson, will be the only persons present for your interview, which will be held in a closed room to preserve your anonymity and the confidentiality of your responses. The interview will be audio-recorded to ensure research accuracy. The interview is expected to take approximately 45 minutes to one hour of your time. The PhD student researcher will have a personal list of topics to guide discussion, and may be taking research notes during the interview, but the environment will be casual, relaxed, and flexible to any ideas and comments. During the interview you will see several probabilistic volcanic hazard maps to prompt discussion.

After the interview

After the interview, you are encouraged to ask any questions about the project that you may have. The researchers will use your anonymous interview results, along with other anonymous interviews, to draw interpretations about the effectiveness of probabilistic hazard maps and the objectives of this study. Remarks made during the interview that are interesting or relevant to the research objectives will be transcribed by the PhD student researcher. Audio-recording ensures the accuracy of these transcriptions. You may request to review and edit a copy of any transcripts from your interview. This request can be made on the Consent Form. Your confidentiality is of high importance and you will never be individually identified with your responses to persons other than the student researcher, principle investigator, and co-investigator.

8. Data storage, retention, destruction and future use

Your interview audio records and partial transcripts will be stored for six years in a confidential and secure location on the University of Auckland campus with the student researcher, Mary Anne Thompson. Data will be published as part of Mary Anne Thompson’s PhD thesis and will be used in peer-reviewed publications authored by Thompson, Jan Lindsay and JC Gaillard. Transcripts from your interview (which you will have the opportunity to review and edit) may be used in these works; however, your identity will not be disclosed with the transcription and will remain confidential. On the Consent Form, you may request to receive a summary of findings, which will be available to you after completion of the project. After six years, the audio records and audio record transcripts will be deleted and destroyed.

9. Right to withdraw from participation

Do I have to consent to participate in this study?

Participating in this study is completely voluntary, and you are under no obligation to consent to this interview. It is your choice whether or not you choose to participate in this study.

What if I decide I don’t want to finish after I already consent and begin the interview?

You can elect to withdraw from the study at any time prior to completion of your interview. Simply state to the PhD student researcher that you no longer wish to continue and that you would like to withdraw your participation. If you withdraw, all of your audio-records and responses will be destroyed and will not be used in the study. Once you have completed the interview, your responses may only be withdrawn by notifying the researchers within 7 days from the date of the interview.
10. Confidentiality

Your individual identity will be known only to the student researcher, Mary Anne Thompson, the principle investigator, Jan Lindsay, and the co-investigator JC Gaillard. The research discussions that take place between you and the student researcher during the interview should not be discussed with persons other than the student researcher, principle investigator, or co-investigator.

11. Contact details

Who can I contact about the research project?

When you have read this information, the PhD student researcher, Mary Anne Thompson, will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact Mary Anne Thompson by e-mail at m.thompson@auckland.ac.nz or by telephone at +64 9 373 7599 ext. 85403. Alternatively, you can e-mail the principle investigator, Jan Lindsay, at j.lindsay@auckland.ac.nz or you can e-mail the co-investigator, JC Gaillard, at jc.gaillard@auckland.ac.nz.

Who can I contact if I have a concern or complaint about the study?

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142; Telephone: 09 373-7599 extn. 87630/83761; Email: humanethics@auckland.ac.nz You may also contact Paul Kench, Head of the School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142; Telephone 09 373-7599 extn. 86440; Email: p.kench@auckland.ac.nz.

12. Approval

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 04 JUNE 2013 FOR (3) YEARS REFERENCE NUMBER 9623.
CONSENT FORM
Bay of Plenty stakeholder group member

*This form will be held for six years.*

I ___________________________ [PRINT NAME] have read the Participant Information Sheet for the study entitled Exchange of probabilistic volcanic hazard information between scientists and stakeholders: insights on the influence of communication format being conducted by Mary Anne Thompson under the supervision of Jan Lindsay and JC Gailard. I have understood the nature of the research, and why I have been selected. I have had the opportunity to ask questions and have had them answered to my satisfaction.

- I agree to take part in this project and agree to being interviewed by the student researcher, Mary Anne Thompson.
- I understand that my participation will take approximately 45 minutes to one hour of my time.
- I understand that I am free to withdraw my participation at any time before completing the interview, and that after completion of the interview my responses may only be withdrawn by notifying the researchers within 7 days from the date of the interview.
- I understand that I will be audio recorded, and that the records will be partially transcribed by the student researcher, Mary Anne Thompson.
- I agree not to discuss the interview with persons other than the student researcher, principle investigator, or co-investigator.
- I understand that my audio-records, transcripts, and responses are confidential and will be securely kept by the researchers for 6 years, after which it will be destroyed.
- I understand that my identity will only be known by the PhD student researcher, principle investigator, and co-investigator.
- I understand that my employer has given assurance that my participation or non-participation will not affect my relationship and employment with the organisation.
- I understand that the hazard maps used in this interview are not peer-reviewed or published and are not to be used for decision-making.
- I □ wish / □ do not wish to receive a copy of the transcripts from my interview to review and edit (please check one).
- I □ wish / □ do not wish to receive a summary of findings after completion of the project (please check one).
E-mail for summary and/or transcripts: ___________________________

Signature________________________ Date_____________________

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 04 JUNE 2013 FOR (3) YEARS REFERENCE NUMBER 9823.
Designing Volcanic Hazard Maps that WORK

You're invited to....

A study to explore how we can better communicate volcanic hazards

As probabilistic methods for hazard analysis grow and evolve, the way in which volcanic hazards are communicated through maps is changing. The outputs of probabilistic tools have higher resolution and complexity than traditional qualitative hazard data, and can be expressed in many different ways on a map.

Yet while scientists are now creating and distributing more probabilistic volcanic hazard maps than ever before, little work has been done to explore the effectiveness and clarity of these maps with the end-users, stakeholders who seek to manage and mitigate volcanic hazards.

A new doctoral study being conducted at the University of Auckland School of Environment seeks to explore how applying different features and formats to volcanic hazard maps influences interpretation and comprehension of probabilistic volcanic hazard information so that we can discover the clearest and best ways to communicate it.

Tell us how maps can be designed to meet your decision-making needs

This study will be conducted using conversational-style interviews with people who may receive and use volcanic hazard maps.

If you are a member of a stakeholder group in the Bay of Plenty who may use volcanic hazard maps for decision-making, this study provides you with the opportunity to shape the information you will receive from future maps so that it better meets your organisation's needs for management and mitigation of volcanic hazard and risk. Better volcanic hazard maps could lead to less stakeholder loss in the event of future volcanic activity.

Help strengthen communication between scientists and stakeholders

If you are a member of a Bay of Plenty stakeholder organisation and are interested in participating in a one-on-one interview, please contact Mary Anne Thompson at m.thompson@auckland.ac.nz or +64 9 373 7599 extn. 88403.

Your participation can help us understand what factors play a role in how volcanic hazard data are understood and used in decision-making, and how we can strengthen the communication pathway for hazard information between scientists and stakeholders.

Vary Anne Thompson
PhD student
University of Auckland
m.thompson@auckland.ac.nz

Juan Lindsay
PhD Supervisor
j.lindsay@auckland.ac.nz

JC Gallard
PhD Co-supervisor
jc.gallard@auckland.ac.nz

G Jo y
PhD Advisor
g.joly@gmsa.co.nz
Interested?

If you are a member of a stakeholder group in the Bay of Plenty who may use volcanic hazard maps in your role, this study provides you with the opportunity to shape the information you will receive from future maps so that it better meets your organisation’s needs for management and mitigation of volcanic hazard and risk. Better volcanic hazard maps could lead to less stakeholder loss in the event of future volcanic activity.

If you are interested in doing an interview for the study or if you would like more information about the study please fill out the form below and give it to the researchers. Alternatively, you may contact Mary Anne Thompson at:

m.thompson@auckland.ac.nz
or
+64 (0)3 373 7599 ext. 88403

First Name: ________________________________
Surname: ________________________________
Organisation: ________________________________
E-mail: ________________________________

☑️ I would like to receive communication about this study (PLEASE CHECK)

Mary Anne Thompson
PhD student
School of Environment
University of Auckland
m.thompson@auckland.ac.nz
+64 (3) 373 7599 ext. 88403

Jan Lindsay
PhD Supervisor
j.lindsay@auckland.ac.nz

JC Gaillard
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j.cosg坷@auckland.ac.nz

Gill Jolly
PhD Advisor
g.jolly@gns.cri.nz

Designing Volcanic Hazard Maps that WORK

All photos and figures courtesy of M.A. Thompson.

This study is currently being reviewed by the University of Auckland Human Participant Ethics Committee. No research will commence until ethics approval has been granted.
Designing volcanic hazard maps to meet your needs

Why?

Recent changes in volcano hazard assessment have seen a shift from traditional qualitative hazard maps that show broad "high," "medium," and "low" hazard areas, to modern quantitative maps that show distributions of the probability or likelihood that a specific volcanic hazard will occur in a certain area.

As probabilistic methods for hazard analysis grow and evolve, the way in which volcanic hazards are communicated through maps is changing. The outputs of probabilistic tools have higher resolution and complexity than traditional qualitative hazard data, and can be expressed in many ways.

Yet while scientists are now creating and distributing more probabilistic hazard maps than ever before, little work has been done to explore the effectiveness and clarity of these maps with end-users.

Objectives

To improve the communication of probabilistic volcanic hazard information between scientists and regional and district level stakeholders by investigating how probabilistic volcanic hazard maps are understood and used by stakeholders for decision-making.

To create guidelines that help scientists build volcanic hazard maps that better meet stakeholders' needs for practical and informed decision-making.

How?

Participants in this study will do a private 45 - 60 minute conversational-style interview conducted by University of Auckland PhD student, Mary Anne Thompson.

You will discuss your experience with volcanic hazards and volcanic hazard maps, and how you might encounter them in your organisational role. You will look at several new probabilistic volcanic hazard maps of the Bay of Plenty region and will discuss the content and usefulness of the information depicted. The interview will be a casual, relaxed, and open discussion. The researchers will encourage you to share your opinions and views.

Your identity will be strictly confidential and will never be disclosed with your responses, audio records, or transcripts.

Clear

- Is the map information clear and easy to understand?
- How do map styles and features affect interpretation?
- How well are probabilities comprehended?

Helpful

- Are the maps' design helpful for making decisions?
- Do the maps show the hazard information that is most helpful or important to stakeholders?

Informative

- Are maps with quantitative information more helpful than maps with qualitative information?
- How do probabilities inform decision-making?
Participant Information Sheet

This sheet has information for people interested in participating in the survey study titled “Exploring the influence of probabilistic volcanic hazard map design on user comprehension and engagement” being conducted by Mary Anne Thompson, Jan Lindsay, and JC Gaillard at the University of Auckland School of Environment.

What is the study about?

Volcanic hazard maps are often considered useful tools for decision-making in areas near potentially active volcanoes. Traditionally, volcanic hazard maps used phrases like “low,” “medium,” and “high,” to describe hazard. Today, maps are becoming more and more quantitative. Modern maps are often based on the results of probabilistic computer models that run hundreds to thousands of simulations of possible volcanic eruptions to see what the likely hazards will be in a real event.

This survey looks at how map design affects the way probabilistic volcanic hazard data is understood in order to identify design elements that we can use to enhance map clarity and usefulness.

What does participation involve?

Participation in this study is completely voluntary. You are under no obligation to participate. Completion and submission of the survey is implied as consent to participate.

If you choose to participate, you will answer 31 questions, mostly multiple-choice, about different probabilistic volcanic ash hazard maps. You will be asked about what you see, what you like, what is helpful, and what is clear or confusing.

The goal is to identify what design properties make the information most helpful, clear, and applicable for potential volcanic hazard map users like you.

Will I benefit from this study?

As a potential volcanic hazard map user, this study provides you with the opportunity to shape the future hazard maps you will receive so that they better suit your needs. Better volcanic hazard maps could lead to less loss in the event of future volcanic activity.

What happens with my answers?

Your answers to this survey are completely anonymous. No personally-identifying information will be collected by the researchers, and your participation is confidential.

The researchers will use the results of the surveys to help design clearer, more effective probabilistic volcanic hazard maps that meet decision-making needs. Results will be published
as part of Thompson's PhD thesis. Results may be published in peer-reviewed scientific journals. You may request a summary of the findings of this study at the beginning of the survey.

Do I have to finish the survey?
No. You may quit the survey at any time and your answers will not be recorded. Please note that completing and submitting the survey is implied as consent to participate. Withdrawal is not possible after submitting the survey due to the anonymous nature of the questionnaire.

Who can I contact about the research project?
If you would like to know more at any stage, please feel free to contact Mary Anne Thompson by e-mail at m.thompson@auckland.ac.nz or by telephone at +64 9 373 7599 ext. 888243. Alternatively, you can e-mail the principle investigator, Jan Lindsay, at j.lindsay@auckland.ac.nz or you can e-mail the co-investigator, JC Gaillard, at jc.gaillard@auckland.ac.nz.

Who can I contact if I have a concern or complaint about the study?
For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142; Telephone: 09 373-7599 extn. 87830/83761; Email: humanethics@auckland.ac.nz. You may also contact Paul Kench, Head of the School of Environment, The University of Auckland, Private Bag 92019, Auckland 1142; Telephone 09 373-7599 extn. 88440; Email: p.kench@auckland.ac.nz.

THIS STUDY WAS APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 15 APRIL 2104 FOR (3) YEARS REFERENCE NUMBER 011505.
APPENDIX B
Copy of online survey
Welcome to the survey on volcanic hazard maps!

Volcanic hazard maps are often considered useful tools for decision making in areas near potentially active volcanoes. Traditionally, volcanic hazard maps used phrases like “low,” “medium,” and “high” to describe hazard. Today, maps are becoming more and more quantitative. Modern maps are often based on the results of probabilistic computer models that run hundreds to thousands of simulations of possible volcanic eruptions to see what the likely hazards will be in a real event.

This 10-20 minute survey looks at how probabilistic volcanic hazard data is represented and understood on maps.

In this survey, you will answer mainly multiple-choice questions about different probabilistic volcanic ash hazard maps. You will be asked about what you see, what you like, what is helpful, and what is clear or confusing. The goal is to identify what design properties make the information most helpful, clear, and applicable for potential volcanic hazard map users like you.

The researchers will use the results to help New Zealand design better probabilistic volcanic hazard maps and offer this opportunity to help shape the maps to meet your decision-making needs. The study is part of a PhD thesis at the University of Auckland. Results may be published in peer-reviewed scientific journals. You may request a summary of the findings of this study.

- Your participation and identity are completely anonymous. The researchers will not collect any personally-identifying information about you.
- Your participation is completely voluntary. You are under no obligation to participate in this survey.
- Completing and submitting the survey is implied as consent. Withdrawal is not possible after submitting the survey due to the anonymous nature of the questionnaire.
- Volcanic hazard maps presented here are hypothetical, have not been published, and should not be used for decision making.
- You may download a full copy of the participant information sheet here.

If you have any questions about this study, please contact the University of Auckland researcher Mary Anne Thompson at m.thompson@ auf.ac.nz or 09-373 7999 ext. 89824.

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANT ETHICS COMMITTEE ON 15 APRIL 2014 FOR 3 YEARS REFERENCE NUMBER 011505.

1. I understand that my participation in this survey is completely voluntary and completely anonymous.
   - Yes
   - No

2. I understand that a summary of findings will be posted at this URL once the study has been completed, and that I may choose to check back at this site in the future to read or download them.
   - Yes
   - No

3. What category best describes your primary field of work?
   - Physical/Chemical/Earth Science (academic or scientific organization)
   - Social Science (academic or scientific organization)
   - Emergency Management and Planning
   - Infrastructure/Resource Management
   - Health
   - Education
   - Engineering
   - Government
   - Agriculture
   - Communication
   - Other (specify)

4. Have you ever experienced volcanic activity, or do you have any memories associated with volcanic activity?
   - Yes
   - No
   If yes, please briefly describe:

5. In your opinion, how important is it to have a volcanic hazard map for the potentially active volcanoes in New Zealand?
   - Very important
   - Important
   - Somewhat important
   - Not important
   - Not important at all
   - Not sure
Below is a map that shows the probability of accumulating 1 mm of ash if an eruption were to occur at Tarawera volcano.

Use the map to answer questions 6 and 7.

6. If Tarawera were to erupt, what is the probability of accumulating 3 mm of volcanic ash at Whakatane?
   Please give a percent value (e.g., 8%) or a range of percent values (e.g., 2-10%)

7. According to this map, how would you describe the volcanic ash hazard at Whakatane based on the event of an eruption from Tarawera?
   - Very high hazard
   - High hazard
   - Medium hazard
   - Low hazard
   - Very low hazard
   - No hazard
   - Not sure
Below is a map that shows the probability of accumulating 1 mm of ash if an eruption were to occur at Tarawera volcano.

Use the map to answer questions 8 and 9.

8. If Tarawera were to erupt, what is the probability of accumulating 1 mm of volcanic ash at Whakatane?

   Please give a percent value (e.g., 6%) or a range of percent values (e.g., 2 - 10%).

9. According to this map, how would you describe the volcanic ash hazard at Whakatane based on the event of an eruption from Tarawera?

   - Very high hazard
   - High hazard
   - Medium hazard
   - Low hazard
   - Very low hazard
   - No hazard
   - Not sure
Below is a map that shows the probability of accumulating 1 mm of ash if an eruption were to occur at Tarawera volcano.

Use the map to answer questions 10 and 11.

10. If Tarawera were to erupt, what is the probability of accumulating 1 mm of volcanic ash at Whakatane?
   Please give a percent value (e.g. 8%) or a range of percent values (e.g. 2 - 10%)

11. According to this map, how would you describe the volcanic ash hazard at Whakatane based on the event of an eruption from Tarawera?
   - Very high hazard
   - High hazard
   - Medium hazard
   - Low hazard
   - Very low hazard
   - No hazard
   - Not sure
The maps in the previous three questions (here, Map A, B, and C) had the same data presented in different ways on the map.

Please use Map A, B, and C to answer question 12 and 13.
12. Please order the three maps (Map A, B, and C) in order of personal preference. Please briefly explain your choice(s):

Drag and drop answer to the box at the right, where:

1. Top = Most preferred
2. Bottom = Least preferred

- Map A
- Map B
- Map C

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Map B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Map C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13. Please your reasons for your ranking in question 11.
B Copy of online survey

14. Please rank the helpfulness of each map style using the grid below. Map A can be made for any ash thickness. Map B can be made for any probability level.

<table>
<thead>
<tr>
<th>Very helpful</th>
<th>Helpful</th>
<th>Somewhat helpful</th>
<th>Not helpful</th>
<th>Not sure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map A</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Map B</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

15. If you were to receive a map for use, which would you prefer?
- Map A
- Map B
- Map A and B together
- No preference

Below is a map that shows what thicknesses of volcanic ash have, on average, a 25% probability (or 1 in 4 likelihood) of occurring if an eruption were to occur at Tarawera volcano. Three keys (A, B, and C) are presented for the map.

Use the map and keys A-C to answer questions 16 and 17.
18. Which key do you prefer for the map?
   - Key A
   - Key B
   - Key C
   - No preference

17. Does the phrasing of the key between A and B change how you perceive the level of hazard presented on the map?
   - No, I perceive the level of hazard the same with both phrasing
   - Yes, “25% probability” makes the hazard seem lower than “1 in 4 likelihood”
   - Yes, “25% probability” makes the hazard seem higher than “1 in 4 likelihood”
   - Yes, “1 in 4 likelihood” makes the hazard seem lower than “25% probability”
   - Yes, “1 in 4 likelihood” makes the hazard seem higher than “25% probability”
   - Not sure

Comments (optional):

Below is a hazard curve based on the same data used to create the maps in the previous questions. This curve has been generated for the town of Whakatane, but the curves can be generated for any location. The curve shows the annual probability of accumulating ash in Whakatane from an eruption at Tarawera.

Please use the hazard curve for Whakatane below to answer questions 18 and 19.

![Volcanic Ash Hazard Curve](image)

18. According to the hazard curve, which of the following statements is true for the ash hazard at Whakatane over the next 1 year?
   - On average, there is a 0.01% probability of accumulating 20 mm of ash from Tarawera
   - There is 10% confidence that there is a 0.005% probability of accumulating 60 mm of ash from Tarawera
   - There is 80% confidence that there is a 0.015% probability of accumulating 40 mm of ash from Tarawera
   - There is 80% confidence that there is a 0.005 – 0.011% probability of accumulating 60 mm of ash from Tarawera
   - There is 90% confidence that there is a 0.005 – 0.011% probability of accumulating 40 mm of ash from Tarawera

19. How easy or difficult is it to read information from the hazard curve pictured above?
   - Very easy
   - Easy
   - Average
   - Difficult
   - Very difficult
   - Not sure
Below is a hazard curve based on the same data used to create the maps in the previous questions. This curve has been generated for the town of Whakatane, but the curves can be generated for any location. The curve shows the annual probability of accumulating ash in Whakatane from an eruption at Tarawera.

Please use the hazard curve for Whakatane below to answer questions 20-21.

20. According to the hazard curve, which of the following statements is true for the ash hazard at Whakatane over the next 1 year?
   - On average, there is a 0.01% probability of accumulating 20 mm of ash from Tarawera.
   - There is 80% confidence that there is a 0.005% probability of accumulating 60 mm of ash.
   - There is 90% confidence that there is a 0.01% probability of accumulating 40 mm of ash.
   - There is 90% confidence that there is a 0.005 – 0.011% probability of accumulating 60 mm of ash.
   - There is 90% confidence that there is a 0.017% probability of accumulating 20 mm of ash.
   - There is 90% confidence that there is a 0.005 – 0.011% probability of accumulating 40 mm of ash.

21. How easy or difficult is it to read information from the hazard curve pictured above?
   - Very easy
   - Easy
   - Average
   - Difficult
   - Very difficult
   - Not sure

22. How helpful would it be to have hazard curves available for certain locations on the hazard map?
   - Very helpful
   - Helpful
   - Somewhat helpful
   - Not helpful
   - Not helpful at all
   - Not Sure
The three sets of maps below show the same volcanic hazard data from previous questions presented in different colour schemes.

Use Sets A, B, and C to answer questions 23 - 25.

**Colour set A**

![Map](image1)

**Colour set B**

![Map](image2)

**Colour set C**
23. Which of the above volcanic ash maps do you prefer?

- Colour set A
- Colour set C
- No preference

24. Please describe the reason for your choice in question 23.

25. Does the colour set change how you perceive the hazard?

- No, the hazard is the same
- Yes, a little bit
- Yes, a lot

Comments:
The map below is a map from a previous question, but with text included above.

Please use the map below to answer question 26.

26. To what degree does the text provided above the map help your understanding of the information on this map?
- Very helpful
- Helpful
- Somewhat helpful
- Not helpful
- Not helpful at all
- Not sure

Comments:

27. In your opinion, how important is it to include explanatory text on the hazard map itself (in addition to any accompanying information provided with the map)?
- Very important
- Important
- Somewhat important
- Not important
- Not important at all
- Not sure

Comments (optional):
28. In what format(s) do you want to receive volcanic hazard maps? You may select more than one answer.
- Paper
- PDF
- JPEG
- KML
- GIS layer
Other(s) (specify):

29. What is your age bracket?
- 18-24
- 25-44
- 45-64
- 65+
- Prefer not to answer

30. What is your ethnicity?
- New Zealand European
- New Zealand Maori
- Other European
- Asian
- Pacific
- Other
- Prefer not to answer

31. What is your highest level of education?
- Did not complete High School
- High School/GED
- Vocational/Trade qualification
- Tertiary degree
- Postgraduate degree
- Prefer not to answer

Volcanic Hazard Map Survey 2014

Thank you for participating in this survey. Your input will help us design a volcanic hazard map that better suits your needs.

If you have any further questions about the study please contact Mary Anne Thompson at m.thompson@auckland.ac.nz.
APPENDIX C

PyBetVH manuscript
(Tonini, Sandri & Thompson, in review in Computers and Geosciences)
PyBetVH: a Python tool for probabilistic volcanic hazard assessment and for generation of Bayesian hazard curves and maps

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ABSTRACT

PyBetVH is a completely new, free, open-source and cross-platform software implementation of the Bayesian Event Tree for Volcanic Hazard (BET_VH), a tool for estimating the probability of any magmatic hazardous phenomenon occurring in a selected time frame, accounting for all the uncertainties. New capabilities of this implementation include the ability to calculate hazard curves which describe the distribution of the exceedance probability as a function of intensity (e.g., tephra load) on a grid of points covering the target area. The computed hazard curves are (i) absolute (accounting for the probability of eruption in a given time frame, and for all the possible vent locations and eruptive sizes) and (ii) Bayesian (computed at different percentiles, in order to quantify the epistemic uncertainty). Such curves allow representation of the full information contained in the probabilistic volcanic hazard assessment (PVHA) and are well suited to become a main input to quantitative risk analyses.

PyBetVH allows for interactive visualization of both the computed hazard curves, and the corresponding Bayesian hazard/probability maps. PyBetVH is designed to minimize the efforts of end users, making PVHA results accessible to people who may be less experienced in probabilistic methodologies, e.g. decision makers. The broad compatibility of Python language has also allowed PyBetVH to be installed on the VHub cyber-infrastructure, where it can be run online or downloaded at no cost. PyBetVH can be used to assess any type of magmatic hazard from any volcano. Here we illustrate how to perform a PVHA through PyBetVH using the example of analysing tephra fallout from the Okataina Volcanic Centre (OVC), New Zealand, and highlight the range of outputs that the tool can generate.

Keywords

Probabilistic volcanic hazard assessment; interactive visualization; Bayesian event tree; hazard curves; graphical user interface
1 INTRODUCTION

Volcanic eruptions, as with all natural hazards, are very hazardous events which can have a devastating impact on human settlements worldwide, in terms of both human and economic losses. Probabilistic volcanic hazard assessment (PVHA) methodologies allow for the quantification of intrinsic uncertainties relating to volcanic eruptions and can therefore play a fundamental role in risk reduction strategies, making them of interest to both scientists and decision makers (Marzocchi and Bebbington 2012). However, despite its growth in the last decade, PVHA is still a relatively young methodology with respect to the more classical scenario-based approaches used in volcanology (e.g., Orsi et al. 2004).

Existing PVHA approaches primarily produce the following results:

- Conditional probability maps (e.g., Bonadonna et al. 2005, 2006; Macedonio et al. 2008; Costa et al. 2009) which show the exceedance probability of one selected intensity threshold (e.g., a value of tephra load), on a grid of points over the target area. The displayed probabilities are conditional to the occurrence of an eruption or of a specific scenario.

- Absolute probability maps (e.g., Sandri et al. 2014, Tonini et al. 2014) are similar to the conditional probability maps, but the displayed probabilities include the probability of eruption in a given time frame, and consider the hazard from all the possible vent positions and eruptive sizes, each weighted with its own probability of occurrence.

- Conditional hazard curves (e.g., Hill et al. 1998; Connor et al. 2001; Bonadonna et al. 2005; Bonadonna 2006; Magill et al. 2006), which show the exceedance probability of different intensity thresholds for a few target points (e.g., airports), conditional to the occurrence of an eruption or of a specific scenario.

The Bayesian Event Tree for Volcanic Hazard (BET_VH, Marzocchi et al. 2010) is an existing tool (downloadable for free at http://bet.bo.ingv.it) for long-term PVHA, which produces both conditional and absolute probability maps, for a wide range of volcanic hazardous phenomena (i.e., lava flows, tephra fallout, pyroclastic flows, lahars, etc.) using a Bayesian event tree model. BET_VH is based on a Bayesian approach, meaning that the probabilities of different volcanic events are represented by a probability density function (pdf). The tool's Bayesian nature allows for quantification of

- the aleatory uncertainty, related to the intrinsic randomness of volcanic processes, and described by a “best evaluation” measure of the pdf, such as the mean or the median, and
- the epistemic uncertainty, related to our degree of knowledge on volcanic processes, and described by a “dispersion” measure of the pdf, e.g. the standard deviation or the 10-90th percentile confidence interval.
Such uncertainties characterize the hazard associated with volcanic eruptions.

BET_VH has been applied to several volcanoes or volcanic areas to perform PVHA for different phenomena, for instance, for tephra fallout at Campi Flegrei, Italy (Selva et al. 2010) and for base surges in the Auckland Volcanic Field, New Zealand (Sandri et al. 2012). Recently, BET_VH has also been used to perform an original multi-hazard assessment at El Misti volcano (Sandri et al. 2014).

Different to its analogue Bayesian Event Tree for Eruption Forecasting (BET_EF, Marzocchi et al. 2008), used to perform short-term eruption forecasting, BET_VH does not include real-time monitoring data as input, but only information connected to long-term analysis (e.g., theoretical model results, a priori beliefs and past frequencies from catalogues). However, a recent prototypical extension of the method has been proposed (Selva et al. 2014) to account also for real-time monitoring data and provide a short-term PVHA. Further, BET_VH and BET_EF tools are currently limited to analyses of magmatic unrest only because non-magmatic unrest is difficult to recognize and quantify. However, another PVHA event tree model currently under development in the frame of the EU project VUELCO is exploring capabilities to include both types of unrest (Rouwet et al. 2014).

Thus far, BET_VH output has been limited to probability maps, which are only partially usable as input to quantitative risk analyses because they account for only one threshold at a time. Hazard curves, in contrast, allow for a continuous range of thresholds or values at once. Absolute hazard curves over a target area have been an important input into quantitative seismic risk analyses for decades (e.g., Cornell 1968) because they allow for the evaluation and comparison of long-term forecasts for a range of hazard values at different levels of uncertainty. Absolute hazard curves could also serve as important inputs into quantitative volcanic risk analyses. However, there are currently no available tools for generating such inputs. This motivated the development of PyBetVH, which incorporates an improved version of the original Bayesian inferential procedure at the base of the BET_VH event tree, enhanced with the additional capability of producing Bayesian absolute hazard curves on a grid of points over the target domain.

PyBetVH is a standalone application fully developed in Python programming language which provides a comprehensive graphical user interface (GUI) for perform a PVHA, from inputing data to visualizing the results. Python grants easy portability and usability to the software, since the language is cross-platform, open source and free of charge. The GUI allows for simple input preparation, easy interaction with the event tree for branch/node selection and calculation, and interactive visualization of the results. In addition, PyBetVH is hosted on the popular VHub virtual platform (https://vhub.org/tools/betvh), where the tool can be either run directly in a browser or downloaded and installed on one’s own computer for free. VHub is a powerful resource in volcanology research which promotes the collaboration among scientists through the sharing of data, ideas, knowledge and tools.
(Palma et al. 2014) and, hosting PyBetVH, will enable it to be accessible to anyone interested in performing a PVHA. Here, the main novelties of PyBetVH are outlined using the example of creating a PVHA for tephra fallout hazard from the Okataina Volcanic Centre (OVC), New Zealand, in order to demonstrate how the tool works.

2 MAIN FEATURES OF PYBETVH

The primary feature of PyBetVH is the computation and interactive visualization of Bayesian hazard curves. Further, the user can decide to compute and show the absolute and/or the conditional version of the Bayesian hazard curves. These characteristics enable the introduction of the following important novelties:

1. the Bayesian nature implies that, on a grid of points covering the target area, PyBetVH computes a set of hazard curves consisting of a best-evaluation hazard curve (the average, describing the aleatory uncertainty) along with several other percentiles’ hazard curves describing the epistemic uncertainty. The hazard curves are implemented according to the methodology proposed by Selva and Sandri (2013), where a Bayesian approach is followed to calculate them at different levels of confidence and in a consistent manner.

2. if the user selects absolute Bayesian hazard curves, PyBetVH computes and displays exceedance probabilities that include the probability of eruption in a user-selected time frame, and account for all the possible vent positions and eruptive sizes (similarly to what done for absolute probability maps in the older version of BET_VH).

3. in order to achieve a complete spatial PVHA on the target area, PyBetVH computes hazard curves on a grid of points at a resolution defined by the user. In case the curves are selected as “absolute”, this makes possible to derive two kinds of Bayesian absolute maps for the chosen time window and target area: the probability map, which shows the probability value of overcoming a user-selected intensity threshold, and the hazard map, which shows the intensity value expected to be overcome at a user-selected probability threshold. Probability and hazard maps are obtained by “cutting” the hazard curves vertically or horizontally at user-selected thresholds for intensity or probability, respectively, in all the points of the target domain. Since PyBetVH hazard curves are Bayesian, the corresponding maps are presented as a best-evaluation map (average) and percentiles maps. In order to better explain this important novelty, in Figure 1 we summarize the meaning of best-evaluation and percentiles hazard/probability maps, and how they can be derived by cutting the Bayesian absolute hazard curves. The results shown in Figure 1 are indeed an anticipation of the output of PyBetVH that we will obtain in the demonstrative application to OVC described in section 5.
We believe that these novelties make PyBetVH a very useful tool for PVHA.

3 THE BET_VH EVENT TREE MODEL

A detailed description of the background theory behind BET_VH is out of the scope of this paper and an interested reader can find more on this probabilistic approach in Marzocchi et al. (2010). Nonetheless, a brief description of the main characteristics of the event tree structure will be recalled in this section in order to allow a better understanding of PyBetVH tool itself. The original event tree model is shown in Figure 2 (top). Each node is assigned a probability by means of a Bayesian approach, meaning

![Bayesian Hazard Curve](image)

*Fig 1* Overview of PVHA results as they can be interactively produced by PyBetVH. The main picture is the Bayesian Hazard Curve for the point represented by the magenta dot in all small maps (in the illustrative example it is the airport of Rotorua), showing the average (solid black line) and the 10th (solid green), 50th (solid red) and 90th (solid blue) percentiles as function of tephra loading (Kg/m²). The corresponding Bayesian Probability Maps for a tephra load of 10 Kg/m² (on the right) and Bayesian Hazard Maps at a probability of 10⁻⁴ per year (on the bottom) are shown at the 10th percentile, average and 90th percentile. Bayesian Probability Maps have been obtained by intersecting the intensity threshold (vertical solid black line) with all the Bayesian Hazard Curve in each point of the target domain, at the selected tephra load threshold of 10 Kg/m². Similarly, the Bayesian Hazard Maps are obtained from the intersection between Bayesian Hazard Curves and the probability threshold (horizontal black dashed line) at the selected exceedance probability of 10⁻⁴ per year.
that a prior probability distribution (usually coming from theoretical models) and information from past data are statistically combined together to obtain a posterior probability (see Marzocchi et al. 2010). BET_VH (and therefore PyBetVH) can calculate both absolute and conditional probability. This corresponds to considering the selected full path or just a single node in the event tree (see Figure 2). Nodes 7 and 8 represent respectively the probability to reach a specific area of the spatial domain and the probability to overcome, in the same area, a given threshold of intensity for a given phenomenon. This definition of nodes 7 and 8 is the same as the current version of BET_VH (Figure 2, top) and allows for compiling of Bayesian probability maps only (e.g., as in Selva et al. 2010; Sandri et al. 2012, 2014; Thompson et al., 2014a in review). In order to calculate Bayesian Hazard Curves at each point of the target domain, the PyBetVH event tree is extended to consider the conditional probability of overcoming an increasing series of intensity thresholds (for example, in the application to OVC that will be shown in Section 5, we use the series of thresholds in tephra load from 0 to 300 kg/m² with a step of 50 kg/m², see also Figure 2, bottom). Since Node 7 describes the probability of overcoming a threshold of intensity equal to 0, in PyBetVH Nodes 7 and 8 have been merged in a single one, here named Node 7&8 (see again Figure 2, bottom).

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**Fig 2** The Bayesian Event Tree as defined after Marzocchi et al. 2010 (top panel) and how it has been modified and implemented in PyBetVH (bottom panel)
4 OVERVIEW OF PYBETVH

The PyBetVH software has been designed with the twofold purpose of 1) performing an improved PVHA through an enhanced Bayesian inference procedure at the base of BET_VH model and 2) simplifying as much as possible all the operations needed to prepare, calculate, visualize and analyse a PVHA, in one comprehensive Graphical User Interface (GUI). The tool has been totally developed using Python programming language, an open-source, general-purpose, interpreted high-level programming language. Python has a very clear syntax, a very rich standard library and it can rely also on a huge number of powerful third-party libraries and modules. The most important ones used to develop PyBetVH are:

- wxPython (http://www.wxpython.org), a toolkit for creating desktop GUI applications for the Python programming language. It allows Python programmers to create programs with a robust, highly functional GUI, simply and easily. It is implemented as a Python extension module that wraps the popular wxWidgets cross platform GUI library, which is written in C++.
- Numerical Python (or NumPy, http://numpy.scipy.org) and Matplotlib (http://matplotlib.org): the first one is a package which provides fast N-dimensional arrays, linear algebra, random number capabilities, Fourier transform and many other tools for scientific computing. The latter is a powerful 2D plotting library which depends on NumPy. The combined use of these two modules is a very popular alternative to multi-dimensional algebra manipulation and plotting tools such as MATLAB (http://www.mathworks.com/products/matlab) and GNU Octave (http://www.gnu.org/software/octave).

The overall execution of a PVHA using PyBetVH can be divided into three main stages: 1) the preparation of the input data, 2) the selection of the desired eruptive settings through the event tree and 3) the interactive visualization and saving of the results.

The first stage, input preparation, consists of filling in one configuration file (always named pybet.cfg, see Figure 3) and preparing a number of other files by using specified formats. All of these files must be contained in the same root folder, from which PyBetVH will read the information in order to calculate the hazard assessment (Figure 4). Volcanic systems can be represented in PyBetVH through a rectangular grid (for volcanic fields) or a circular geometry (for central volcanoes) as shown in Figure 5. A description of the configuration file, together with a brief description of the file formats expected for all the input files, is shown in the Appendix, while a more detailed description is provided in the Electronic Supplementary Material.
As in previous implementation of BET_VH, defining the inputs to PyBetVH is the most expensive work in terms of scientific efforts, because all of the available knowledge about the volcanic system has to be quantified as probabilities at each node of the event tree. The event tree is the main object around which PyBetVH is designed and, once the PVHA input has been loaded, the visual event tree becomes active. The visual event tree comprises the second stage of the assessment, during which the user can easily select a desired path of the event tree in order to calculate probabilities associated with the given eruptive settings. The selected path/node is shown on the right panel and, as illustrated in the snapshot on bottom in Figure 4, the selected path or node is associated to the absolute or conditional probability

Fig 3 Configuration file for the case study of OVC
respectively. This distinction will be more evident in the third stage of the assessment, where the results are shown using a Visualization Toolkit (see Figures 6 to 8), which makes possible, among the other features, to interactively switching between absolute and conditional probability, or to select a particular intensity/probability threshold for which to produce a probability/hazard map. The Visualization Toolkit appears as the “Compute” button is pressed. Depending on the selected event tree path, the kind of plots and information visualized are different:

- up to and including Node 6, the typical outputs are a vent opening map and (i) the Probability Density Function together with the corresponding Empirical Cumulative

![Fig 4 Main window frame of PyBetVH when launched (on top) and after having loaded a PVHA setting (on bottom). In the bottom snapshot all the panels of the main frame are active and some information on the volcano are shown (panel on top-right, “selected volcano”) together with the corresponding event tree (bottom-left). Aside of the event tree can be visualized interactively the selected path/node of the event tree. Differently from the scheme in Figure 2, nodes 7 and 8 have been replaced by the new node “N7&8: Hazard Curves” in the visual tree. The example refers to the OVC case study.](image-url)
Distribution Function in case absolute probability is chosen (Figure 6), or (ii) a Pie Chart in case of conditional (Figure 7);

- if Node 7&8 is selected, Bayesian hazard curves, Bayesian hazard maps and Bayesian probability maps are shown (see Figure 8).

All of the canvas areas have a simple toolbar on bottom which allows to zoom (lens icon), pan (crossed arrows icon), go back to the original view (house icon), move to previous (left arrow) or following view (right arrow) and save to disk (floppy disk icon). On the left side of the canvas area, some parameters of maps and plots can be interactively set using a control panel. For all of the visualized results, it is possible to switch from absolute to conditional results and to save data in simple text (.txt) format. Moreover, from top to bottom in the control panel, one can set: i) the point for which the Bayesian hazard curve is shown (this can be done also by directly clicking on the desired point on the maps, and the selected point is marked by a magenta dot, see Figure 8); ii) the probability and intensity thresholds for the Bayesian hazard and probability maps respectively, and the desired statistical quantity to be shown (average and percentiles). For each widget, the corresponding “Update Map” button refreshes the canvas with the new settings. The background image for all maps is automatically downloaded by Google Maps, if the internet connection is available, or loaded together with the other input files if stored in the same root folder (see Appendix and Electronic Supplementary Material).

In the next section the Okataina Volcanic Centre in New Zealand is used as example in order to better describe how to use PyBetVH and test it against a real case study.

5 PERFORMING A PVHA WITH PYBETVH: THE OVC EXAMPLE

The Okataina Volcanic Centre (OVC) is a 700 km² active caldera located in an explosive volcanic belt called the Taupo Volcanic Zone in New Zealand. We chose this case study because of the availability of ready-to-use input data for PyBetVH up to Node 6, as they have been defined in Thompson et al. (2014a, in review). We note that a detailed analysis of the PVHA input and results for the OVC is outside the scope of this paper, and refer the reader to Thompson et al. (2014a, in review) for a more detailed discussion of these. We emphasize that the results are only used to explain the capabilities and features of PyBetVH.

Thompson et al (in review) performed a PVHA of tephra fallout from the OVC using the previous implementation of BET_VH (Marzocchi et al. 2010) with a forecast time window of 1 year. Here we briefly summarize the used settings and which we adopt in the present example:

- an annual eruption prior probability based on a Poisson process with a rate determined by the geological record, and likelihood based on the eruptive catalog (11 eruption episodes over 26 ka, corresponding to the current phase of activity)
three possible eruptive styles defined on the basis of the geological record of the past 26 ka: two eruptive styles (small and large) are characterized by the production of basaltic magma and one by rhyolitic magma. Their relative probabilities are based on the 26ka eruptive catalog

a total of 483 possible vents locations (see Figure 5 top), obtained by discretization of the volcanic area with a regular grid of 23x21 squared cells of 2 km; a distribution for the spatial representation of conic volcanoes

**Fig 5** Map of vent location as it appears when the show vent location button is pressed. In PyBetVH vent locations can be defined as a regular grid (as for the OVC example, on top) or with a conic geometry (on bottom, the example is the vent locations as they are defined for El Misti volcano in Sandri et al., 2014), in order to simplify the spatial representation of conic volcanoes
probability of vent opening (conditional to eruption occurrence) is defined on the basis of expert elicitation, and updated by Bayesian inference using OVC geological record, leading to only 227 vent locations with non-null probability (Figure 7 bottom)

- the tool used for tephra dispersal modelling is TEPHRA2 (Bonadonna et al. 2005; https://vhub.org/resources/tephra2), run through a Monte Carlo approach to stochastically sample 50 years of NOAA reanalysis for the local wind field. The eruption and particle
parameters are based off of the work of Bonadonna et al. (2005) for the rhyolitic eruptive type, and from analogous Plinian basaltic eruptions (e.g., Cerro Negro) for the basaltic eruptive type.

In order to show how PyBetVH could be used to extend the work by Thompson et al (2014a, in review) and to introduce the computation and visualization of Bayesian hazard curves, we re-define the probabilities at Node 7&8 by using the results from the same set of simulations for tephra fallout performed in Thompson et al. (2014a, in review), but instead of considering a threshold of 10 kg/m2, we consider a
set of increasing thresholds of tephra load: 0, 50, 100, 150, 200, 250 and 300 kg/m². In particular, for node 7&8 we set prior probabilities as the frequency (extracted from the Monte Carlo simulations by TEPHRA2) of overcoming each tephra load threshold, for every possible size and vent location.

All of these pieces of information were then input to PyBetVH (see Appendix and Electronic Supplementary Material for more information on the file formatting).

The visualization of the absolute and conditional probabilities of vent opening are given in the bottom panels of Figures 6 and 7, respectively. The conditional probabilities are much higher than the corresponding absolute values, as expected, since they do not include the probability of eruption (which is of the order of 10⁻⁴ per year).

Figure 8 provides a snapshot of the visualizations of a Bayesian absolute (i) hazard map (top left panel), (ii) probability map (top right) and (iii) two specific hazard curves for two selected points (bottom panels). By clicking on the hazard or probability map, the user can choose any point of interest on the target domain, and automatically visualize its set of Bayesian absolute hazard curves.

Figure 1 summarizes all the types of results that can be obtained and visualized using PyBetVH and highlights the wealth of information provided by Bayesian hazard curves. Such robust information could serve as valuable input into quantitative volcanic risk assessment. By vertically cutting the curve for a given point of the target domain at a selected intensity threshold in the tephra load $I^\text{th}$, the user can obtain a set of statistical values (average and percentiles) describing the probability distribution of the $I^\text{th}$ exceedance probability at that point. Iterating this cut for all the points in the target domain, and mapping separately each statistical value, we can derive a set of Bayesian probability maps, which correspond to the average and various percentiles that describe the probability distribution of the exceedance probability to overcome $I^\text{th}$ in the whole domain. This set of probability maps provides an idea of the epistemic uncertainty attached to the best-evaluation probability map (in which only the average of the Bayesian hazard curve is extracted and shown). This type of information is not calculated or provided by current volcanic hazard assessments, in which typically only one probability map (commonly the average) is given at best.

PyBetVH can also generate maps using probability thresholds $\pi^\text{th}$, in addition to hazard intensity thresholds. By horizontally cutting the Bayesian hazard curve for a given point of the target domain at a selected probability threshold $\pi^\text{th}$, we obtain a set of statistical values (average and percentiles) which describe the probability distribution of the intensity that is expected to be overcome with a probability equal to $\pi^\text{th}$ in that point. Iterating this cut for all of the points in the target domain, and mapping separately each statistical value, we can derive a set of Bayesian hazard maps, which correspond to the average and various percentiles that describe the probability distribution of the intensity expected to be overcome with
a probability equal to \( \pi^{th} \) in the whole domain. Again, these hazard maps provide an idea of the epistemic uncertainty associated with the best-evaluation hazard map, and bring added value to PVHA and that decision makers might want to take into account.

6 CONCLUSION

In this paper, we present PyBetVH, a new software implementation of the PVHA tool BET_VH. PyBetVH is equipped with a GUI which graphically supports the data input, the execution and the interactive visualization of the results of a PVHA. The most important new contribution presented is the user-friendly tool’s ability to calculate and interactively visualize Bayesian absolute hazard curves which consider all the natural variability in terms of eruption occurrence, vent position, and eruptive size. Such hazard curves are currently an uncommon output of PVHA. However, we propose that absolute hazard curves could play a very integral role in quantitative risk analyses by being coupled with fragility curves to
assess quantitative risk on a continuous and detailed spectrum, as it is commonly done in seismic risk studies (e.g., Cornell 1968). The interactive visualization of Bayesian hazard curves, Bayesian hazard maps and Bayesian probability maps can be very helpful for immediate evaluation of the highest-hazard areas and/or of the most hazardous eruptive scenarios, and the level of epistemic uncertainty.

The ease of visualization of the PVHA results in PyBetVH has a twofold importance. On one hand, it might allow a more direct communication and transfer of PVHA results from scientists to decision makers. In this respect, there is an ongoing effort to evaluate the effectiveness of probabilistic results to communicate PVHA output to stakeholders and decision makers. In a series of interviews and surveys with New Zealand earth scientists and stakeholders, Thompson et al. (2014b, in review) found that more than 89% of respondents found Bayesian hazard map and Bayesian probability map styles helpful. No statistically significant difference was found in whether participants preferred to receive one or the other, or a set of both, suggesting that both styles of map are valuable hazard analysis outputs for stakeholders. Bayesian hazard curves were ranked as helpful tools by more than half of respondents in the study.

It is worth noting, however, that the tool leaves the selection of the intensity and/or probability threshold to the user. When scientists produce a single probability map or a single hazard map, they implicitly assume a level of accepted risk (Marzocchi 2013). This is very important, as scientists are not necessarily trained to select such values in the framework of risk analysis, a task typically delegated exclusively to authorities. With PyBetVH, scientists can provide their full knowledge, in terms of Bayesian hazard curve, to decision makers, and let the decision makers choose, through a user-friendly visualization toolkit, where to cut them to obtain their desired maps.

We acknowledge that the PyBetVH software development is an ongoing project and new and important features are planned to be introduced in future versions. In particular, there are two important new BET-based event tree models that will be implemented: 1) a new module based on the existing BET_EF event tree model, which will account for data available in real-time via volcanic monitoring and would allow the user to also perform short-term forecasting during a volcanic crisis, and 2) the development of the new event tree model BET_UNREST which will extend the hazard forecasting to non-magmatic unrest events.

7 APPENDIX

The main file to prepare as input to PyBetVH is pybet.cfg, a simple text file organized in sections named by a [section] header and entries of the type name = value (Figure 3). The first section, [Main Settings], defines some general parameters about the volcano (name, center, shape and geometry) and the PVHA (forecast time window and statistical distribution sampling). All the other sections define the
parameters needed by each single node of the event tree. The file is based on the standard Python class ConfigParser which provide a very clear syntax and it can be easily compiled by the user. The folder containing pybet.cfg should also contain other files, that are call in the configuration file itself, as it can be gathered in Figure 3. A description of each single file is here very briefly outlined in Table 1. In the “Main Settings” section the user can set the background image file name (at present only .png files can be loaded): alternatively, if the key word “None” is set as in Figure 3, no image will be load and a map will be automatically downloaded by PyPHaz from Google Maps, if an internet connection is available.

Table 1 Summary of all the text files need to prepare as input to pyBetVH with a brief description of the format. \( P \) are the prior probability, \( \lambda \) are the equivalent number of data, \( Y \) are the past data, \( N \) are the total number of past data. \( Lon, Lat \) are UTM longitude and latitude of each target grid point. \( Nv, Ns, Np, Ni \) and \( Ne \) are respectively the number of vents, sizes, target grid points, intensity thresholds and past eruptions with measured intensity available. Suffix ## in file names indicates that, if more than one outcome is considered, then a corresponding number of these files need to be prepared and saved into the directory.

<table>
<thead>
<tr>
<th>File</th>
<th>Description</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node4</td>
<td>Prior probability (( P )) of vent opening, given an eruption and corresponding past data occurred in each vent location (( Y )).</td>
<td>( P_1, Y_1 ) ... ( P_{Nv}, Y_{Nv} )</td>
</tr>
<tr>
<td>Node5</td>
<td>Prior probability (( P )) of eruptive size classes, given an eruption in a given vent location and corresponding number of past data of a given size occurred in a given vent location (( Y )).</td>
<td>( P_{1,1}, ..., P_{Ns,1}, A_{i1}, Y_{1,1}, ..., Y_{Ns,1} ) ... ( P_{1,Nv}, ..., P_{Ns,Ns}, A_{Ns}, Y_{1,Nv}, ..., Y_{Ns,Ns} )</td>
</tr>
<tr>
<td>Node6##</td>
<td>Prior probability (( P )) of having the outcome ##, given an eruption in given vent location of a given size class and corresponding number of past data producing the outcome (( Y )) respect to the total past data (( N )).</td>
<td>( P_1, \lambda_1, Y_1, N_1 ) ... ( P_{Ns}, \lambda_{Ns}, Y_{Ns}, N_{Ns} )</td>
</tr>
<tr>
<td>Node6-intensities</td>
<td>List of intensity thresholds, one row for each considered outcome. In theory, there can be only one threshold, but in that case hazard curves will collapse to single points</td>
<td>( ith_1, ..., ith_{Ni} )</td>
</tr>
<tr>
<td>Node6-areas##</td>
<td>Coordinates and identity number of the target grid points on which the Bayesian Hazard Curve will be calculated</td>
<td>( Lon_1, Lat_1, 1 ) ... ( Lon_{Np}, Lat_{Np}, Np )</td>
</tr>
<tr>
<td>Node7&amp;8-prior##</td>
<td>Prior probability (( P )) to overcome the increasing series of thresholds for each target grid point, given a size and a vent location. In the last column (( \lambda )) the equivalent number of data for each combination must be set.</td>
<td>( P_{1,1,1,1}, ..., P_{1,1,1,Ne}, \lambda_{1,1,1} ) ( P_{1,1,2,1}, ..., P_{1,1,2,Ne}, \lambda_{1,1,2} ) ... ( P_{1,Nv,1,1}, ..., P_{1,Nv,1,Ne}, \lambda_{1,1,1} ) ( P_{1,2,1,1}, ..., P_{1,2,1,Ne}, \lambda_{1,2,1} ) ( P_{1,2,2,1}, ..., P_{1,2,2,Ne}, \lambda_{1,2,2} )</td>
</tr>
</tbody>
</table>
Node7&8-pastdata##

<table>
<thead>
<tr>
<th>$P_{1,Nv,Ns,1}$, …, $P_{1,Nv,Ns,Ni}$, $\lambda_{1,Nv,Ns}$</th>
<th>$P_{2,1,1,1}$, …, $P_{2,1,1,Ni}$, $\lambda_{2,1,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>…......................................................................</td>
<td>$P_{Nv,Ns,Np,1}$, …, $P_{Nv,Ns,Np,Ni}$, $\lambda_{Nv,Ns,Np}$</td>
</tr>
</tbody>
</table>

Measured intensity value in a past eruption ($Y$) at each target grid point, having occurred from a given vent location ($V_j$) and of a given size ($S_j$). In case we have $Ne$ past eruptions with available measures of intensity, the block is repeated $Ne$ times.

### 8 ACKNOWLEDGEMENTS

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### 9 REFERENCES


Thompson M. A., Lindsay J. M., Jolly G., Sandri L., Marzocchi W., Bonadonna C., Biass S. (2014a, in
review) Exploring the influence of vent location and eruption style on tephra fall hazard from Okataina Volcanic Centre, New Zealand

