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Volcanic risk assessment: integrating hazard and social vulnerability analysis

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VOLCANIC RISK ASSESSMENTS: INTEGRATING HAZARD AND SOCIAL VULNERABILITY ANALYSIS

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ABSTRACT

The vulnerability of communities at risk from volcanic activity at Volcan Tungurahua, Ecuador and Mount Rainier in the USA provided the focus for this thesis. The research aimed to develop an integrated approach to risk assessments that combined both hazard and vulnerability analysis. In phase one, the study developed a novel methodology to assess volcanic threat that utilised previously published data. This semi-quantitative approach integrated measures of both hazard and exposure factors, allowing the relative threat to different communities to be ranked. By avoiding the complex quantitative analysis associated with traditional risk assessments of the multiple hazards associated with volcanic activity, this methodology may be applied where comprehensive historic and geological data may be lacking, as well as facilitating understanding amongst non-specialists and members of the public.

The second phase of the research investigated human vulnerability, with an exploratory study carried out in Ecuador. This utilised a questionnaire survey aimed at eliciting an individual's beliefs and attitudes towards volcanic risk, which provided the basis for a more comprehensive exploration of social vulnerability conducted in the USA. This investigated further the role of socio-economic features and psychological characteristics, such as risk perception, hazard salience and self-efficacy, in promoting self-protective behaviour, and examined the relative importance of these factors in determining vulnerability.

The theoretical underpinnings of this research suggest that individuals with certain socio-economic characteristics may incur greater losses during a disaster, whilst perceptual processes may influence how an individual responds to a hazardous event. Little evidence was found to support the socio-economic model of vulnerability, which prevented the integration of the two research phases. However, perceptual factors were found to be significant predictors in the adoption of protective hazard adaption. This suggests that targeting risk mitigation and communication strategies to address these psychological constructs may be more important for reducing overall vulnerability than focusing efforts towards specific socio-economic groups.

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LIST OF ACRONYMS

AFM	Acoustic Flow Monitoring station
ANOVA	Analysis of Variance
COE	Comité de Operaciones de Emergencia
CRED	Centre for Research on the Epidemiology of Disasters
CVO	Cascades Volcano Observatory
DCB	Defensa Civil de Baños
DEM	Department of Emergency Management
EFA	Exploratory Factor Analysis
EM-DAT	Emergency Events Database
FEMA	Federal Emergency Management Agency
GVP	Global Volcanism Program of the Smithsonian Institution
IDNDR	International Decade for National Disaster Reduction
IGEPN	Instituto Geofísico de la Escuela Politechnica National
IRD	Institut de Recherche pour le Development
ISDR	International Strategy for Disaster Reduction
OVT	Observatorio Volcánico del Tungurahua
PCA	Principal Component Analysis
PMT	Protection Motivation Theory
PRA	Probabilistic Risk Assessments
QRA	Quantitative Risk Assessments
PSOC	Psychological Sense of Community
SCI	Sense of Community Index
SPSS	Statistical Package for the Social Sciences
USGS	United States Geological Survey
VEI	Volcano Explosivity Index

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AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

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CHAPTER 1: INTRODUCTION

1.1. RATIONALE

Forming the basis for disaster prevention, preparedness and emergency response measures (including land-use planning, evacuation plans and communication strategies), volcanic risk assessments aim to quantify the risk to a population by combining numerical probabilities of various possible eruption scenarios with hazard analysis (Dunkley & Norton, 2002). Previously, these tended to focus on understanding the physical processes that underlie volcanic hazards, whilst anthropogenic components of risk and their implications for framing mitigation and emergency response plans were less well studied. Latterly, progress has been made towards addressing this issue by integrating hazard assessment and vulnerability analysis into more comprehensive, coherent and multi-dimensional hazard management policies (Cardona, 1997; Dibben & Chester, 1999; Tobin & Whiteford, 2002a; McEntire, 2005).

Most volcanic risk assessments define vulnerability as a measure of the susceptibility of man-made structures to potentially damaging volcanic hazards (Lirer & Vitelli, 1998; Dibben & Chester, 1999), or the degree of loss to a given element or group of elements, such as people, property or economic activity (Dunkley, 1999). These characterisations are useful in demonstrating the need for, and cost-benefit of, hazard mitigation (*ibid*), but this approach fails to assess the effects felt by individuals and communities (Dibben & Chester, 1999), or the overall consequences for society (Bankoff *et al.*, 2004). In terms of the development of pre-eruptive mitigation plans, the geo-centric approach fails to acknowledge the anthropogenic issues that directly contribute to the varying levels of risk different individuals or community groups may be exposed to in the event of an eruption. For example, the distribution of social, political and economic power can have a greater influence on the consequences of a disaster than the extreme nature of the physical phenomenon (Chester *et al.*, 2002). This may be particularly so in developing countries, where the opportunities to prevent and cope with natural disasters may be reduced due to economic, social and cultural factors (Alcantara-Ayala, 2002), and the nature of marginalisation (Wisner *et al.*, 2004).

It is now recognised that vulnerability has a social dimension, and is not limited to a measure of the potential physical damage. However, the cultural and political characteristics of an area (e.g. limited access to resources; influence in the decision-making process), and the socio-economic and psychological characteristics of an individual, which can lead to increased vulnerability, are often given less consideration in an applied science approach (Bankoff *et al.*, 2004). These qualitative human aspects, including cultural understandings and perceptions of risk (Krimsky & Golding, 1992), are an important feature of vulnerability and should be explicitly considered in efforts to develop adequate strategies for the prevention and mitigation of natural disasters. Understanding the processes and perceptions that influence how individuals behave in the face of volcanic risk is of fundamental importance, and would allow mitigation measures, communication strategies and education programmes to be directed more effectively.

Households within identified volcanic risk zones display differences in their level of precautionary adaptation, from none to extensive. In turn, the adoption of protective behaviour (e.g. purchasing insurance, storing emergency supplies or evacuation) has implications for household vulnerability in the event of an eruption. Many factors influence whether people take precautionary action to protect themselves, including past experience, lack of reliance on public protection, or strong emotions, mainly fear. It is possible that self-protective behaviour reflects differences in risk perception, or beliefs about the efficacy and practicability of personal harm prevention, and that these influence people's precautionary actions. If differences in key socio-economic variables correlate with perceptions of risk and self-efficacy, perhaps one can predict private householder's precautionary adaptation to the risk of volcanic activity, and hence their relative vulnerability just from socio-economic variables such as age, gender, income or level of education. By integrating this readily available measure of social vulnerability into more traditional risk assessments, a multi-dimensional approach to hazard management could be developed. This study grew out of such speculation.

1.2. AIMS AND OBJECTIVES

The overarching aim of this research was to develop a novel approach to volcanic risk assessments that integrated the analysis of both geophysical hazards and social vulnerability. Social vulnerability is defined as the socio-economic dimension of risk; the social, cultural, economic, perceptual and behavioural characteristics that shape an individual or community. Previous efforts have often included the physical vulnerability of things of human value, such as the number of people at risk, infrastructure and buildings (Lirer & Vitelli, 1998; Pomonis *et al.*, 1999; Alberico *et al.*, 2002; Papathoma & Dominey-Howes, 2003; Spence *et al.*, 2004; Douglas, 2007; Fuchs *et al.*, 2007), but few have considered the characteristics of the individuals or communities that act to increase risk (Cardona, 1997; Dibben & Chester, 1999; Cutter *et al.*, 2000; Wood & Soulard, 2009). Assessment and mitigation methods should not only be hazard-specific but also place-specific, taking into account the unique dimensions of a community which directly influence both vulnerability and resilience.

Broadly, the research explored two themes. Firstly, to develop a simplistic approach to volcanic threat assessments that utilised readily available information to allow the relative risk to a number of communities around two volcanoes in different regions, both potentially at risk from volcanic eruptions, to be quantified and ranked. The term *threat* assessment is used in contrast to *risk* assessment, as the approach developed represents a *qualitative* measure of the risk posed by the volcanoes studied. The aim was to develop a methodology that could be readily interpreted and understood by non-specialists, such as emergency managers and members of the public, and could be applied equally well at less comprehensively studied volcanoes, where sufficient data to conduct a traditional quantitative risk assessment may be lacking. The second phase of the research sought to investigate the beliefs, attitudes and perceptions that people have according to social, cultural and socio-economic differences, which shape social vulnerability and resilience within the communities studied. The aim was to identify specific socio-economic characteristics associated with differences in the adoption of precautionary behaviour, which could be integrated within the developed threat assessment methodology to provide an additional level of complexity for understanding social vulnerability.

By attempting to integrate these two distinct approaches, this research sought to develop a holistic, multi-dimensional approach to volcanic risk assessments; one that combined volcanic hazard evaluation (physical mechanisms and historic eruptive behaviour), with an analysis of anthropogenic features (economic, demographic and social), and an assessment of the more contextual psychological characteristics of the community (risk perception, self-efficacy and trust etc). On a broader level, this research may have important implications for the development of effective and timely hazard mitigation measures, particularly for targeting risk communication and education strategies towards the most vulnerable within an at-risk population. Work of this nature has not been conducted before in relation to volcanic risk, therefore the study necessarily took on an explorative approach.

The interdisciplinary nature of this research necessitated the use of techniques and methodologies employed within disciplines outside of the natural sciences, specifically those used in social science research and psychology, where the object of study is human attitudes and beliefs. Some of these techniques and the assumptions underlying them do not adhere to the same principles which govern more quantitative disciplines, but are considered standard within social science research. Additionally, the appropriate terminology used within the social sciences and psychology has been retained, which may be unfamiliar to some readers. Where uncertainty exists, the words or phrases have been defined where first encountered.

1.3. CASE STUDY SELECTION

Threat assessments were carried out in communities around Volcan Tungurahua in Ecuador and Mount Rainier in the United States of America (Figure 1.1). Geophysically similar, Mount Rainier and Volcan Tungurahua are both large stratovolcanoes, with similar eruptive hazards and, during an eruption, would both represent a threat to a large population. The two volcanoes have comprehensive but divergent approaches to their current volcanic hazard management plans, allowing differences in approach to be explored. In addition, studying two areas with highly contrasting socio-economic populations and different political structures allowed the developed assessment methodology to be applied to two widely differing regions.

Figure 1.1 Map of the world showing the location of the two case study volcanoes.

1.3.1. Volcan Tungurahua

Tungurahua is one of the most active volcanoes in Ecuador and has been erupting almost continuously since 1999. This activity has been characterised by periods of quiet degassing and more intense Strombolian eruptions with explosions, ejection of incandescent material, lava flows, small pyroclastic flows and tephra fall, the latter blanketing half the country. Numerous rain induced lahars have scoured fresh tephra from the steep slopes high on the mountain, travelling down the many river drainages that head on the volcano. Disruption in the local area due to lahar inundation has frequently forced the closure of roads between Baños, Pelileo and Penipe, as well as the highways to Ambato and Riobamba. Almost continuous ashfall to the west of the volcano has affected the wider region, whilst damage to agricultural land and the death of livestock has impacted the local economy. During a period of particularly intense activity in 2006 (two months after the fieldwork phase was completed) pyroclastic flows inundated several small villages and hamlets on the north-western flanks of the volcano, killing at least five people.

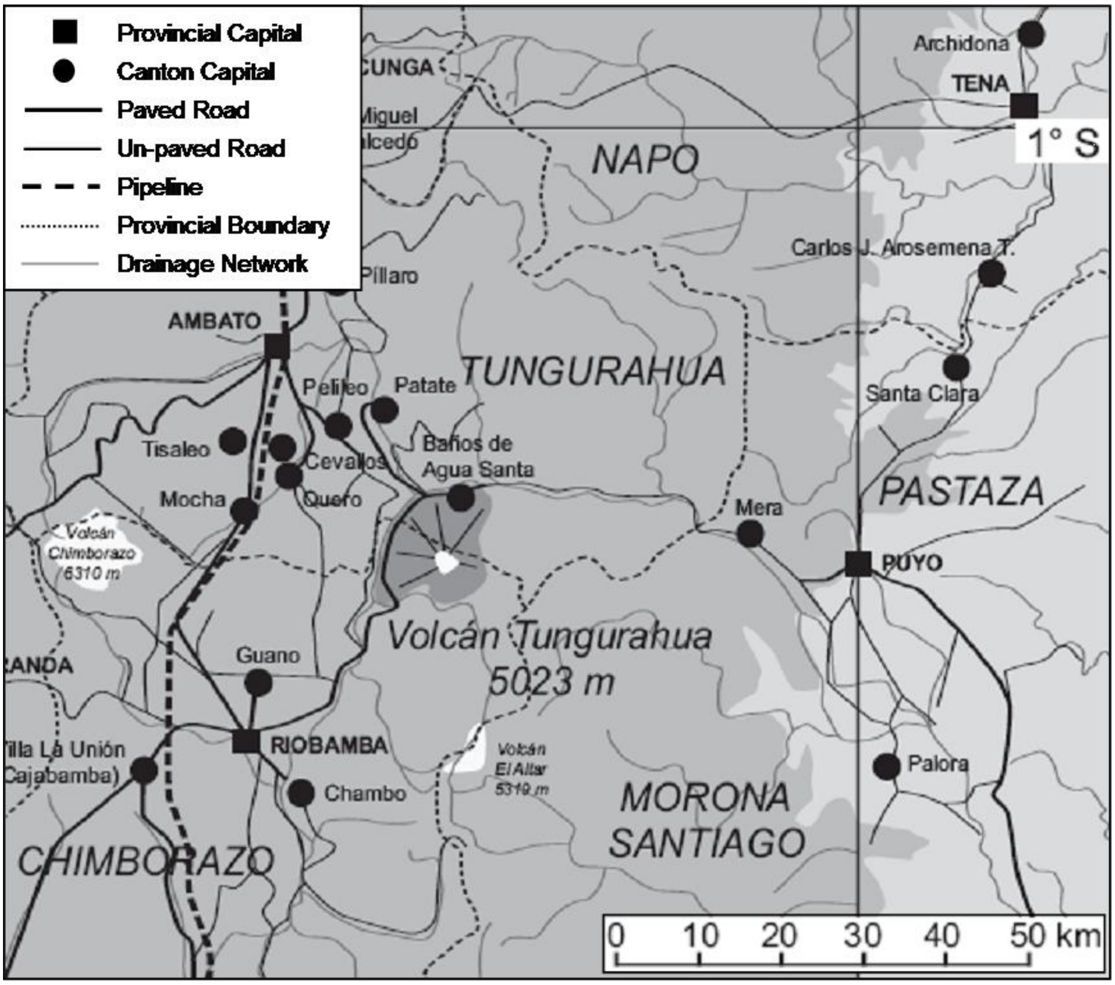


Figure 1.2 Regional map showing location of Tungurahua, and the communities of Riobamba and Baños (modified from IGEPN).

The volcano is situated 120km south of the country's capital city Quito, in the Cordillera Oriental between the highlands of the Ecuadorian Andes and the gateway to the Ecuadorian Amazon. The volcano dominates the landscape above the small city of Baños de Agua Santa, approximately 8km to the north and more than 1,800m below the summit crater (Figure 1.2). The largest urban area in close proximity to the volcano, with a population of approximately 18,000 inhabitants, Baños is an important national and international tourist destination, famed for its thermal springs. The town has many hotels, guest houses, restaurants and tour companies. Tourism also provides indirect employment in other industries, including transportation and food production. Although tourism is the main economic activity within the town, agriculture and cattle-rearing are the primary sources of income in the surrounding rural areas. Known as the gateway to the Amazon, Baños' roads and highways are vital to the communication and economic activity of the region. Along with several small villages located on the western and north-western flanks of the volcano, Baños is directly threatened by pyroclastic flows and lahars, and experiences an almost daily dusting of ashfall, despite the predominant wind direction carrying the worst of the ash to the west. The city and parts of the surrounding area have been evacuated twice since activity commenced.

In October 1999, prompted by the reawakening of the volcano and an escalation in activity, government authorities, in consultation with the scientists from Quito's *Instituto Geofísico de la Escuela Politecnica Nacional* (IGEPN), instigated the evacuation of an estimated 26,000 people from Baños and the surrounding area. When the feared major eruption and pyroclastic flows failed to materialise, residents became involved in violent clashes with soldiers amid claims they had looted evacuated properties. After three months, residents finally forced their way home. This 'false alarm' and subsequent civil unrest could have had serious implications for the success of future volcanic risk management strategies within the area, but two subsequent evacuations prompted by increased activity in July and August 2006, and December 2010 have been conducted without incident. Further complicating future management strategies, is the continuing widespread unrest between the traditionally dominant Spanish-descended elite and the indigenous population, who make up a large proportion of the rural community.

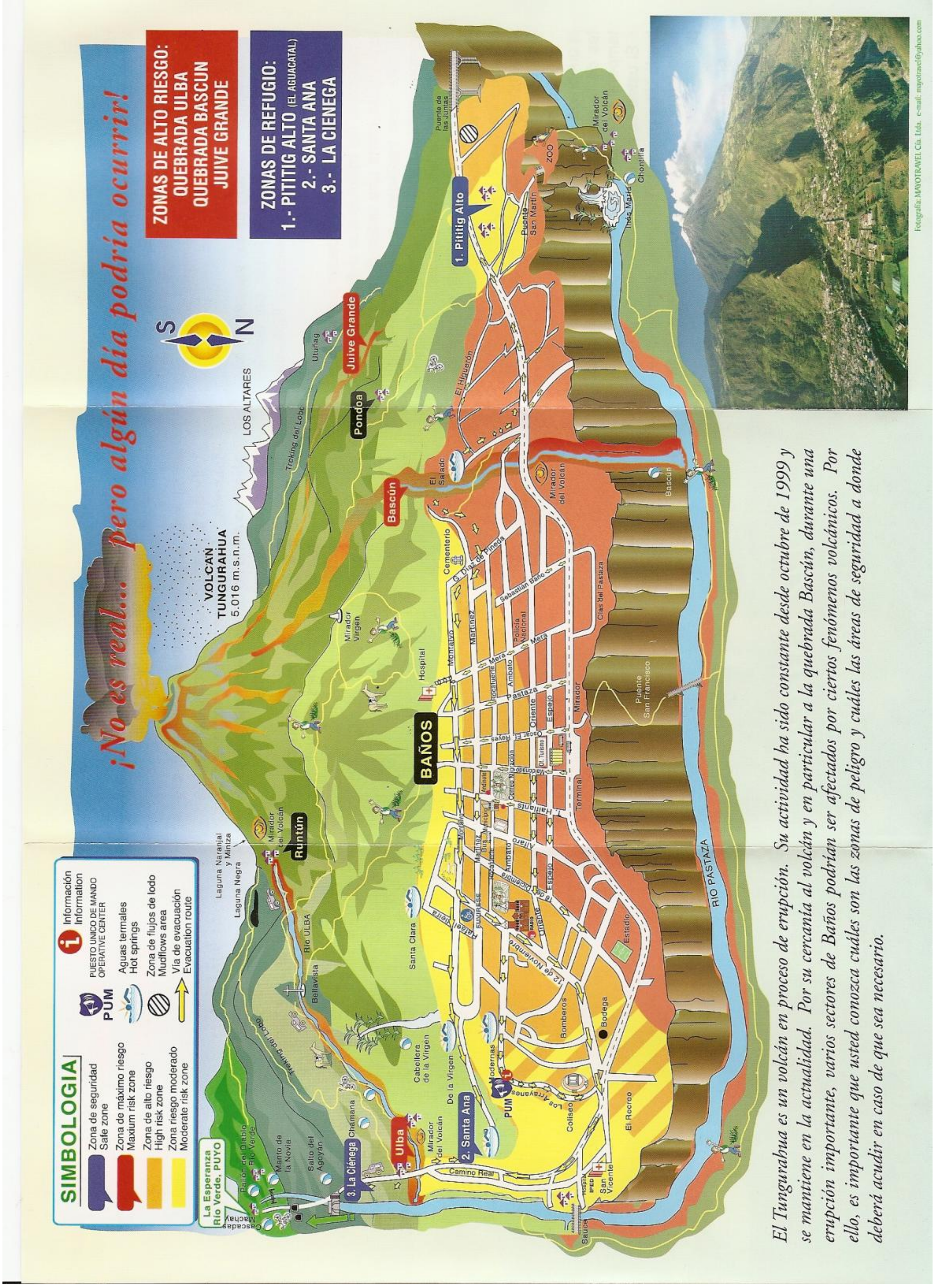
1.3.1.1. Scientific Monitoring and Hazard Mitigation

Details of the hazard mitigation strategies employed during the ongoing volcanic unrest were explored during the researcher's fieldwork season in Ecuador. Informal interviews were conducted with the local Director of the *Defensa Civil de Baños* (DCB), scientists from both IGEPN and the *Observatorio Volcánico del Tungurahua* (OVT), located in the hamlet of Guadalupe approximately 8km northwest of Baños. The past volcanic activity and hazards at Volcan Tungurahua have been studied by the Ecuadorian and French *Institut de Recherche pour le Développement* (IRD), and since 1988 it has been monitored by IGEPN from Quito and the observatory in Guadalupe. Observations through seismological, geochemical, thermal, geodetic and acoustic monitoring systems have recorded seismic energy release, fluctuations in SO_2 emissions, thermal anomalies associated with lava intrusion, and lahar generation. Additional visual observations when weather permits, allow ash plume heights to be estimated, and incandescence to be observed at night. The OVT has several acoustic-flow monitoring (AFM) stations on the volcano, including two located in the Juive and Vazcún valleys, which provide early warning of lahars, as well as eight seismic monitoring stations, two tilt meters to measure deformation, and twenty ashfall check-points. Information gathered using the various observational techniques is disseminated by scientists during bi-monthly meetings with the *Comité de Operaciones de Emergencia* (COE). As well as scientists from IGEPN, the mayors of Baños and the surrounding villages, fire department chief, police, red cross, and key members of the local DCB attend.

As well as their role in providing scientific monitoring, there is an observation and communication system in place, run jointly by the local DCB, the OVT and approximately fifteen local volunteers. These volunteers comprise community members from villages and hamlets situated on the flanks of the volcano. They report, via short-wave radio, to the civil defence on the occurrence of any localised heavy rainfall and/or the observation of actual lahar events. In conjunction with the OVT managed AFM system, this information provides advanced warning of potential locations for lahar inundation, particularly in relation to the road network, allowing appropriate mitigation measures to be taken. The IGEPN collate all this information and publish a weekly activity report on their website. In addition, OVT scientists present weekly bulletins on the local radio station, as well as submitting daily reports to advise on current activity, which is read each morning during the radio news programme.

Responsibility for setting the volcano alert level rests with the national civil defence, using information provided by the DCB and scientific/technical information from IGEPN. The current system recognises four levels of alert, used to indicate the volcano's current level of activity. These are:

- White – alerts authorities to begin preparing or updating mitigation plans in anticipation of the occurrence of an impending event.
- Yellow – requires verification that personnel and means are available to manage probable emergency situations and the execution of simulated evacuations (alert level may last weeks or months).
- Orange – requires notification of the public that an emergency is possible and of any preparatory measures they should take. Also requires the mobilisation of personnel and equipment for a possible evacuation and intensification of community self-protection measures (may last days or weeks).
- Red – the actual occurrence of the hazard. Emergency plans are implemented or executed (may last hours or days).



El Tungurahua es un volcán en proceso de erupción. Su actividad ha sido constante desde octubre de 1999 y se mantiene en la actualidad. Por su cercanía al volcán y en particular a la quebrada Bascún, durante una erupción importante, varios sectores de Baños podrían ser afectados por ciertos fenómenos volcánicos. Por ello, es importante que usted conozca cuáles son las zonas de peligro y cuáles las áreas de seguridad a donde deberá acudir en caso de que sea necesario.

Figure 1.3 Stylised volcanic hazard map published in pamphlet form for the general public by Baños City Hall (Carranza-Aillon, 2000).

The current alert level at Tungurahua is Orange (June 2011), and this has largely been the situation since increased activity during August 2006 caused widespread ashfall, localised pyroclastic flows and five reported fatalities (during which time a Red alert was issued). Political considerations have in the past overridden scientific advice regarding the application of an appropriate alert level. Those who rely on tourism for their livelihood pressurised the authorities to decrease the alert level, as occurred in Baños prior to 2006, although higher alert levels remained in place for surrounding villages. Conversely, funding levels (for the repair of lahar damage etc) are affected by the current alert level, producing pressure to maintain a higher level to protect funding. Final responsibility for calling an evacuation rests with the town mayor, following advice from the OVT and the director of the DCB. The evacuation would be coordinated by the DCB with help from the police and fire department, with citizens following pre-defined evacuation routes publicised on a map produced by City Hall (Figure 1.3).

1.3.1.2. Case Study Communities

Two towns were selected for this study in order to allow comparisons to be drawn between communities with different levels of risk to volcanic hazards (Figure 1.2). The town of Baños was selected due to its close proximity to the volcano, and its exposure to several different hazards associated with Tungurahua volcanism. Initially, this study looked for suitable communities to survey downriver from the volcano, which are at risk from potential lahars. However, the steep-sided banks of the Pastaza river are sparsely populated, with any settlements being highly dispersed, and consisting mainly of rural farmsteads. Therefore, the city of Riobamba, located approximately 30km to the southwest of the volcano was selected. The city lies downwind of the volcano in the path of potential tephra fall and has frequently been affected by ash fall during the ongoing eruption. Although previous community survey work has been conducted in several locations around the volcano, this has mainly focused on health issues arising from the 1999 evacuation and exposure to ashfall (Tobin & Whiteford, 2001; Tobin & Whiteford, 2002a; 2002b; Whiteford *et al.*, 2002).

1.3.2. Mount Rainier

Mount Rainier is located in the Pacific north western USA in the state of Washington. At 4,392m, it is the highest peak in the Cascade Range of mountains, which stretch south from Canada to northern California. It is located approximately 70km to the southeast of the Seattle/Tacoma metropolitan area, and is the dominant feature of Mount Rainier National Park. A stratovolcano, the steep sided mountain has a summit area almost completely covered in glacial ice and snow. The edifice of the volcano is built of lava flows with interlaying tephra and pyroclastic deposits. Structural weakness of the upper flanks resulting from hydrothermal alteration has caused periodic major flank collapses, and constitutes a major and ongoing threat to communities around the volcano.

Past activity has been characterised by periods of effusive lava production, explosive eruptions and numerous debris avalanches and lahars, although not all of these have been associated with volcanism. Two major lahars have occurred following collapses of the northeast and northwest flanks, deposits of which underlie the now heavily populated Puget Sound region. This area stretches from Mount Rainier to the Puget Sound lowlands, Tacoma and south Seattle and covers approximately 5,800km^2. Over 150,000 people currently reside in areas identified as at risk from inundation by lahars. Although Seattle would only be threatened by a particularly large lahar, deposits from past eruptions indicate that such events have occurred and therefore, the number of people at risk could be considerably higher. The last period of significant volcanism occurred approximately 1,000 years ago but one or two small eruptions have occurred since the 1820s, as well as several small debris avalanches and many small lahars.

The region of the Pacific Northwest of America, where the volcano is located, is dominated by the urban areas of Seattle and Tacoma. Manufacturing, concentrated within this urbanised corridor of the densely populated Puget Sound region, is the leading sector of Washington State's economy, with the two cities forming the primary industrial centres. The area's rural economy is primarily based on agriculture and forestry. Although guidelines exist in Washington state to discourage development within areas subject to geological hazards, the population within Mount Rainier National Park continues to increase (Sisson, 1995). In addition, between 1.5 and 2 million tourists visit the park each year (National Park Service, 2003). To ensure these settlements and visitors can be protected, the volcano is constantly monitored for signs of renewed activity.

1.3.2.1. Scientific Monitoring and Hazard Mitigation

The University of Washington Geophysics Program and the United States Geological Survey (USGS) Volcano Hazards Program, continuously monitor earthquakes at Mount Rainier and other Cascade volcanoes through a network of seismometers. This network detects several hundred earthquakes, which occur at or near Mount Rainier each year. The Cascades Volcano Observatory (CVO), located in Vancouver, regularly monitor deformation at the volcano. If unusual activity is detected, additional instruments will be deployed on and around the volcano to monitor earthquakes, deformation and other symptoms of volcanic unrest. This information will then be used to issue advisories and warnings to emergency response officials and the public.

In 1998, with the assistance of the USGS, Pierce County (situated to the west of Mount Rainier National Park) installed the first automated lahar early-warning system on Mount Rainier. The system includes ten AFM stations linked to a computer by radio. Two of the stations are set in the likely path of the lahar and if they stop transmitting, will trigger an immediate warning. Sirens will sound, alerting up to 30,000 people in the valleys surrounding the mountain to move to higher ground. Orting, a small town with a resident population of 3,760 people, is at considerable risk from lahars due to its location on the banks of the rivers Puyallup and Carbon. Both rivers originate from glaciers on the flanks of the volcano approximately 50 km away. The town has three sirens connected to the early warning system and people are directed to follow pre-planned evacuation routes to higher ground should the warning sound. It is estimated that residents would have approximately 40 minutes to move to safety in the event of a lahar. Many towns close to Mount Rainier initiated evacuation drill practice for school children, and began drawing up large scale disaster plans following the Mount St Helens eruption in 1980. This eruption of a nearby Cascade's volcano is used as a reference for much of the official hazard assessments, mitigation planning and emergency management at Mount Rainier.

1.3.2.2. Case Study Communities

Three towns were selected for this study in order to allow comparisons to be drawn between communities with different levels of vulnerability and exposure to volcanic hazards (Figure 1.4). The small rural community of Carbonado was selected due to its proximity to the volcano (approximately 35km northwest of the summit crater) and its potential exposure to several different hazards associated with Mount Rainier volcanism. The city of Sumner, located in the Puget Sound Lowland, 65km downriver to the northwest of the volcano, is at significant risk from lahars lying as it does at the confluence of two major rivers which head on the volcano. In contrast, the city of Ellensburg is located to the east of the Cascade Mountains, and lies downwind in the path of potential ashfall. Previous studies involving communities at risk from an eruption of Mount Rainier have concentrated on those situated to the west, particularly in the potential lahar hazard zones (see Inverson *et al.*, 1998; see Davis *et al.*, 2006; Johnston *et al.*, 2006; Wood & Soulard, 2009). This study is unique in considering a community to the east of the volcano, as well as the small town of Carbonado, potentially at risk from multiple hazards, e.g. debris avalanche, lateral blast, lahars and ashfall.

Figure 1.4 Map of Washington state, highlighting the location of the three case study communities relative to Mount Rainier.

1.4. RESEARCH PROBLEMS

Several problems affected the first fieldwork season based in Ecuador. This impacted the time available to conduct research and limited data collected. As well as significant personal health issues, a period of political unrest delayed the start of survey work in Baños whilst the researcher was confined within the capital city of Quito. During March 2006, indigenous groups began protesting against the government's involvement in negotiating a Free Trade Agreement with the United States. The native groups believed the agreement would result in an influx of cheap subsidised goods from the US that would negatively impact the Ecuadorian agricultural economy, and subsequently damage the culture of the indigenous people, who are predominantly involved in farming production within the country . Protest rallies escalated into the blockading of roads across Ecuador with burning tyres, trees and rocks. This included the Pan-Andean highway, the single route between Quito and Baños.

Following almost two weeks of blockades the then President Palacios (the country's sixth in nine years) declared a state of emergency in the five worst affected provinces, including the highland provinces of Cotopaxi, Canar, Chimborazo and Imbabura, as well as parts of Pichincha, where Quito is located. This effectively suspended the constitutional rights to public assembly, restricted freedom of movement and imposed a curfew. Thousands of police and soldiers were deployed to clear the blocked highways, although protest rallies in the capital continued until the end of the month. As an interesting aside, at the end of March trade talks were frozen by the US following a dispute between the government of Ecuador and a US oil company over alleged violations of a contract for the production of crude oil in the Ecuadorian Amazon, and the trade agreement remains stalled to this day (for further information on the dispute see: AFP, 2006; MercoPress, 2006; BBC News Online, 2006a, 2006b, 2006c). Due to these road blockades, a significantly reduced period of time was left available for conducting the survey within Baños and resulted in the collection of only a small dataset. In light of this, several changes were made to the focus and scope of the research design, and these are reflected in the aims and objectives outlined above.

CHAPTER 2: REVIEW OF THE LITERATURE

This research focuses on volcanic risk management, and considers how components of socio-economic and community vulnerability may be integrated within traditional hazard assessments to produce an interdisciplinary approach that considers both the geophysical hazard, and the social and cultural context of risk. This chapter reviews and critiques relevant literature to elucidate these issues, placing particular emphasis on the importance of the social nature of risk and disaster.

Discussion of the literature begins by briefly defining some of the key concepts encountered within the field, and identifies some of the problems associated with these definitions in light of the interdisciplinary nature of the research. This is a pertinent issue with regards vulnerability, and is expanded upon further. Increasing trends in natural disaster occurrence are reported, and reasons for the recent increases are explored. This provides insight into the importance of the social and cultural context of risk. The merits of various approaches to risk management, with a focus on risk assessments, are considered and opportunities for integrated approaches are discussed.

The concept of vulnerability is considered in greater depth, and problems associated with the term's definition and usage within research, policy development and risk management are examined. The importance of socio-economic characteristics and psychological factors, as determinants of vulnerability are explored. General theories of risk perception are outlined, followed by a more specific examination of the role of risk perception in prompting adaptive behaviours for reducing vulnerability. Additional important psychological variables are considered, with the aim of providing a wider context for the current research. A continual theme throughout the literature discussed here, are issues and problems associated with cross-disciplinary research, particularly between natural scientists/engineers and the social/psychological sciences, and how these may create barriers towards successful risk mitigation.

2.1. KEY TERMS DEFINED

Prior to any discussion of human vulnerability to volcanic hazards, it is prudent to define the key terms used in the study of hazards and their associated risks, because their usage in scientific literature is often ambiguous. Here we briefly define the key concepts but later further expand on those terms found to be particularly problematic within the literature, often due to cross disciplinary differences in use or meaning.

2.1.1. Disasters

The Concise Oxford Dictionary defines disaster as a sudden accident or natural catastrophe that causes great damage or loss of life (Thompson, 2005). Additionally, such an event:

> *"...usually occurs unexpectedly and has a severe impact on [the] life and health of many people and/or causes considerable material damage and/or impairs or endangers the life of a large number of people for a long period of time, to such an extent that resources and funding available at [the] local or regional level cannot cope without outside help" (Thywissen, 2005)*

Disasters can result when the natural, modified or constructed environment produces a potentially destructive agent, which combines with a vulnerable population and causes sufficient disruption to individual and social needs to threaten physical survival, social order and meaning (Oliver-Smith, 1998). An event need not be extreme in order for a disaster to occur, only that a community's ability to cope with it is exceeded (Kelman, 2007), e.g. the term disaster should only be used when the losses experienced exceed accepted norms within the affected society (Degg, 1992). Disasters are the result of a spatial interaction, or overlap, between a hazardous environment and the infrastructure, socio-political organisation and community groups that form a society. Therefore, disasters are not only the product of a hazard but of the social, political and economic environment (Blaikie *et al.*, 1994). Their essence may be found in the organisation of communities, rather than in the environmental phenomenon which causes the destructive or disruptive effects for a society, and for this reason disasters may be considered a social construct (Oliver-Smith, 1998). In a Social Science Research Council report, Smith (2006, p. 1) writes:

> *"It is generally accepted among environmental geographers that there is no such thing as a natural disaster. In every phase and aspect of a disaster - causes, vulnerability, preparedness, results and response, and reconstruction - the contours of disaster and the difference between who lives and who dies is to a greater or lesser extent a social calculus"*

2.1.2. Natural Hazards

A natural hazard is a naturally occurring process or event which has the potential to create loss. It is a source of future danger that represents a potential threat to humans and their welfare (Smith, 2001), and is caused by environmental factors extraneous to man (Degg, 1992). The term natural hazard has been subject to fierce semantic debate, particularly amongst social scientists in relation to disaster research (Hewitt, 1983; Cannon, 1994; Mileti, 1999; Steinberg, 2000; Wisner *et al.*, 2004; Haque & Etkin, 2007). At its most extreme, the influences of human social structures are seen as greater determinants of the consequences of a hazard event than the natural causal mechanism. Hewitt (1983) argued that hazards were neither explained nor uniquely linked to the geophysical processes that may initiate damage, and that too much emphasis was placed upon these processes. Haque & Etkin (2007, p. 274) assert that:

> *"Human and societal elements are important not only because people are victims when extreme environmental events take place, but also because humans define the very essence of a 'natural' hazard."*

There is some legitimacy to this conceptualisation, as a hazard does not exist without a human population. If a natural event does not intersect both spatially and temporally with people or property, such an event, e.g. a volcanic eruption, is simply a normal geological process. However, for the purposes of this review, the term natural hazard simplifies the terminology and allows, where necessary, a distinction to be drawn between those hazards that result from natural processes and those directly caused by the activities of man, i.e. those termed 'technological hazards'.

2.1.3. Risk

At its most basic, risk can be defined as the exposure of something of value to the possibility of loss, injury or other adverse circumstances (Pidgeon & Butler, 2009). There exists two distinct approaches to its conceptualisation; those who believe risk can be objectively quantified through risk assessments, and those who see risk as inherently subjective (Slovic & Weber, 2002). In the former approach, risk is defined as the danger a hazard represents to vulnerable buildings or people (Bolt, 1999). Not only is it the exposure of something of human value to a hazard (Smith, 2001), it is also a function of the probability and seriousness of an undesirable consequence (Pidgeon *et al.*, 1992). Therefore, risk can be defined in terms of the potential danger produced by a natural hazard, e.g. earthquake or volcanic eruption, the degree of vulnerability of people and infrastructure exposed to that hazard, and their value (Dobran, 2000).

Using an objective approach allows risk to be quantified in numerical risk assessments. The identification, quantification and characterisation of threats which form the basis of risk assessments are distinct from the communication, mitigation and decision making processes which define risk management, but both form important facets of risk analysis (Slovic & Weber, 2002). Elements which interact and can be used in risk assessments include the potential exposure of buildings, facilities and communities within a specific location to the physical effects of a hazardous situation or event, and the vulnerability of the community in terms of potential loss of life, injury or economic cost (Murck *et al.*, 1997). Numerous equations have been developed from various different disciplines and for different hazards in an attempt to allow quantification of the concept of risk. Generally they comprise the following elements:

$$\text{Risk} = \text{Vulnerability} \times \text{Hazard} \times \text{Value}$$

The capital worth (of land, buildings or infrastructure), termed *value*, is the number of human lives, or the productive capacity (factories, power plants or agricultural land) in economic terms that is at risk. The proportion of the value which is likely to be lost as a result of a given event (an earthquake or volcanic eruption) is termed *vulnerability*, whilst *hazard* is the probability of the area being affected by the physical phenomena (Fournier d'Albe, 1979).

Objective risk analysts believe these elements can be quantified using probabilistic estimates based on theoretical models. Social scientists argue that these models are, in themselves, subjective, and based on the assumptions and judgements of the scientists. They are in this way similar to the assumptions and assessment techniques used by non-scientists when evaluating risk (Slovic & Weber, 2002). Critics of quantitative risk assessments also argue that by focusing the unit of analysis on the monetary value of buildings/infrastructure at risk or the number of people exposed, these assessments ignore many of the contextual characteristics of a region that may act to attenuate or amplify risk such as social vulnerability. The vulnerability created for many people through their normal existence must also be connected to the risks presented by natural hazards (Wisner *et al.*, 2004).

2.1.4. Vulnerability

Definitions of vulnerability generally fall into two categories and this divergence is a manifestation of the different research agendas of the two main disciplines involved in hazard research; the natural sciences and the social sciences. Firstly, there are those that view vulnerability only in terms of the sensitivity of a system or population to a specific hazard, and this is often termed *physical vulnerability* (Brooks, 2003). This approach leads to the quantification of vulnerability in terms of the value of buildings affected, or in the number of lives lost. Secondly, there are those who view vulnerability as a function of the internal properties of a system, e.g. the social, economic, political and environmental factors that may amplify or attenuate the impacts of a hazard, and this is often termed *social vulnerability* (*ibid*). Here, vulnerability can be seen as the capacity of an individual or group to anticipate, cope with, resist and recover from the impacts of a natural hazard (Blaikie *et al.*, 1994).

Socio-economic factors, including population density, hazard awareness, resources for mitigation and recovery (Murck *et al.*, 1997), material welfare, education, politics, age, race and gender (Degg, 1992), help determine the degree to which someone's life and livelihood is put at risk from naturally occurring events. The most vulnerable groups in society are those who find it most difficult to reconstruct their lives following a disaster (Blaikie *et al.*, 1994). It is often suggested that these groups are generally those living in poverty, the elderly or the very young, women and ethnic minorities, although empirical evidence does not always support such simplistic interpretations (Chou *et al.*, 2004; Raschky, 2008). Psychological factors may also play a significant role in determining vulnerability by influencing how people behave in the face of an adverse event (Dibben & Chester, 1999).

Forming central themes within this thesis, the concepts of risk (and its assessment) and vulnerability (its various definitions, and why disparate levels within and between communities may occur) are addressed in greater depth later in the chapter.

2.2. NATURAL DISASTERS

During the last half century, the adverse consequences resulting from natural hazards have increased, despite improvements in science, monitoring and technology. The proliferation of global media coverage, instantly conveying details of disasters around the world, as well as spiralling losses, has heightened the notion that risks from natural hazards have increased. There is little evidence to suggest there has been an increase in the occurrence of natural events (O'Keefe *et al.*, 1976; Kunkel *et al.*, 1999; Berz, 2000; Smith, 2001; Munich Re Group, 2009), but rather sociological pressures, including population growth and urbanisation, immigration, trends in land occupancy, an increase in poverty levels, inadequate organisational systems and pressures on natural resources, as well as environmental degradation and climate change have contributed to increase the frequency and magnitude of disasters, by placing more people at risk from environmental extremes (Degg, 1992; Smith, 2001; Cardona, 2004; Wisner *et al.*, 2004; Smolka, 2006; Donner & Rodriguez, 2008; Raschky, 2008).

2.2.1. Trends in Natural Disaster Occurrence

A brief study of the Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database (EM-DAT, 1988-), a global resource containing the occurrence and effects of over 16,000 mass disasters from 1900 to the present (both natural and technological), confirms the number of reported natural disasters per year has increased. A number of criticisms of the data have been made, including the selection criteria for classifying an event as a disaster (and hence its inclusion or omission from the database), reliance on news agencies and non-governmental organisation reports as primary sources of data, under-reporting to protect political interests, and duplications resulting in over-estimates for the number of people affected or injured (Witham, 2005; Eshghi & Larson, 2008). Additionally, data for many countries and regions are sparse prior to the 1970s (Brooks *et al.*, 2005).

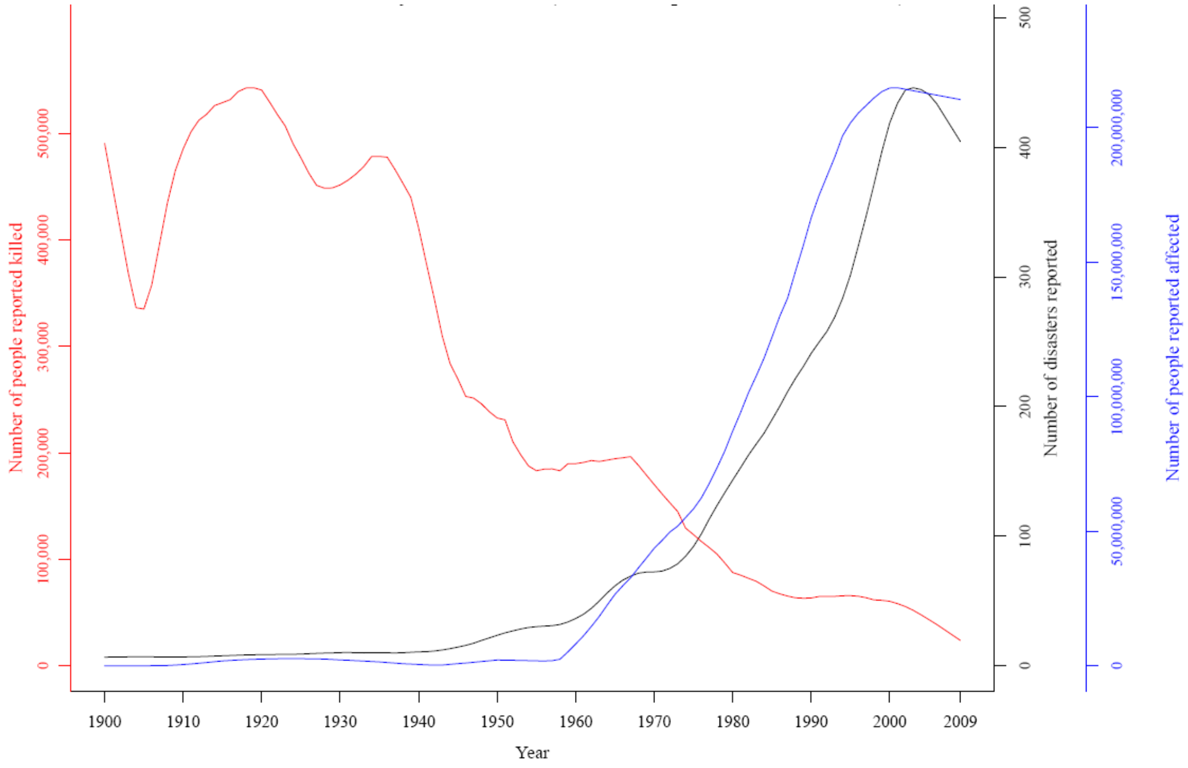


Figure 2.1 Line chart showing a summary of natural disasters; 1900 – 2009 (linear-interpolated smoothed lines) (EM-DAT, 1988-).

However, EM-DAT provides one of the only widely available tools for exploring global disaster trends over the last 100 years. Focusing on natural disasters (drought, earthquakes, epidemics, extreme temperature, floods, insect infestations, landslides, storms, volcanoes and wildfire), the EM-DAT database indicates that since 1900 there have been more than 9,000 disasters, about 80% of which occurred in the last 30 years (Figure 2.1). During the 1970s there was an average of 90 disasters per year, but in the last 10 years this has risen to an average of almost 400 (Rodriguez *et al.*, 2009). This dramatic rise may be explained by (i) an increase in the incidence of geophysical and meteorological events, (ii) improved reporting, or (iii) an increase in the number of people living within close proximity to the sources of environmental hazards.

Although the number of natural disasters has increased during the last century, evidence suggests that the number of geological events has remained relatively constant, whilst disagreement exists over whether the number of meteorological events has increased as a result of global climate change (EM-DAT, 1988-; Glickman *et al.*, 1992). Some evidence that climate change is modifying patterns of climate-related hazards, such as cyclones, droughts and flooding is beginning to accumulate (Bruce, 1999; IPCC, 2007; UNISDR, 2007a). Other authors argue that the increase in meteorological disasters is solely attributable to the increasing exposure of people and assets due to shifts in socio-economic factors, rather than to any demonstrable change in the climate (Changnon, 2003; Pielke Jr *et al.*, 2003; Raghavan & Rajesh, 2003; Barredo, 2009). The rising number of natural disasters may be partially explained by developments in telecommunications technology, media reporting and international cooperation, which may have improved recording of events, particularly of smaller incidents in remote regions. However, it is unlikely that improved reporting and any effects of climate change can account completely for the dramatic increase in the number of disasters. Instead, our greatly expanding urban society, as well as underlying development trends, such as migration, increasing population densities, globalisation and poverty have placed more people in harms way.

During the same period, there has been a concomitant increase in research efforts and resource expenditure on hazard mitigation but this has failed to ameliorate losses. An over emphasis on technocratic solutions and post disaster aid, rather than a focus on addressing the underlying sociological causes of disaster may explain the failure of mitigation efforts to control the rising tide of disaster occurrence. However, some success has been seen in that although overall, the number of disasters continues to rise, the number of fatalities has decreased, halving since 1970 (Schneiderbauer & Ehrlich, 2004). The relative number of deaths has declined even more when considered in the context of continued population growth (White *et al.*, 2001).

Whilst loss of life has been reducing, the number of people affected (either injured or displaced) has increased significantly (Figure 2.1), along with economic losses. An average of 90 million people were affected by natural disasters per year between 1974 to 1983, compared with an average of 250 million people per year for the decade 1994 to 2003 (Guha-Sapir *et al.*, 2004). Over the past 40 years the cost in property damage has been doubling every seven years (ICS, 2008). Claims for damages due to meteorological events have risen from $45bn during the 1960s (in today's prices), to $370bn in the 1990s (Brown & Damery, 2002), and the average annual cost for natural disasters as a whole has risen from less than $28bn per year in the 1970s, to almost $70bn per year by the beginning of the 21st century (EM-DAT, 1988-). The year 2008 was particularly severe in terms of the number of people killed (235,000), and the economic cost ($190bn), whilst the number of natural disasters (354), and the number of people affected (214 million) was slightly down on the average. These figures demonstrate how mega-disasters can impact the disaster statistics for any one year, because just two events in 2008 accounted for 96% of deaths, 57% of the numbers affected and 62% of economic losses; the Sichuan earthquake in China and Cyclone Nargis in Myanmar (Burma) (Rodriguez *et al.*, 2009). However, measures to reveal the true cost of disasters are not well understood due to a lack of official records, and the complexity inherent in quantifying the numerous factors involved (Eshghi & Larson, 2008).

2.2.2. Inequitable Losses from Natural Disasters

Although the effects may be experienced in any country exposed to natural hazards, the distribution of losses is not equally felt. A disproportionate number of disaster victims (both in terms of those killed and the numbers affected) live in developing countries, despite evidence that richer nations are subject to a similar number of disasters (Kahn, 2005). It is estimated that 90% of natural disaster fatalities occur in developing countries (UNISDR, 2007b), and The International Federation of Red Cross & Red Crescent Societies (IFCR, 2002) estimate that between 1991 and 2000 there were 23 deaths per disaster in the richest countries, compared with 1,052 deaths per disaster in the poorest. A salient example of the disparity in losses between different countries is demonstrated by two earthquakes, both measuring magnitude 6.6 on the Richter scale. The 1994 Northridge earthquake in California claimed 57 lives and resulted in 1,500 injuries, whilst the Bam (Iran) earthquake of 2003 killed a reported 43,200 people and required the evacuation of up to 100,000 people (Eshghi & Larson, 2008). The inequity between developed and developing countries is not confined to loss of life but includes economic cost. Although the most expensive losses tend to be reported in developed countries due to the higher insured value of property, losses in terms of percentage of GDP are greater for less developed countries. Losses from natural disasters between 1985 and 1999 were estimated at an average of 2% of GDP for richer countries, but 13% for poorer nations (IFCR, 2002). In 2005 Hurricane Katrina caused $129bn worth of damage in the United States, representing less than 1% of GDP. The Myanmar Cyclone caused losses totalling just $4bn but this represented almost 30% of the country's GDP (Hoyois *et al.*, 2006; Rodriguez *et al.*, 2009).

The inequality in disaster losses was recognized by O'Keefe (1976), who acknowledged that under-developed countries suffered the greatest loss of life per natural disaster, and that increasing vulnerability to extreme physical events was connected with the continuing process of underdevelopment. In addition, as populations continue to expand and resources continue to be controlled by a minority, the standard of living for much of the world's population drops, increasing further their vulnerability to environmental perturbation (O'Keefe *et al.*, 1976). This has led to a shift in viewing disasters as extreme events created by natural forces, to seeing them as manifestations of unresolved development issues (Yodmani, 2001; Guha-Sapir *et al.*, 2004).

Extreme disasters such as the 1995 Kobe earthquake, the 2004 Indian Ocean Tsunami and Hurricane Katrina, highlight the trend towards the globalisation of disaster impact, with human and economic consequences felt across many countries, and economically around the world. Hurricane Katrina resulted in severe oil shortages and a sharp global price rise due to the damage limiting oil-production and refining capacity (Smolka, 2006). The Boxing Day Tsunami directly affected eleven countries, whilst tourist deaths accounted for loss of life in over fifty countries (Huppert & Sparks, 2006). The increasingly interdependent global economy, and the emergence of countries such as the rapidly developing regions of Asia and South America, which are geographically exposed to many different natural hazards, will only exacerbate the globalisation of risk. The importance of mitigation expertise and technology transfer between developed and developing nations has therefore never been more crucial, not only for humanitarian purposes but in helping to maintain a stable world economy. This may explain why the interest in hazard management has increased during the last 20 years (Chester *et al.*, 2002). As well as increased investment and research into mitigation, there has been a shift from traditional hazard management that focuses on the science of hazard analysis, to a more integrated approach which also considers the social and cultural influences that may increase vulnerability.

There remains many problems with the implementation of current management practices, and many argue that disaster mitigation and prevention should be built into international development programmes (Press & Hamilton, 1999; Heijmans, 2001; Twigg, 2001a; Freeman *et al.*, 2002; Guha-Sapir *et al.*, 2004). In addition, the people responsible for making decisions and those affected by the decision, may not be experts in the relevant science and technology (Stern & Fineberg, 1996). Some incidents have occurred where interpretations and assurances made by decision makers were inaccurate, eroding trust in the management process (Voight, 1990; Tobin & Whiteford, 2002a; Haynes *et al.*, 2008b). There is also a continued reliance on post-disaster aid rather than preventative investment. The World Bank and the USGS estimate that worldwide economic losses from natural disasters during the 1990s could have been reduced by $280bn if just $40bn had been invested in disaster preparedness and prevention strategies (quoted in Guha-Sapir *et al.*, 2004 pg. 45). One problem associated with an over reliance on relief aid demonstrated by past disasters, is the failure of aid to reach the worst affected victims. Instead, it benefits those who are the most well-connected within a society, whilst particularly vulnerable communities fall into a cycle of dependence on relief aid, a culture which must be broken in order to build internal resilience to future shocks (Wisner *et al.*, 2004).

2.2.3. Volcanic Hazards

Issues in mitigation and management across the hazard types are broadly comparable but the frequency of events is very different. For the period 1994–2003, floods represented 33% of natural hazard events, storms 23%, epidemics 15.2%, droughts 15%, earthquakes 7%, tsunamis 7%, landslides 4.5% and volcanic eruptions 1.4%, (Leroy, 2006). When compared to the loss of life and economic costs associated with other natural disasters, volcanoes seem relatively benign. Out of a total of almost 3,000 disasters between 1975 and 2005, there were 134 volcanic disasters, in which 26,703 people lost their lives (almost 23,000 of these deaths are attributable to a single event; the 1985 eruption of Nevado Del Ruiz, Columbia (Voight, 1990)), whilst 3.4 million people were affected (EM-DAT, 1988-). This represents 0.07% of the 5.1 billion people affected by natural disasters during this period. However, some 10% of the worlds population live either on or near potentially active volcanoes, representing approximately 500 million people (Sigurdsson, 2000), and nine of the world's fifty fastest growing cities are found in areas of active volcanism (Chester *et al.*, 2001). Many densely populated, developing regions of the world are found near high-risk volcanoes (Voight, 1990; Tilling & Lipman, 1993), and although the risks from volcanic eruptions are generally recognised, continued population growth and urban expansion into more hazardous regions continues (Chester *et al.*, 2001). These factors suggest that loss of life and damage to property resulting from volcanic activity, is likely to follow the trend for increasing losses demonstrated by other natural hazards.

Volcanic hazards exhibit some unique characteristics when compared to other geological hazards. In many instances, subject to appropriate monitoring, increasing volcanic unrest can be identified, and appropriate mitigation strategies put into action. Additionally, volcanic eruptions may be associated with the production of several different hazard types at the same time (e.g. ash, lahars and pyroclastic flows). The spatial distribution of primary hazard products associated with volcanism are generally confined within a predictable geographical region, and fall into two basic categories, (i) low impact/low energy but affecting a wide area (e.g. air-fall tephra), and (ii) high impact/high energy, generally limited to much more restricted areas (e.g. lahars and pyroclastic flows). These areas, including river valleys, tend to be preferentially settled by human populations and in comparison with other geological terrain, volcanic regions appear to be one of the most densely populated on Earth (Small & Naumann, 2001). It may be perceived by these populations that long term benefits outweigh any short-term risks (Chester, 1993). These benefits include the presence of nutrient rich soils associated with weathered volcanic material (Small & Naumann, 2001), which may be scarce due to high population densities (Newhall *et al.*, 2000), the exploitation of geothermal resources for the production of energy, the attraction of tourists to the mountainous terrain (McNutt, 2000) and the exploitation of mineral resources. In addition, people often have deep seated economic, social and cultural attachments to the land (Newhall *et al.*, 2000; Chester *et al.*, 2002).

Many people view natural hazards as low-probability events and for much of the time risk remains an abstract concept. The characteristics of volcanic eruptions may compound this view, with large eruptions being rare events, often occurring at intervals of hundreds of thousands of years. This interval between periods of volcanic activity reduces the perceived risks posed by an eruption (Blaikie *et al.*, 1994). So whilst residents may be familiar with more frequent smaller eruptions or unrest, they may fail to realise that their homes and schools are built on deposits of much larger, explosive eruptions (Newhall *et al.*, 2000). The activities of the state can further erode the public's perception of risk. Government sponsored schemes of economic development around the Bay of Naples in southern Italy have led to population increase and rural to urban in-migration, which now places at least 700,000 people at risk from a future eruption of Vesuvius (Chester *et al.*, 2002), or the much larger Campi Flegrei. More recent hazard management attempts advocate the payment of compensation to encourage individuals to relocate from the high-risk zone. This switch in policy may compound the view that successive national governments are unable to implement a sustainable hazard mitigation programme within their wider development remit, even within a more developed country such as Italy.

2.3. CONCEPTUAL APPROACHES TO RISK MANAGEMENT

Disasters are not only the products of natural hazards but of social, political and economic factors. They are the result of spatial interactions between a hazardous environment and a vulnerable population, and any attempt to manage volcanic hazards requires not only the quantification of risk from a specific hazard, but also an understanding of the economic, social and cultural environments which shapes vulnerability (Wisner *et al.*, 2004). Fournier d'Albe (1979) recognised that because, generally, natural hazards cannot be altered or influenced:

> *"Our possibilities of reducing risk are limited to whatever can be done to reduce the exposed value and the vulnerability of life and property" (pg.322).*

In general, volcanic hazards are regional problems and only pose a threat to part of a country under anything but the most extreme, long term and therefore, most unlikely eruption scenarios. Appropriate land-use planning, the establishment of emergency evacuation procedures and the communication of potential risks to affected populations are fundamental in minimising vulnerability. However, many mitigation measures rely on costly engineering solutions and are palliative, in that they attempt to reduce losses once an eruption has started (Chester *et al.*, 2001). In contrast, general prediction in the form of hazard mapping and risk assessment provides information regarding the type and magnitude of expected hazards. This is based on evidence from past eruptions and can be used to formulate mitigation strategies, which, for example, restrict new economic development in particularly hazard prone areas, or encourage civil defence and evacuation planning. Chester *et al.* (2001) defines this approach as:

> *"the study of the past behaviour of a volcano to determine the frequency, magnitude and style of eruptions and to delineate high risk areas, using geological and historical evidence and eruption statistics to produce…….maps showing the range of volcanic hazards under different eruption scenarios."*

The availability of resources for appropriate risk mitigation, and the relative vulnerability of human populations in different regions of the world, has led to a disparity in the approach to hazard management found in developed and developing countries. Many less economically developed countries lack the resources and expertise necessary to ensure that risks from volcanic activity are given sufficient priority (Dibben & Chester, 1999). Whilst some of the most developed countries in the world, e.g. the United States of America, Japan, Italy and New Zealand, have a long established and well advanced approach to hazard mitigation. This often relies on both predictive technological measures, as well as expensive engineering works. These include barriers erected to redirect lava flows on Mount Etna (Abersten, 1984) and

Hawaii (Bolt *et al.*, 1975), and Sabo dams to channel debris flows in Japan (Ikeya, 1989; Hubert, 2004). Sabo (meaning 'sand protection' in Japanese) dams, comprise a series of man-made channels and levees built to protect surrounding settlements and roads, and are built at several volcanoes including Mount Unzen and Sakurajima. In both developed and developing countries, an assessment of a society's vulnerability to an eruption is less frequently considered.

Although theoretically progress has been made towards integrating the physical and social aspects of hazard and risk research, the quantitative and qualitative approaches in policy and disaster management practice remain somewhat polarised. Management solutions continue to be dominated by technocratic approaches, including engineering works and expensive monitoring programmes (Pelling, 2001). Whilst efforts are concentrated on hazard analysis and risk characterisation, as well as assessments of physical vulnerability (Fuchs *et al.*, 2007), less emphasis is placed on more socially defined and therefore less quantifiable influences on risk. This is largely due to the framing of disaster, which until recently was dominated by experts and specialists in the natural sciences (Cardona, 2004).

2.3.1. The Dominant Approach

The traditional theoretical framework of natural hazard management viewed geophysical extremes as the main determinants of disaster, and the application of technocratic, engineering solutions were seen as the most appropriate response to resolving hazardous impacts (Hewitt, 1983; Hood *et al.*, 1992; McEntire, 2005). The emphasis of this formally 'dominant' approach was on understanding the hazard (O'Keefe *et al.*, 1976; Cutter, 1994), particularly the physical processes involved, e.g. where they were likely to occur, their magnitude, duration, speed or onset and frequency (White, 1974; Hewitt, 1997; McEntire, 2005). This paradigm viewed the social, political and economic determinants of disaster as less important and attempted to control nature (Hewitt, 1983) through the use of an overly narrow, techno-centric approach to disaster risk management (Gopalakrishnan & Okada, 2007). Cardona (2004) suggests that focusing exclusively on the physical phenomena, which are predominantly unpredictable, perpetuates the notion that damages and losses are unavoidable. This notion, which implies that hazard agents are the sole determinant of disaster (O'Keefe *et al.*, 1976), has contributed to a misreading of disaster and risk by exposed populations, and been used by political authorities to avoid blame.

When Fournier d'Albe (1979) recognised that losses were not only the result of the severity of the physical phenomenon but of the vulnerability of exposed elements, a more complete understanding of risk and disaster developed. Utilised within the fields of applied sciences (e.g. geography, economics, planning and environmental management), the concept of vulnerability was concerned explicitly with potential losses in terms of physical damage or the number of lives lost. Risk was thus quantifiable in economic terms, promoting the use of cost-benefit analysis, and providing vital information for emergency preparedness and response (Cardona, 2004). However, this approach perpetuated the view of the dominant paradigm, i.e. that the hazard is the sole origin of disaster, and by limiting the definition of vulnerability to the exposure of physical elements, the approach ignored the overall consequences for society (Chester, 1993; Cardona, 2004; Wisner *et al.*, 2004).

Both the natural and applied science approach to risk management recognise that no risk can exist unless there is a human population to be affected, but differences between societies are viewed as less important than the geophysical extremes which are considered the main determinants of risk (Hood *et al.*, 1992; Chester, 1993). Techniques of risk assessment and hazard monitoring were seen as key priorities, and the role of national governments and international agencies were largely defined in terms of the transfer of this knowledge and technology, particularly from developed to developing countries. Little or no consideration was given to the differences between places or the reasons why a population may be vulnerable. An over reliance on reactive responses, including international relief aid, was advocated under the dominant approach and justified on economic, social and ethical grounds. However, this approach often benefits those who are already well off, leading to further marginalisation of the poorest members of the community (Hewitt, 1997; Chester *et al.*, 2002). In addition, a reliance on post-disaster relief, insurance cover (Smolka, 2006) and technocratic engineering solutions may make hazards more acute by changing peoples behaviours, such that they are willing to take greater risks (Chester, 1993).

2.3.2. The Radical Critique

In more recent years, the dominant approach has exerted less influence on the research literature, policy development and international agenda setting, following the emergence of a social theory of disaster, which criticised the deterministic approach (Cardona, 2004). This 'radical critique' views hazards as a normal aspect of society, and that explanations of extreme events are not possible in purely physical terms (Hewitt, 1983). In particular, disasters are seen as the product of increasing vulnerability due to the exacerbation of political, economic and social problems within a population by a geophysical trigger (Susman *et al.*, 1983). It is for this reason that major disasters are predominantly a phenomena of areas of the world undergoing major social, economic and environmental change (Hewitt, 1983, 1997). Therefore, vulnerability cannot be measured without considering the capacity of the population to absorb, respond and recover from the impact (O'Keefe *et al.*, 1976). This differential capacity of a population to respond, explains why comparable events may produce negligible consequences in one community but result in a disaster in another (Cardona, 2004; Eshghi & Larson, 2008).

The influences of the sustainable development paradigm, which has pervaded the international approach to many environmental issues, further emphasises the need for an equitable approach to risk management, particularly for populations in developing countries. This in turn shapes the rationale behind more recent policy development and government response to natural hazards. A more pro-active response to risk management has evolved, based on the idea that natural disasters are the product of societal problems (Hood *et al.*, 1992). This human cultural approach (Gopalakrishnan & Okada, 2007) to risk reduction should be tied to development policies that attempt to address issues of health and economic marginalisation, and not just the quantification of hazardous events (Oak & Bender, 1990), or advocate an over reliance on engineering solutions. In arguing that natural hazards are predominantly human induced, the radical approach supports the adjustment of human behaviour to minimise potential environmental threats, rather than changing the environment to suit human needs (Hood *et al.*, 1992).

Much of the work advocating the radical critique concerns hazard characteristics not typical of volcanic activity, e.g. long onset, widely distributed effects, long duration and mainly impacting the most marginalised members of society, e.g. floods or drought. Generally volcanic activity is characterised by rapid onset, spatially limited, relatively short duration, and in terms of the most hazardous products (pyroclastic flows and lahars), impact all members of a community equally. There is much to recommend both the dominant approach, with its emphasis on quantification, prediction and engineering solutions, and the radical critique, with its focus on integrating disaster management into development planning. A combination of these two approaches to risk management that places equal emphasis on the scientific understanding of volcanic hazards, as well as an awareness of the social, cultural and behavioural characteristics of those at risk is a more recent development. This integrated disaster risk management approach (Gopalakrishnan & Okada, 2007; Wei & Okada, 2008), forms the central theme for this thesis, and was first specifically addressed within the policy community during the latter stages of the International Decade for Natural Disaster Reduction (IDNDR).

2.3.3. The International Decade for Natural Disaster Reduction

During the 1980s a number of major disasters occurred, including several notable volcanic eruptions; Mount St Helens (1980), El Chichón (1982) and Nevado del Ruiz (1985) (Tilling, 1989; Voight, 1990). Such high profile events, and a recognition of the increasing occurrence and consequent losses from natural hazards, prompted the United Nations to establish the IDNDR to run throughout the 1990s (Chapman, 1999; Chester *et al.*, 2001). Part of this programme included the Decade Volcano Demonstration Project which focused work on sixteen specific volcanoes, including those in developed countries (e.g. Mount St Helens, USA; Etna, Italy and Unzen, Japan) and developing countries (e.g. Galeras, Columbia; Merapi, Indonesia and Nyiragongo, Congo). The aim of this initiative was to demonstrate work on the entire range of activities needed in volcanic hazard mitigation (Tilling & Lipman, 1993).

Shifting natural disaster management from a reactive strategy of post disaster response to a more proactive strategy of pre-disaster planning was the basic aim of the IDNDR (Smith, 2001). Initially the emphasis of the programme was on top-down planning and mitigation, expensive prediction systems and reducing hazards though technical measures involving high capital expenditure (Blaikie *et al.*, 1994). It was later recognised that the strategy of the IDNDR should also be aimed at integrating hazard reduction with social demands, with the benefits of this approach including social and cultural acceptability, political feasibility, and economic and environmental sustainability (Oak & Bender, 1990). By the middle of the decade, these social, economic and political dimensions of risk were recognised as equally important elements for consideration within an integrated risk management strategy (Smith, 2001; Wisner *et al.*, 2004). With this in mind the successor programme to the IDNDR, the International Strategy for Disaster Reduction (ISDR), aimed to increase community resilience in the face of disaster, and was based on reducing socio-economic losses through improved public awareness of risk (Smith, 2001). These initiatives demonstrate a willingness on the part of the international community to begin tackling the issues which have led to increased loss-bearing in developing countries, and a move away from the dominant approach, with its over-emphasis on forcing continued reliance on technological expertise from the developed world.

2.3.4. Integrated Risk Management

An approach to risk management that integrates hazard analysis with an assessment of the sociological dimensions of vulnerability was suggested by Chapman (1999). This approach recognises that pro-active planning, rather than a reliance on reactive response, not only provides the basis for more successful risk reduction but is also potentially more cost-effective in the long term. Chapman's theoretical approach begins with an analysis of the natural hazard, followed by an assessment of the risks and exposure vulnerability, and an examination of the potential responses. It goes on to consider the stages of strategy formulation and decision making, which provide the interface between the potential hazard and the affected population (Figure 2.2).

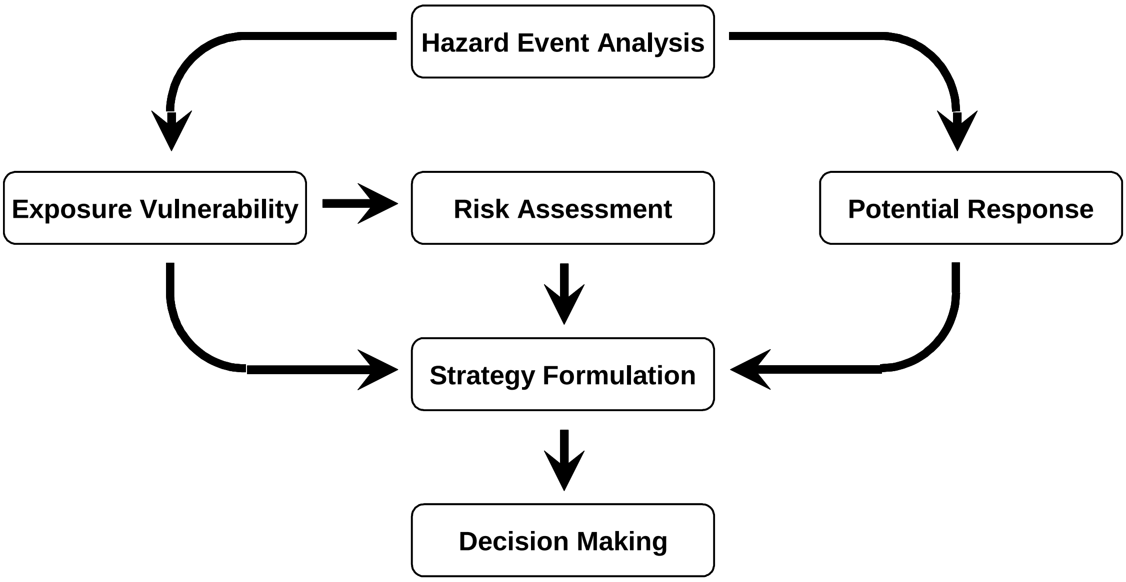


Figure 2.2 Diagram showing the six key processes of the risk management cycle (Chapman, 1999, pg. 139).

Many commentators often discuss only one or two aspects of this approach, e.g. hazard analysis and risk characterisation (Arana *et al.*, 2000; Vallance *et al.*, 2003; Zimbleman *et al.*, 2003), physical vulnerability (Pomonis *et al.*, 1999; Petrazzuoli & Zuccaro, 2004), or human vulnerability (Dibben & Chester, 1999; Cutter *et al.*, 2000; Wood & Soulard, 2009), rather than considering the whole risk management cycle (Blong, 1996; Wisner *et al.*, 2004). Each stage of this risk management process is discussed briefly below, whilst those which form key components of this research, and are arguably the most contentious issues in current hazard management discourse, e.g. risk assessment and vulnerability, are discussed further, later in the chapter.

Hazard Analysis

Hazard analysis quantifies the frequency and magnitude of the hazard event that can be expected. For volcanic eruptions this involves geological research and an examination of the historical records to determine the types of hazards to which an area may be exposed (e.g. lahars or pyroclastic flows), the size of possible eruptions, and a statistical analysis to determine the expected frequency or return period. The rarity of large eruptions, which may have intervals of hundreds of thousands of years, often precludes assessing frequency based on sample observations, as the data is often insufficient for analysis on a sound statistical basis (Booth, 1979; Fournier d'Albe, 1979; Chester, 1993). It is also estimated that only 20% of the world's potentially explosive volcanoes have records extending back over 10,000 years (Huppert & Sparks, 2006). An initial hazard analysis also provides the basis for the development of volcanic hazard maps which display areas within the proximity of a volcano that may be subject to specific volcanic hazards, and when combined with risk analysis include probability estimates.

Exposure Vulnerability

The analysis of vulnerability considers what is exposed to the physical hazard and includes the population, buildings, economic activities and other related infrastructure. Chapman (1999) places most emphasis on the quantification of potential property damage from a given intensity of hazard and the resulting cost of damage, as well as costs associated with the loss of productivity in industry, unemployment and increases in public health and social expenditure. However, this process should also aim to understand the social and economic mechanisms which control the relative level of vulnerability for a specific area, including access to natural, physiological, social and financial resources (Wisner *et al.*, 2004), and the perceptual, social and cultural values and traditions which shape them (Alexander, 2000).

Risk Assessment

A risk assessment will aim to estimate the probability of a defined loss, and is a function of the vulnerability of a population and the probable size of impact to be expected from a known magnitude event (Booth, 1979; Fournier d'Albe, 1979; Chapman, 1999). Factors used in the assessment or quantitative estimation of risk have been defined at their most basic by many authors through the previously discussed; *risk = value x vulnerability x hazard* relationship. Here, vulnerability is a measure of the degree of loss which is likely as a result of a given event, and hazard is the probability of any particular area being affected by a destructive volcanic manifestation within a given period of time (Fournier d'Albe, 1979; Scandone *et al.*, 1993; Blong, 1996). In areas at risk from the most hazardous volcanic phenomena (pyroclastic flows and lahars), vulnerability is likely to be almost 100% (Pomonis *et al.*, 1999), with little prospect of reduction by protective action other than evacuation. It is generally much less than 100% in the case of tephra fall, and is subject to some degree of control, e.g. improvements in building regulations which increase roof strength to a level which can withstand significant loading from volcanic ash (Fournier d'Albe, 1979). Hazards are often difficult to quantify mainly because violent eruptions are rare events on a human time-scale.

Potential Response

In Chapman's (1999) integrated approach to risk management, he suggests six categories of response to a potential hazard. These include:

i) *Avoid the hazard* - Risk can be reduced or eliminated by appropriate land-use planning that directs human activity away from hazardous areas.

ii) *Modify the causal factors of the hazard* - Diminish or nullify the impact of the natural event by changing its characteristics. Although some successful attempts have been made to divert lava flows, e.g. at Mt Etna and on Hawaii, pyroclastic flows and lahars provide little scope for modification by human activity (Pomonis *et al.*, 1999). One notable exception is the crater lake siphon tunnels at Kelut volcano, Java. These tunnels are designed to allow water levels in the lake to be reduced in response to volcanic unrest. They are designed to prevent a reoccurrence of the 1919 lahar that killed approximately 5,000 people when an explosive eruption threw almost 40 million cubic meters of water out of the crater lake (Smith, 2001).

iii) *Modify the hazard environment* - Change the characteristics of the affected area to reduce impacts, e.g. flood prevention of low-lying areas using levees, or the afforestation of hillsides to reduce surface run-off. Due to the unpredictable nature of volcanic eruptions and our inability to control events, this strategy may not always be feasible.

iv) *Modify loss potential* - Accepting the occurrence of an event and our inability to control it, focuses attention on measures that can help reduce the impact on property and human life, i.e. through building codes or the implementation of a warning system that allows evacuation from the hazardous area. Successful evacuations of the high risk areas around Mt Pinatubo in the Philippines (Gaillard *et al.*, 2001; Gaillard, 2008) and on Montserrat (Dunkley & Norton, 2002), following accurate forecasting of volcanic eruptions were attributed with saving many lives. However, Mount Ruapehu in New Zealand erupted just days after scientists declared its activity had subsided, and six volcanologists were killed whilst studying Galeras in Columbia when the volcano erupted unexpectedly (Dobran, 2000). Waiting for volcanic unrest before attempting to manage the hazard has severe limitations, particularly in densely populated areas. It is also generally accepted that risk reduction measures undertaken pre-disaster, particularly during development are not only cheaper but more effective than reactive responses (Burton *et al.*, 1978; Oak & Bender, 1990; Aysan, 1993).

v) *Share the losses* - Attempts to minimise the impact on people through sharing the expense once the hazard has occurred and losses have been accepted. This includes insurance, through private companies, and disaster relief aid, either from government agencies or international organisations. In the case of volcanic eruptions, where some loss may be inevitable, this form of response is typical.

vi) *Do nothing* - Where the outcome of hazards are accepted and losses are borne. In some situations this may be the most cost-effective strategy, e.g. where losses are small and/or the cost of mitigation is greater than any benefits received. This involuntary loss-bearing remains the principle response to most hazards and is often the only option available to less economically developed countries (Chester, 1993).

It should be noted that if pre-eruption planning and preparedness were universally practised, considerable differences would still exist in both the nature and time-scale of social responses. These would depend on many social factors such as the density of the population at risk, the state of technological and economic development, and the social and administrative structure of the region or country (Fournier d'Albe, 1979).

The above strategies only consider response in the context of societies and/or communities, and not of the individual. These are shaped by individual perceptions, which are conditioned by environmental, social and psychological factors, and the influence of cultural traits, social norms, cognitive limitations (Chester, 1993), and the personal characteristics of the recipient, as well as by the nature of the information provided (Johnston & Benton, 1998). Risk perception and communication form a central element of the risk management cycle and should seek to inform each successive step in the process through hazard identification, risk assessment, policy development, policy implementation, and evaluation.

Strategy formulation

Providing an interface between the hazard and the population at risk, plans may be made for loss prevention or mitigation. The behaviour and relationships between the entities involved in a volcanic crisis, including the source of the hazard, the scientists who study it, the administrative authorities who decide what action to take, the media who divulge the information and those who are exposed to the risk, determine the extent of the risk as well as the possibilities for minimising it (Chapman, 1999). Management responses may include a combination of measures, with their selection often based on the differing agendas of stakeholder groups. In addition, decisions about hazard management must be made in a socio-economic and political context.

Decision Making

Viable management options are arrived at by employing objective criteria and rational methods of decision making. Alternative options are weighed in terms of their ability to deliver the goal of hazard mitigation. Defining the nature of the problem, framing the questions and formulating policy aims should form the first stages of the decision making process. The decision to plan and organise for action in case of an eruption will depend on the number of people and value of the property located within the areas identified as high risk, balanced against the cost of mitigation measures (Chapman, 1999). Cost-benefit analysis should also consider the loss of income resulting from the non-exploitation of certain areas, against the risk of total loss of investments in the event of an eruption (Fournier d'Albe, 1979; Hincks *et al.*, 2006).

Transparency throughout the decision-making process is considered essential, especially in communicating where uncertainties lie, the assumptions used in dealing with these and a clear expression of the range of alternative approaches which could be possible given the information available. Reliability in the scientific data cannot be guaranteed, and given the very real possibility of a false alarm (see Tobin & Whiteford, 2002a; 2002b; Lane *et al.*, 2003), convincing officials that an evacuation of thousands of people is necessary, especially when they may be accustomed to small eruptions, could be problematic (Newhall, 2000). In addition, many political solutions to the problems of natural hazards conflict with other legitimate human values and there is likely to be some political conflict necessitating compromise. Such electoral pressures may influence public policy, for example, corporate business interests may be favoured over the needs of the local community, or harm to current voters may be weighed more strongly resulting in policy bias towards discounting future harms (Hood *et al.*, 1992). One important aspect is the use of existing institutions which can play a significant role in hazard reduction because their organisational infrastructure already exists, and often they have already gained social and cultural acceptance (Oak & Bender, 1990). These institutions may include mitigation, aid and relief agencies; national, state and local government agencies; non-governmental organisations (NGOs), environmental groups, and community organisations; as well as the cultural traditions and customs which shape the essence of shared collective experience within a community or region affected by a disaster (Gopalakrishnan & Okada, 2007).

Chapman's six stage process for hazard management attempts to integrate questions of economic and social vulnerability into each stage of the process. The importance of scientific research by volcanologists in quantifying hazard type, frequency and magnitude remains a central tenet, but this is supplemented with an understanding of vulnerability, including during the process of risk quantification. Information from the vulnerability analysis also provides the foundation on which strategies are formulated and decisions are made. It offers an approach to volcanic risk management that places equal emphasis on questions of hazard, risk and vulnerability.

2.3.5. Summary of Risk Management Issues

The increase in the occurrence of natural disasters and the associated loss of life and economic costs, particularly in developing countries which are least able to deal with their consequences, has led to a reappraisal of the accepted approach to volcanic risk management. Traditionally, key priorities were the quantification of hazards and risk, in terms of expected frequency and magnitude of events. This resulted in management which focused mainly on reactive responses, with volcano monitoring and eruption prediction forming the basis, with the necessary technical and scientific knowledge being transferred from developed to developing nations. In the event of an eruption, communities relied on international relief aid and this may be responsible for perpetuating vulnerability by altering peoples behaviour and perceptions, such that they are willing to take greater risks. This approach to volcanic risk management is evident in past examples of eruption events and remained central to international programmes aimed at reducing disasters, including the IDNDR. Although it was recognised almost three decades ago that this approach failed to consider the cultural, social and economic differences between places and the influence of these factors on vulnerability, it was not until the middle of the last decade that such elements were integrated into the international framework.

The increasing vulnerability of people to extreme physical events is now recognised as intimately connected with the continuing process of under-development. The central importance of these factors in magnifying the consequences of natural events, and of being the ultimate cause of disasters, is more widely accepted. A more proactive methodology for dealing with natural hazards, including volcanic eruptions has emerged. The role of volcanic hazard assessment remains, but this should be integrated within a programme that studies factors which influence a community's susceptibility to losses, including economic, social and culture factors. This should lead to responses which are incorporated within development strategies that aim to address aspects of vulnerability in order to reduce their significance in the face of volcanic eruptions. Pre-eruption planning and community preparedness, through the dissemination of information via education and communication strategies is a vital component of this.

It is increasingly accepted that precautionary planning, which considers aspects of the population as the real causes of disaster, is the most appropriate response to volcanic risk management. The extent to which this has or can be integrated within an economically deprived country's political system, remains problematic. Additionally, the emphasis on measuring vulnerability in terms of quantifying the value of what is exposed to the physical hazard persists, including building costs but also loss of human productivity and health expenditure. It remains the case that less consideration is given to the perceptual, social and cultural beliefs and values that shape vulnerability. These can be modified through education and communication programmes, which may prove a more successful method for reducing risk.

2.4. RISK ASSESSMENT METHODOLOGIES

Almost all aspects of human existence have some element of risk associated with them. This risk cannot be eliminated completely (Kaplan & Garrick, 1981), but in order to reduce its impact, it can be assessed and managed. The major goal of risk analysis is the precise estimation and quantification of risk (Kates & Kasperson, 1983), in a process that '*…seeks to supply pure descriptions of objectively verifiable facts concerning the empirical realities of risk*' (Manion, 2007, p.383). Although individuals assess risks intuitively every day, often in a more complex and multi-dimensional way than do risk assessors (Hawkes & Rowe, 2008), society demands a more objective assessment of the so-called involuntary risks associated with modern technology or the environment, such as nuclear power generation, chemical pesticide use, or volcanic activity. A key part of this process is the quantitative or qualitative evaluation of risk. Qualitative assessments utilise basic calculations, negating the need for comprehensive data. This contrasts with quantitative risk evaluation, which relies heavily on numerical modelling and/or the statistical analysis of instrument data or data from past events. Both approaches involve an appraisal of risk, consisting of initially identifying potential hazards followed by an assessment of the risk associated with each hazard. It has been argued that the extent to which either approach can be said to be purely objective is questionable (Darlington *et al.*, 2001; Slovic & Weber, 2002; Lee & Jones, 2004; Manion, 2007).

2.4.1. Quantitative Risk Assessments

Quantitative risk assessments follow a basic three step process in seeking to answer three key questions (Kaplan & Garrick, 1981; Kates & Kasperson, 1983; Lee & Jones, 2004; Smith & Petley, 2009):

i) Identification of the hazard - what can happen or go wrong?
ii) Estimation of the likelihood of such an event occurring - how likely is it that it will happen?
iii) Evaluation of the consequences of the hazard – if it does happen, what might be the likely losses?

From the results of this three step process, appropriate mitigation and management decisions can be taken to reduce risk to an acceptable level. A more comprehensive model of the risk assessment process has been suggested by Lee & Jones (2004), and is shown in Figure 2.3. The authors suggest this be viewed as an idealised model, with the number of stages actually completed depending upon the context in which the assessment is undertaken. In order to calculate risk, the basic evaluation process can be expressed as the relationship between the probability of a hazardous event occurring within a specified area (hazard), a measure of the elements at risk in terms of the monetary value of assets or the number of people exposed within the hazard area (vulnerability), and the consequences of the hazard event of a given magnitude, expressed as a percentage of the elements at risk (value or loss) (Fournier d'Albe, 1979; Kaplan & Garrick, 1981; Scandone *et al.*, 1993; Blong, 1996; Bell & Glade, 2004).

Various equations have been developed to express this relationship, the most simple being; *risk* = *hazard* x *vulnerability* x *loss* (Fournier d'Albe, 1979). In reality, this process is often significantly more complex, with consideration of additional elements such as magnitude (Smith & Petley, 2009), time (Bell, 1999a pg. 5), a spatial element (Lee & Jones, 2004 pg. 8), and human resilience (Bankoff *et al.*, 2004; Wisner *et al.*, 2004).

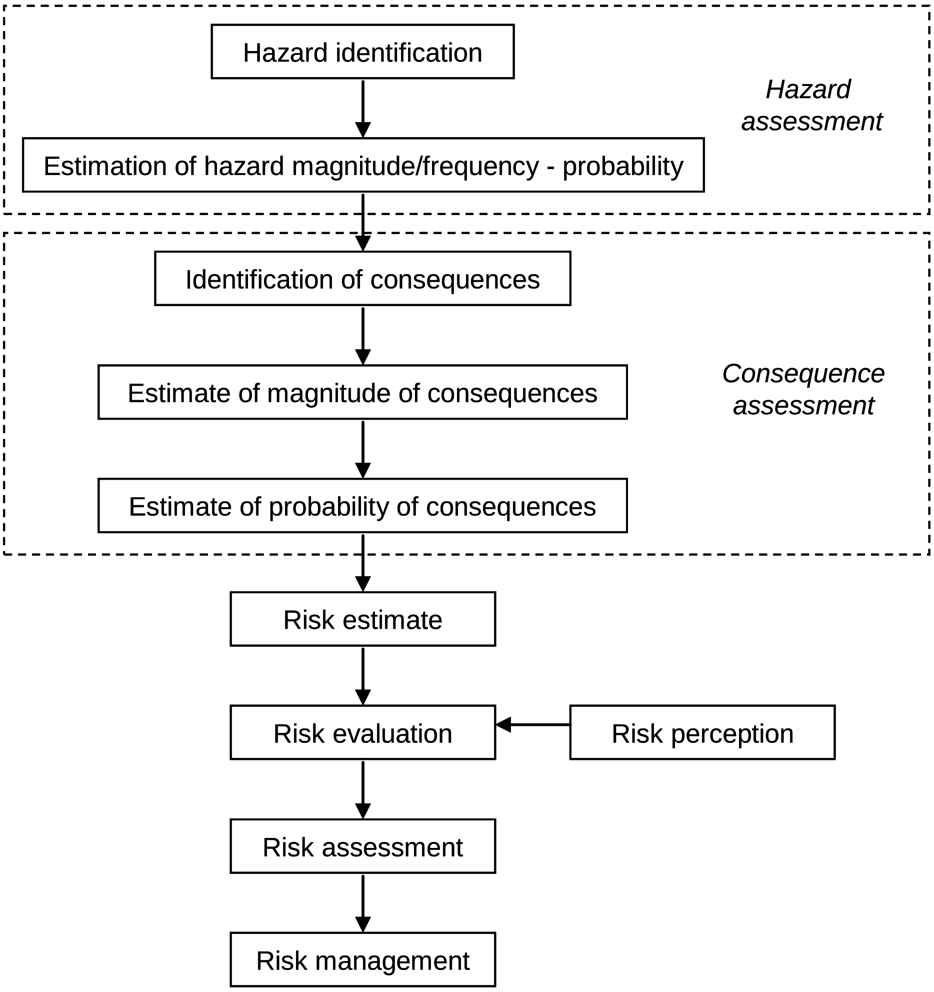


Figure 2.3 Flow chart detailing an idealised eight stage risk assessment process (modified from Lee & Jones, 2004).

A comprehensive study utilising this basic risk equation was conducted for the Vesuvius area, based on the known eruption record of the volcano, e.g. eruption size, frequency and volcanic phenomenon (Scandone *et al.*, 1993). In this assessment, the authors used the population living in each town around the volcano, derived from census statistics, to assign a *value*. *Vulnerability* was estimated using mortality figures from volcanic activity in the preceding century for each volcanic phenomenon, with an evaluation of the spatial extent of each for different eruption sizes. Both the probability of each size of eruption, and the probability of each different volcanic phenomenon was estimated to evaluate *hazard*. The results of these three components were summed for each eruption size and for each phenomenon to determine total *risk*. Using this approach, towns around the volcano were rated from low, through medium and high, to very high risk. Although this approach provided a useful initial assessment of risk in the Vesuvius area, it only considers loss of life, excluding building and infrastructure damage, economic disruption, injury, illness, or the effects of an evacuation.

A more complete representation of risk is suggested by Lee & Jones (2004), relating specifically to landslides, although applicable to other environmental hazards:

$$R_s = P(H_i) \text{ x } (E \text{ x } V \text{ x } E_x)$$

Here the specific risk (R_s) equals the expected degree of loss due to a particular magnitude event (H_i), occurring within a specific area over a given period of time. $P(H_i)$ is the probability of a particular hazard occurring within the specified area and time frame. E is the total value of elements at risk threatened by (H_i), whilst V is the vulnerability or proportion of E likely to be detrimentally affected by a given magnitude event, expressed as a percentage of E, or on a scale of 0 to 1. E_x is the exposure or proportion of total value likely to be present and therefore susceptible to being adversely impacted by the hazard, expressed on a scale of 0 to 1. Each component of E, such as buildings, transport infrastructure and people, should be calculated separately and then summed to determine the total risk. Similarly, the process should be repeated for all probable hazard magnitudes (*ibid*). Once an assessment has been completed it may be possible to complete a cost/benefit analysis that compares the estimated cost of property damage, and/or the number of deaths attributable to the hazard over a given period of time, against the cost of hazard mitigation (Bell, 1999a). It is this reductionist approach, e.g. prioritising risk by specific values (either financial or probability) that can help inform hazard management, but has also been the focus of significant criticism from social scientists who argue that this approach fails to address the wider social and cultural impacts (Chester, 1993; Bankoff *et al.*, 2004; Cardona, 2004; Wisner *et al.*, 2004).

2.4.1.1. Computer Modelling

Additional complexity can be added to volcanic risk assessments by utilising numerical computer modelling in order to predict the magnitude and spatial limits of the volcanic hazards associated with difference eruption scenarios (Saucedo *et al.*, 2005). Computer modelling can be defined as the process by which an appropriate mathematical reality is extracted from a complex physical reality. The aim being to allow the interpretation of field or laboratory data, and/or to provide a quantifiable prediction of possible behaviour (Barbour & Krahn, 2004). However, limitations exist in attempting to model certain volcanic phenomena due to a lack of understanding of the underlying mechanisms involved in their development and propagation, e.g. lava dome growth and pyroclastic flows and surges (Sparks & Aspinall, 2004). Such epistemic uncertainties result in models based on subjective assumptions in a similar way to the often criticised elements of more qualitative or semi-quantitative risk assessment methodologies. Although additional field observations or research may improve these models, one method of overcoming these unknowns is through the use of Monte Carlo simulations. This is a computational method of repeated random sampling of the accessed uncertainties, which produces statistical probabilities of the most significant sources of uncertainty (Hincks *et al.*, 2006).

Problems can arise when computer models are used as the basis for public policy development by governments or hazard management agencies who are unaware of the levels of uncertainty contained within such models. Oreskes *et al.* (1994) argues that validation and verification of such models is impossible due to the open nature of natural systems (as opposed to the closed systems implicit in computer modelling), and the lack of a complete understanding of the natural phenomena (which if we had, would negate the need for modelling). Models can only be measured in terms of their accuracy against observed data, and should therefore be viewed as representations, providing a useful guide for further study (*ibid*). More recent work has attempted to address the issues of validity and reliability (Araujo *et al.*, 2006; Jakeman *et al.*, 2006; Knutti, 2008; Holmes *et al.*, 2009; Kocabas & Dragicevic, 2009; Bellocchi *et al.*, 2010; Warmink *et al.*, 2010), but key to future work should be informing hazard managers of the uncertainties inherent within such models, and ensuring their results are used as a guide to policy and not as its basis.

2.4.1.2. Event Tree Analysis

Where the historical data of past events is insufficient for conducting reliable statistical modelling of risk, such as for modern technological hazards, decisions trees, in the form of event tree or fault tree analysis may be used. This semi-quantitative methodology (Newhall & Hoblitt, 2002) is where a known chain of events must take place before a disaster can occur, to which a process of inductive logic is applied (Smith & Petley, 2009), and is one of a suite of techniques that make up the set of methodologies known as Probabilistic Risk Assessments (PRA) (Manion, 2007). An event tree is a graphical representation that specifies a range of outcomes, the frequency of which can be calculated by the product of the frequency of the initial event and the probabilities of each intervening step. A fault tree utilises the opposite process and works back from a particular outcome, tracing the chain of intervening events to the causal agent(s) (Crossland *et al.*, 1992; Newhall & Hoblitt, 2002). A substitute for both fault tree and event tree analyses are Bayesian networks. Where decision trees provide details of all the possible scenarios and paths involved in the propagation of risk, and can therefore become quite large, a Bayesian network, or influence diagram, shows the dependencies between variables and may provide a more compact representation of the problem (Einstein & Sousa, 2006).

Fault and event tree analysis techniques have been developed and used extensively for assessing the risks associated with a diverse range of technological systems, from the mining and oil industries, to civil engineering projects, transportation infrastructure, and more recently in assessing anti-terrorism and security measures (Manion, 2007). Although less frequently applied to environmental hazards, the technique has been applied at several volcanoes, e.g.; Mount St Helens (Newhall, 1982, 1984), Vesuvius (Marzocchi *et al.*, 2004; Baxter *et al.*, 2008; Neri *et al.*, 2008), Arenal (Meloy, 2006) and Cerro Negro (Connor *et al.*, 2001). Newhall & Hoblitt (2002), describe a simplified methodology for estimating the probability of specific volcanic events within a given timeframe utilising event tree analysis. This generic process may be used to assess hazards at a particular volcano or to prepare semi-quantitative hazard maps. Nine levels or branches of probability are included, and progress from an initial event (the trunk), e.g. the probability that the volcano will become restless, to increasingly specific

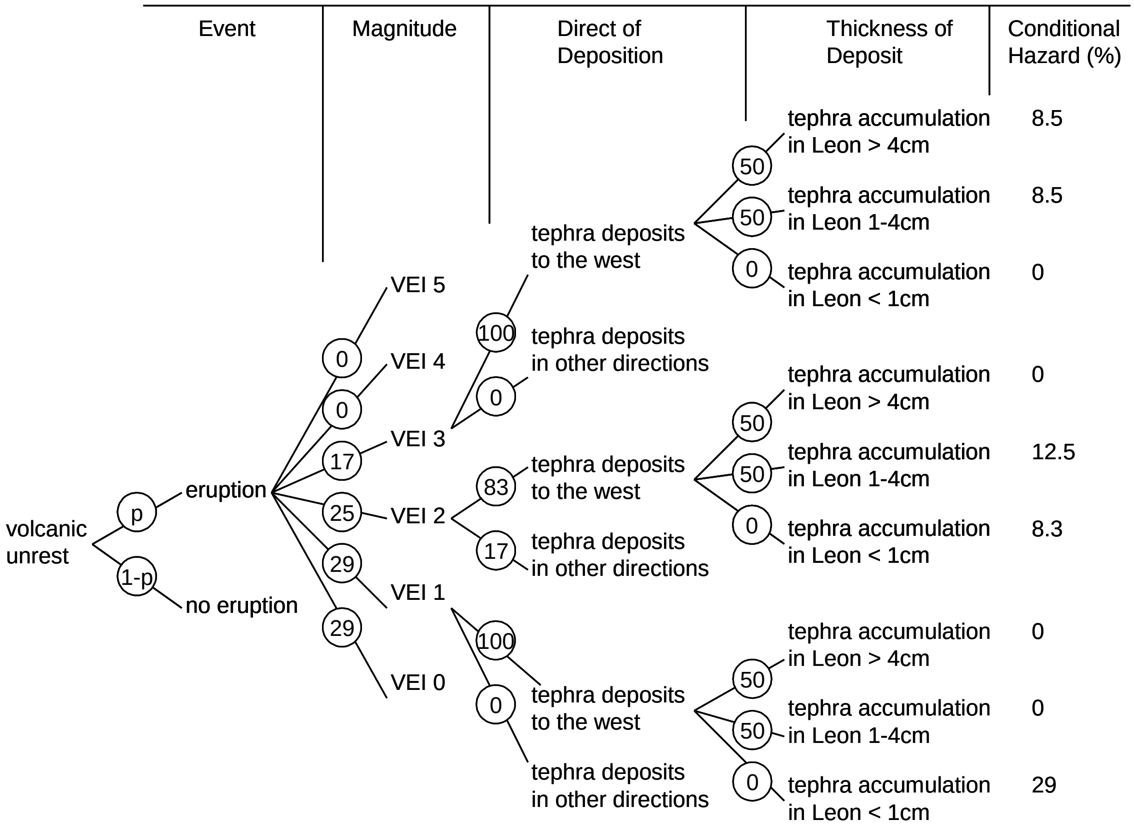


Figure 2.4 Event tree for tephra accumulation in León. Probabilities based on historical and geological records of past Cerro Negro eruptions (Connor *et al.*, 2001).

outcomes (branches), e.g. the probability that an individual who is present will be killed by a specific hazard. Probability estimates are based on empirical evidence drawn from the historic and geological record of the volcano under study. Where this evidence is limited, several methods of addressing the issue of uncertainty are suggested. Data from analogous volcanoes or eruptions may be used (Connor *et al.*, 2001; Newhall & Hoblitt, 2002), or one or more scientists may estimate levels of uncertainty, where the results from the latter method "*may be as good as any other*" (Newhall & Hoblitt, 2002, pg. 17).

Figure 2.4 shows an example of a probabilistic, volcanic hazard assessment event tree for the tephra fallout hazard at a specific town located to the west of Cerro Negro volcano in Nicaragua. Conditional probabilities were assigned to the branches of the event tree, based on the historical record of volcanic activity from when the volcano formed in 1850 to 1999. Conditional probabilities are probabilities based on the occurrence of some other preceding event (Newhall & Hoblitt, 2002). In the above example, the probability that Leon will experience tephra accumulation of > 4cm is dependent upon the occurrence of tephra deposition to the west of the volcano, and that an eruption measuring 3 on the Volcanic Explosivity Index[1] (VEI) has occurred, following volcanic unrest. The analysis for smaller, more frequent eruptions was based upon observations from the historical and geological record, and it is this which is summarised in the event tree. Due to the briefness of the record at this volcano, the analysis for larger, less frequent eruptions relied upon the results of numerical simulations, and calculates the thermo-fluid-dynamics of ash dispersion in the atmosphere by considering such variables as; the position of the volcanic vent, the density of ash diffusion from the eruption column, column height, grain size, mass of material ejected, initial velocity at the vent, wind speed and direction, tephra particle

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[1] Defined by Newhall & Self (1982), the Volcanic Explosivity Index (VEI) is a system developed to estimate the magnitude and intensity of a volcanic eruption and is measured on a scale from 0 to 8, with each successive integer representing an order of magnitude increase in explosivity of approximately a factor of 10.

fall size, the kinematic viscosity of the air and eruption duration (Connor *et al.*, 2001). This demonstrates the considerable data requirements and inherent complexities involved in the process of evaluating the parameters of risk for a single volcanic phenomena at just one volcano.

2.4.2. Qualitative Risk Assessments

The requirement for huge amounts of data and significant computational effort render quantitative risk assessments significantly more demanding to conduct than qualitative assessments (Lee & Jones, 2004). This is particularly true in relation to volcanic eruptions, which frequently produce multiple hazards during a single eruption, for which the risk must be calculated separately (Newhall, 1999; Magill & Blong, 2005b). Qualitative risk assessments can be performed where only low or variable levels of information are available, which would limit the effectiveness of calculating potential losses and probability estimates. They generally provide a relative measure of risk or asset value based on ranking or separation into descriptive categories such as low, medium or high risk, or on a scale from 1 to 10 (Crandell *et al.*, 1984). In this approach, it is not necessary to quantify threat frequency, or to determine the financial value of assets at risk. Qualitative assessments rely heavily upon expert judgements, which require transparent logic and supporting documentation so the reasoning behind particular scores or rankings can be justified (Lee & Jones, 2004; Cox *et al.*, 2005). They are generally quicker and easier to conduct, and allow more simplistic interpretation. For this reason, it can be easier to incorporate participation of local non-experts within the process, and improve understanding amongst lay stakeholders (Cox *et al.*, 2005; Pelling, 2007). Although this type of assessment may lack some of the rigor of a detailed, statistical analysis, and provides no basis for cost-benefit analysis, it may be the most appropriate and valid where constraints of time, resources or a lack of data exists (Lee & Jones, 2004).

2.4.2.1. Relative Risk Ranking

Recognising the difficulty in making accurate predictions about the characteristics of future volcanic eruptions due to long return periods and changes to eruption styles over time, Magill & Blong (2005b) developed a method for ranking volcanic hazards and events that does not rely on precise values. Volcanic risk to the Auckland region of New Zealand from the effects of multiple volcanoes and volcanic fields was calculated as the product of the likelihood, extent and effect, for each hazard, and for every event and outcome considered. Hazard likelihood and extent were determined from the geological record for each hazard, and each was assigned to an order of magnitude category based upon the VEI system. Where geological data was missing, subjective assessments were made based on historical eruptions of a similar magnitude and style to that expected. In a companion paper, (Magill & Blong, 2005a) the authors considered values for effect based on two outcomes; building damage and loss of human life, for every hazard caused by each volcanic event. Values were assigned to each risk parameter (likelihood, extent and effect) by defining categories within which each hazard was placed, with a value assigned for each category. Each parameter was measured as a proportion, with category 1 assigned a value of 1 and subsequent categories showing exponential decay (Magill & Blong, 2005b). Using these assigned values total risk was calculated, and the relative risk from each hazard ranked for building damage, loss of life and combined loss. The study provides a useful preliminary assessment of risk in the region, which could be adapted for other areas exposed to multiple volcanic risks, or other natural hazards (Magill & Blong, 2005a). However, several major assumptions were made in the study, and by confining effects to building damage and loss of life, the wider social and cultural impacts were ignored.

A more qualitative ranking methodology was devised to inform the prioritisation of long-term hazard evaluation, mitigation activities and monitoring capabilities for the most threatening volcanoes in the USA. The USGS carried out a systematic assessment of the threat posed by the 169 geologically active US volcanoes (Ewert *et al.*, 2005;

Ewert, 2007), by assigned numerical values to fifteen hazard factors and ten exposure factors, defined in Table 2.1. Exposure factors were derived from numerous sources including population databases, maps and airport passenger counts. The principle source of information for hazard factors, e.g. volcano type, eruption frequency and magnitude, and volcanic phenomenon was provided by the Smithsonian's Global Volcanism Program[2] (GVP) volcano reference files (Siebert & Simkin, 2002-). Scores were assigned based on whether the volcano met specified criteria, e.g. volcano type scored 0 or 1. Cinder cones, basaltic volcanic fields and fissure vents, which are generally associated with mild explosivity, scored 0, whilst more explosive stratovolcanoes, lava domes, and calderas scored 1. If the maximum known eruption was rated VEI ≤2, a score of 0 was assigned, whereas a maximum known VEI of ≥7 rated a score of 3. Exposure factor scores were assigned based on the size of the population potentially at risk from the volcano (e.g. living within a 30km radius), the presence of infrastructure near the volcano, and whether there were historically recorded fatalities and/or evacuations resulting from volcanic activity. Once all scores were assigned, the individual factors were added to calculate a hazard score and exposure score, which were multiplied to generate each volcano's overall threat score. All the volcanoes were then divided into five threat categories from very high threat to very low. The study identified eighteen "very high" threat volcanoes, including eleven in the Cascade Range, five in Alaska, and Kilauea and Mauna Loa on the island of Hawaii. Both Mt St Helens and Mount Rainier were identified as very high threat due to their explosive behaviour and lahar potential, which could impact large populations, extensive infrastructure development and high density air-traffic corridors (Ewert *et al.*, 2005).

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[2] The Global Volcanism Program is a database and archive maintained by the Smithsonian Institution, which documents both ongoing and past volcanism for all the earth's volcanoes during the last 10,000 years.

Table 2.1 Hazard and exposure factors used in the Ewert *et al.* (2005) threat assessment of US volcanoes (for full threat assessment criteria see Appendix 1).

Hazard Factors	Exposure Factors
Volcano type (scored 0 or 1)	Log^{10} of population at 30km (scored 0-*x*)
Maximum VEI (scored 0-3)	Log^{10} of population downstream/downslope (scored 0-*x*)
Explosive activity - VEI 3 (scored 0 or 1)	Historical fatalities (scored 0 or 1)
Major explosive activity - VEI 4 (scored 0 or 1)	Historical evacuations (scored 0 or 1)
Eruption recurrence (scored 0-4)	Local aviation exposure (scored 0-2)
Holocene pyroclastic flows (scored 0 or 1)	Log^{10} of daily air-passenger count (scored 0-*x*)
Holocene lava flows (scored 0 or 1)	Power infrastructure (scored 0 or 1)
Holocene lahars (scored 0 or 1)	Transportation infrastructure (scored 0 or 1)
Holocene tsunami(s) (scored 0 or 1)	Major development/sensitive area (scored 0 or 1)
Hydrothermal explosion potential (scored 0 or 1)	Volcanic island (scored 0 or 1)
Sector collapse potential (scored 0 or 1)	
Primary lahar source (scored 0 or 1)	
Observed seismic unrest (scored 0 or 1)	
Observed ground deformation (scored 0 or 1)	
Observed fumarolic or magmatic gassing (scored 0 or 1)	

This qualitative ranking methodology makes no attempt to place a monetary value on people or things, or to calculate probabilities of loss. To avoid the notion that a probabilistic analysis of the hazards and the economic impact of those hazards has been carried out, the term risk is replaced with *threat* (Ewert, 2007). Additionally, no distinction is drawn between differences in vulnerability, with populations potentially at risk from volcanic activity treated as uniformly threatened (Wood & Soulard, 2009). For volcanoes where eruption frequency and magnitude are poorly understood, the derived rankings represent a minimum assessment of potential threat, although additional studies can provide new data, allowing ranking factors to be revised (Ewert *et al.*, 2005; Ewert, 2007). For example, field studies by Jicha (2009) of Koniuji Island in the central Aleutian island arc provided geochronologic and geochemical data suggesting a more frequent eruption recurrence interval and the potential for sector collapse. This would elevate Koniuji's overall threat score from 16 to 40, and increase it from a low threat volcano to a moderate threat (*ibid*).

2.4.3. Summary of Risk Assessment Methodologies

The choice of whether to conduct a quantitative or qualitative risk assessment depends upon the nature of the problem, the desired accuracy of the outcome, the quality and quantity of the scientific data, and the resources available (Dai *et al.*, 2002). Quantitative assessments can provide predictions, based on probability estimates, of when the next eruption may occur, as well as the likelihood and spatial extent of different hazard types. Based on empirical data, this type of assessment is often considered more scientifically robust, however, they can be as subjective as qualitative assessments. Slovic & Weber (2002) argue that there is not such thing as real or objective risk. Probabilistic and quantitative estimates of risk are based on theoretical models, "*whose structure is subjective and assumption-laden, and whose inputs are dependent on judgement*" (*ibid*, pg. 4). As noted by Kates & Kasperson (1983), such judgements often rely on extrapolation, either from past experience, experiments or from computer simulations, which all entail scientific uncertainty;

> *"…the magnitude of which is variable, the handling of which is crucial, and the explicit expression of which often separates better from weaker studies".*

The level of uncertainty associated with quantitative risk estimates is usually high (Smith & Petley, 2009), but has an inverse relationship with the scientific knowledge of the causal hazard (Kates & Kasperson, 1983). For example, for frequent events with well understood causal mechanisms, levels of risk can be calculated with greater accuracy than infrequent events, such as volcanic eruptions, which may have recurrence intervals of tens to hundreds of thousands of years.

The limitations of using past behaviour to predict future volcanic activity were noted almost three decades ago by Crandell *et al.* (1984). Firstly, as well as the possibility of insufficient length in the record to document high impact, low-frequency events, more frequent but smaller events may not leave recognisable deposits or deposits may not be preserved at all (Crandell *et al.*, 1984; Cronin *et al.*, 1997; Magill & Blong, 2005b).

Secondly, historical activity may not provide an accurate guide to future behaviour because the behavioural patterns of volcanoes can change over time (Crandell *et al.*, 1984), and during individual eruptions (Magill & Blong, 2005b). Thirdly, the stability of a volcano can decrease as its size and height increases. This may lead to edifice collapse, an event which may not have occurred previously, and whose likelihood cannot therefore be assessed (Crandell *et al.*, 1984). Finally, topographical changes due to erosion and construction may cause different areas around the volcano to be affected by different volcanic phenomena than during previous eruptions (*ibid*). It is therefore not possible to produce precise predictions of eruptions and their consequences, because the characteristics of volcanic activity will affect both the reliability and validity of quantitative risk evaluations. Most volcanic systems are simply too complex, our understanding of them too rudimentary (Newhall & Hoblitt, 2002; Sparks & Aspinall, 2004), and the historical record too limited (Crandell *et al.*, 1984; Connor *et al.*, 2001; Newhall & Hoblitt, 2002; Magill & Blong, 2005b; Ewert, 2007).

Qualitative risk assessments represent a potential methodology for overcoming the shortcomings associated with the use of quantitative analysis in relation to volcanic risk. By drawing on the expert judgement of scientists to categorise risk, they do not rely on comprehensive data coverage, they avoid the need for complex numerical calculations, and therefore require less time and resources to complete. Additionally, they can incorporate stakeholder participation, as well as providing a conceptualisation of risk that may be simpler to grasp amongst lay members of the public (Pelling, 2007). Others argue that an approach based solely on expert judgement lacks standardisation, which may impact the consistency of categorisation decisions (Cox *et al.*, 2005). To address this, it is essential that the basis for risk decisions, regarding likelihood and consequence, are fully transparent and comprehensively documented. Qualitative risk assessments will still encounter the problems inherent with assessing the complexity of volcanic activity and inadequacies in the eruptive record, but such assessments make no claims about the data on which they are based being comprehensive, or that the results provide an objective assessment of risk (Renn, 1998).

Both approaches to risk assessment generally now include some consideration of human vulnerability, usually in the form of exposure factors such as loss of life or buildings/infrastructure. However, both approaches continue to prioritise economic concerns over other aspects of value (Pidgeon & Butler, 2009), and there remains little consideration of the more contextual social and cultural aspects of vulnerability identified by social scientists (Chester, 1993; Bankoff *et al.*, 2004; Cardona, 2004; Wisner *et al.*, 2004). This remains a fundamental barriers to establishing an integrated approach to the understanding of risk, further compounded by the cross-disciplinary differences in the language used, particularly in defining concepts of vulnerability.

2.5. VULNERABILITY

2.5.1. Semantic Issues

The different conceptual approaches to risk reduction are characterised by the values and interests of diverse disciplines, from distinct scientific fields to engineering, economics, policy development, emergency planning and relief agencies. Each discipline seemingly has its own definitions for key elements of the risk management model. Research on the terminology of disaster reduction by Thywissen (2005) outlines almost thirty different, and often contradictory definitions of vulnerability, from science and social science writers, engineering research, disaster management and the United Nations. Part of the problem lies in the ‘semantic overflow’ suffered by the word vulnerability (Delor & Hubert, 2000), which can refer to susceptibility to harm (Burton *et al.*, 1978; Mileti, 1999; IPCC, 2001; Klein *et al.*, 2004), consequences of failure (UNDRO, 1991; Teidemann, 1992; Buckle *et al.*, 2000; Smolka, 2006), inherent weaknesses within a system (Blaikie *et al.*, 1994; Rashed & Weeks, 2003), or the reductionist view which focuses on the characteristics of a person or group (Dibben & Chester, 1999; Cannon *et al.*, 2002; IFCR, 2002; Wisner *et al.*, 2004). The different public policy stages of risk management (risk identification, risk reduction, disaster management and risk transfer) necessitate a multidisciplinary approach (Cardona, 2004), but to develop a cooperative, holistic discourse on risk reduction requires an effort to unite these disparate approaches utilising a common and shared language. Although much work has been done to this end, there remains a lack of understanding which often constrains the effective practice of risk management.

There is general agreement that the extent to which an individual, group or community can cope with physical extremes is an important component of vulnerability (Dibben & Chester, 1999; Chiwaka & Yates, 2005). This differential vulnerability is due to economic, political and cultural factors (Huppert & Sparks, 2006), as well as psychological characteristics, access to resources and social networks (Dibben & Chester, 1999; Wisner *et al.*, 2004), and more specific factors such as level of preparedness and ability to evacuate (Eshghi & Larson, 2008). This has led to the postulation that vulnerability, and by implication risk, is socially constructed (Stallings, 1997; Castree, 2001; Twigg, 2001a; White *et al.*, 2001; Cardona, 2004). However, practitioners should avoid confusing the notion of vulnerability with risk. Risk is the product of the probability of a hazard occurring and the degree of vulnerability, therefore two communities both exposed to a given hazard will exhibit differences in risk if they differ in their relative vulnerability. Whereas risk is dependent on the particular magnitude of a specific natural event, vulnerability is independent of magnitude but depends upon the context within which the event occurs (Rashed & Weeks, 2003). The contextual socio-economic processes and individual decision making, both in the past and present, make vulnerability a dynamic concept (Dibben & Chester, 1999), but it also involves a predictive quality, enabling the conceptualisation of what may happen to an individual or group under particular risk conditions (Cannon *et al.*, 2002).

There should be a move away from definitions of vulnerability that see it purely in terms of the value of expected losses, either economic (Spence *et al.*, 2004; Smolka, 2006) or in terms of human lives (Piegorsch *et al.*, 2007). It should include measures of exposure and sensitivity to hazard, and of adaptive capacity (White *et al.*, 2001). Whilst defining vulnerability for use in risk assessments should include a component where actual or potential loss (usually in dollar terms) is quantified, equal emphasis should be placed on measuring relative loses between differentially vulnerable groups, and on assessing people's capacity to replace losses or sustain acceptable living conditions (Buckle et al., 2000). Exposure to damage of amenities, services, infrastructure and economic activity, although seen as less important by many social scientists, remain important components of vulnerability (Buckle *et al.*, 2000). This is not least because in an insurance context, reducing material losses from certain pervasive hazards including volcanic eruptions may not be possible. As noted by Smolka (2006); '*people can be evacuated… but moving buildings and infrastructure is impossible*'. Accepting this, the complexities involved in such systems may inhibit attempts to quantify them for the purposes of risk management.

2.5.2. Resilience

The shift in emphasis in disaster research to a vulnerability paradigm has led to a move away from considering a community's ability to cope with and resist the impacts of a disaster to one that stresses their vulnerability. However, both Furedi (2007) and Manyena (2006) argue that risk reduction research should place an equally strong emphasis on resilience. Exposure to hazards and risks may increase vulnerability but individuals and communities may equally posses qualities that reduce their vulnerability. Termed resilience, this is not just the absence of vulnerability but the possession of qualities that may prevent or mitigate losses, as well as improving ones ability to recover from a disaster (Buckle *et al.*, 2000). Thomalla *et al.* (2006), views resilience as one of three major components of vulnerability (the others being exposure and sensitivity). Levels of resilience are determined by the impacts felt, the capacity to adapt to these and the ability to cope (*ibid*). It is the intrinsic capacity of a system, community or individual to adapt to and survive a shock, and more fundamentally to return to its original state. By building local knowledge and augmenting existing capacity, it goes beyond simply reducing aspects of vulnerability (Manyena, 2006). A more recently developed concept in risk research, resilience appears to be suffering a similarly intransigent semantic fate as vulnerability. In general however, where vulnerability is seen as the characteristics of an individual, group or community that amplify the consequences of an environmental event (in terms of natural hazards), resilience is the qualities within these systems that allow them to cope with adverse conditions, reduce the losses suffered and to recover following the event. This suggests that any analysis of risk that includes an assessment of a systems vulnerability to a particular hazard, should equally include consideration of that systems resilience. In both cases the fundamental qualities which contribute to both vulnerability and resilience should be identified.

A conceptual model of vulnerability that has had a significant impact on the way vulnerability is perceived is the Blaikie *et al.* (1994) Pressure and Release Model. This recognises that a disaster is the result of two opposing forces. On the one side the physical exposure to hazard, e.g. earthquakes, cyclones, flooding or volcanic eruptions. On the other side, the processes generating vulnerability, e.g. the economic, demographic and political processes in society, as well as rapid population growth and reduced access to resources (Twigg, 2001b). Most communities are not homogeneous in their social make-up and certain characteristics may correlate with increased vulnerability. Although there is limited empirical data, there is epistemological evidence that suggests a causal relationship between vulnerability and certain socio-economic characteristics (Aysan, 1993). These include; class, gender, ethnicity (Varley, 1991), caste, disability, age or seniority (Blaikie *et al.*, 1994; Twigg, 2001a), poverty (Lewis, 1997), lack of education or employment, illness (Bolin & Stanford, 1998), single parent families and those living in isolated communities (Buckle *et al.*, 2000).

2.5.3. Socio-economic Determinants of Vulnerability

Research exploring the relative importance of certain socio-economic factors in determining levels of vulnerability has been conducted at various spatial dimensions, from the country level, down to the community and individual scale. At the national level, Toya and Skidmore (2007) analysed over forty years of disaster data from EM-DAT and found that income and educational attainment were important country-level development measures for reducing deaths and economic impact from natural disasters (Toya & Skidmore, 2007). Similar research by Kahn (2005) looked at a twenty year period of EM-DAT data from 1990 to 2002 and found that democratisation appeared to insulate a country from the effects of earthquake hazards, as more democratic nations suffered less deaths during a disaster. He also found that a 10% increase in a countries GDP decreased national earthquake deaths by 5.3% (Kahn, 2005). However, a review of the EM-DAT database focusing on climatic hazards for the last three decades of the twentieth century (Brooks *et al.*, 2005) did not find GDP to be a significant indicator of vulnerability. Mortality from climatic hazards was found to be exacerbated by a nation experiencing or recovering from conflict, whilst adaptive capacity was enhanced by improvements in civil and political rights, as well as levels of literacy (Brooks *et al.*, 2005).

At the county level, research into 832 flood events in Texas between 1997 and 2001 (Zahran *et al.*, 2008) provides some empirical evidence that specific factors relating to the socio-economic environment contributed to increasing the rates of death and injuries. Specifically, they found that flood impacts were unequally distributed in affected communities and that low income and minority groups were at greater risk of death or injury (*ibid*). Other work in the United States conducted on a county scale looked at the spatial and temporal patterns in social vulnerability to natural hazards for the past fifty years (Cutter & Finch, 2008). This work identified several areas within the US with higher levels of social vulnerability, but the socio-economic factors found to contribute to the differences in risk to natural hazards varied by region.

Characteristics identified in the study included race and socio-economic status (for the lower Mississippi Valley counties), ethnicity and poverty (along the Texas-Mexico border) and economic dependence and an aging population (in the Great Plains area). The dynamic nature of social vulnerability both over time and geographically across a country suggests that a flexible approach to risk management is required (*ibid*). Mitigation methods should therefore not only be hazard-specific but also place-specific, taking into account the unique dimensions of a community which directly influence both vulnerability and resilience.

At a community and individual level, two cyclone-prone coastal regions in the Indian state of Andhra Pradesh were surveyed by Bosher *et al.*, (2007) to determine what socio-economic resources villagers' had access to in order to enhance their resilience to tropical cyclones. The researchers found that caste was an important factor in determining vulnerability by inhibiting access to public facilities, and by the absence of political connections and social support networks. Some evidence was found that informal social networks, particularly utilised by women, partially mediated the lower castes' reduced social capital but not sufficiently to overcome the negative effects of their reduced status (Bosher *et al.*, 2007). Although these disparities existed within the society studied prior to the disaster, the consequences of these differences between people were further highlighted by the existence of an environmental threat. Similar micro-scale research was conducted following the 2001 flood in Rawalpindi, Pakistan. Mustafa (2003) conducted a survey of residents in the Lai Nullah watershed during the summer of 2002. This focused on the short-term aspects of relief and recovery in the aftermath of the disaster. Many of the households and businesses questioned had suffered structural or property damage, loss of livelihoods and sickness as a consequence of the floods. A strong gender dimension emerged in the experiences of the disaster, perceptions of its cause and expectations of relief and recovery. In particular women were found to perceive the risk as greater and to have different expectations for relief aid. The cultural practice of strict segregation by gender may limit the inferences that can be drawn from this study and its applicability to other cultures.

Gender differences have been found in other studies, for example, during a period of enforced evacuation following episodic and escalating volcanic unrest at Tungurahua in Ecuador, Tobin and Whiteford (2002a), carried out work to address community resilience. They interviewed three groups of evacuees who had different experiences of the evacuation process and found that overall, health status declined following the evacuation but that women suffered disproportionately more illness than men. However, work by Waite (2000) concluded that the multi-dimensional nature of vulnerability meant that women-headed households, although more vulnerable than male-headed households in certain circumstances, were not, as is often postulated, disadvantaged in all dimensions of vulnerability.

Poverty has been identified in several of the studies discussed above and although poverty may be a major contributing factor to increasing vulnerability (Eshghi & Larson, 2008), vulnerability and poverty should not be considered synonyms (Alcantara-Ayala, 2002; Cannon *et al.*, 2002; Chiwaka & Yates, 2005). Poverty does not mean that an environmental shock will automatically impact more on lower income individuals or households, rather it is likely that poverty may translate into a lack of access to resources which limits their ability to recover from hazard events. This suggests that rather than an aspect of pre-event vulnerability, poverty should be seen as a limiting factor on post-disaster recover or resilience.

Another study that aimed to identify the risk factors for mortality from the 1999 Taiwan earthquake, considered the socio-economic characteristics of the 1,610 victims of the disaster and found that demographic characteristics were strongly associated with earthquake related deaths (Chou *et al.*, 2004). The results indicated that women were at greater risk than men, mortality risk also increased with age for the adult population and with decreasing age for children under the age of 16 years. The death toll increased with decreasing monthly wage and those suffering ill health, disability or mental illness were also found to be at significantly greater risk. These results indicate how gender, age, income and disability may be key determinants of vulnerability to earthquake hazards and how at an individual level, the impacts of a disaster disproportionately impact certain people more than others (*ibid*).

Although aged people have been identified as increasingly vulnerable, it has been noted that they may have gained from life experiences and past exposure to disasters, coping strategies not available to younger people (Buckle *et al.*, 2000; Ngo, 2001). Coping strategies acquired in this way may act to attenuate vulnerability, as was demonstrated during a gas shortage suffered in the state of Victoria, Australia in 1998. Here, contrary to the expectations of hazard managers, older members of the community actually coped better than expected (Buckle *et al.*, 2000). It is unlikely that the protective mechanisms developed over a lifetime would be sufficient to completely mitigate the effects of other characteristics of aging such as reduced income, physical frailty, ill heath or isolation. In research aimed at assessing disaster impacts on the elderly, Ngo (2001), reviewed relevant literature from the fields of medicine, psychology and sociology. It was found that elderly and non-elderly individuals experienced similar levels of actual material loss, but due to their often smaller or fixed incomes this loss represented a greater relative loss. Whilst excepting that the elderly victims of disaster are not homogeneous, a relationship between increased age and morbidity and mortality rates was also found.

As well as the socio-economic characteristics discussed above, the importance of social and cultural influences, as well as the personal characteristics, attitudes and beliefs of the individual as determinants of social vulnerability have been widely discussed (Dibben & Chester, 1999; Wisner *et al.*, 2004; Thomalla *et al.*, 2006). Of particular importance amongst these is the way in which individuals perceive the risk from natural hazards. This in turn can affect how risk communication messages are received, influencing how an individual responds to a hazardous event, and whether protective measures are adopted. In this way, risk perception becomes an important component within the matrix of individual, social and cultural factors which act to amplify or attenuate vulnerability.

2.6. RISK PERCEPTION

Whereas experts utilise sophisticated intellectual techniques to evaluate risk, the lay public rely on intuitive judgement, typically called risk perception (Slovic, 2000). Frequently, difficulties arise because the results of objective risk assessments differ significantly from a communities intuitively defined perceptions of risk (Smith & Petley, 2009). It was this discrepancy which led to developments within the field of risk perception research during the mid 1960s, largely prompted by the disparity between the public's fear, and scientific and governmental claims regarding the rise of nuclear technologies. Discrepancies between public perception and scientific estimations of the dangers associated with particular technologies, was seen to have important implications for managing risk. Understanding how lay people make subjective judgments about the characteristics and severity of risk became an important element within the field of risk research. Since this time, several different theories of risk perception have developed, coming from the specialisms of psychology, sociology and anthropology.

The different approaches to risk perception research build upon the work of early pioneers within the field, particularly Starr (1969) an engineer who aimed to uncover what risks were considered acceptable by society. Using a 'revealed preference' approach, which assumed that levels of public expenditure revealed the policy preferences of the public, he suggested that people seemed significantly more willing to accept risks when they were seen as *voluntary* (e.g. driving a car), than when they were viewed as *involuntary* (e.g. nuclear power). This approach also suggested that ignorance through inadequate knowledge and a lack of information fuelled the public's irrational fears towards emerging technologies. The assumption being that by providing additional information, people can more accurately understand the dangers, leading to an lessening in their perceptions of the risk (Freudenburg, 1993). This is now seen as a rather simplistic view of how risk perceptions within an individual develop, e.g. in reality, there is not such a clear distinction between voluntary and involuntary risk categories. For example, someone may choose to work in a dangerous chemical factory if the alternative is unemployment. Similarly, an individual may choose to live on the slopes of an active volcano because the fertile soil increases their farm's agricultural productivity above subsistence level. Therefore, a risk may be more voluntary than another risk if its avoidance is connected with greater personal sacrifice on the part of the risk-bearer (Smith & Petley, 2009). It has also been shown that shifting perceptions requires more than just additional information (Douglas, 1985). An individual's perceptions of risk develop as a result of their personal characteristics, which are focused through the prism of the society in which they live and the institutions on which they may depend. It can also vary significantly over time. Risk perception is the intuitive judgement of riskiness by individuals and groups in the context of limited and uncertain information (Slovic, 2000). From a social science perspective it can be seen as involving:

> *"... [the] beliefs, attitudes, judgments and feelings, as well as the wider social or cultural values and dispositions that people adopt towards hazards and their benefits."* (Pidgeon *et al.*, 1992, p. 89)

People's responses to, and understandings about risk, are informed by socially and culturally constructed conceptions and evaluations about the world (Boholm, 1998). The decisions that people make, and their behaviour in the face of a specific hazard are guided in part by their perceptions of risk (Slovic & Weber, 2002), but the complexities of the cognitive processes involved in the formulation of these perceptions indicate the importance of many other factors in determining behaviour.

2.6.1. Theoretical Approaches

2.6.1.1. Heuristics and Biases

An influential early perspective on risk perception was that of Tversky and Kahneman (1974). They suggested that members of the public utilised heuristics to evaluate information and make judgements about probabilities. These intuitive heuristics provide shortcuts for thinking, but can also lead to inaccurate judgments in some situations, thereby becoming *cognitive biases*. Three heuristics were identified; 'representativeness', 'availability' and 'anchoring'. More recently, a fourth heuristic has been identified, termed 'affect' (Finucane *et al.*, 2000). Of these *availability* was often cited as the most important for understanding risk perception (Sjoberg, 2000). Here the probability of a phenomena is judged according to its cognitive availability (Freudenburg, 1993), i.e. how easily examples can be recalled or imagined. This assumption generally holds true; events that occur frequently become more salient in the memory, and are subsequently judged to be more likely (Pidgeon *et al.*, 1992). However, particularly dramatic or vivid events may become overemphasised, particularly through reporting in the mass-media, leading to an overestimation of their likelihood, whilst more pervasive but less sensational events may be underestimated. As well as criticisms of the methodologies employed in much of the research utilising this framework (see Sjoberg, 2000), Fischhoff *et al.* (1982) showed that the cognitive mechanisms used in processing risk information were more multidimensional than suggested. An alternative theory to examine this multidimensionality was developed.

2.6.1.2. Psychometric Paradigm

One of the most influential approaches to the study of perceived risk was developed by the Decision Research Group in Oregon, which conceived a taxonomy for hazards to help understand and predict responses to their associated risks, and was called the Psychometric Paradigm (Fischhoff *et al.*, 1978; Slovic *et al.*, 1984). This approach was designed to help explain why some hazards are perceived as particularly risky, whilst others are not, and the discrepancy between lay people's reactions and expert opinions

(Slovic & Weber, 2002). Additionally, it aimed to identify patterns in the perceived qualities that characterise a particular hazard, using this to explore relationships between these characteristics and the perception of risk (Pidgeon *et al.*, 1992). The early work by Fischoff *et al.* (1978) demonstrated how experts utilise quantitative concepts such as likelihood and consequences when assessing risk, whilst the public make additional judgements concerning such qualitative factors as involuntariness, controllability, dread and catastrophic potential (Marris *et al.*, 1998). Using judgments on a quantitative scale to assess various qualitative characteristics about the riskiness of a number of specific hazards, and multivariate statistical techniques, three key properties of risk attitudes and perceptions were identified, these were; 'dread', 'unknown risk' and 'magnitude'. Dread risk at its extreme is defined as a perceived lack of control, dread, catastrophic potential, fatal consequences and the inequitable distribution of risks and benefits. 'Unknown risk is measured along a scale considering whether the hazard is observable, known, novel and likely timescales for the manifestation of harm (Slovic & Weber, 2002). The third factor; magnitude of the risk, relates to the number of people affected (Boholm, 1998).

One main criticisms of the paradigm was that instead of viewing the qualitative risk characteristics as constructs of the people who perceived the risk, it saw them as inherent attributes of the hazards themselves (Marris *et al.*, 1998). Research tended to analyse average risk ratings across hazards, a methodology which ignores individual variation in risk perception. When individual data is used, and each hazard is analysed separately, the proportion of explained variance is significantly reduced (Sjoberg, 2002). However, the aim of the psychometric model was to explain why people perceived different hazards differently, rather than why different people perceived the same hazard differently (Siegrist *et al.*, 2005). Despite this, it is now generally acknowledged within the psychometric paradigm that there are significant individual differences in risk perceptions as a result of personal characteristics, as well as attitudes, beliefs and behaviours that result from identification with, and membership of, particular social groups or cultures (Pidgeon *et al.*, 1992).

Some research has been conducted to determine whether different socio-economic characteristics correlate with differences in perceived risk. These generally found only very weak relationships between risk perception and variables such as age, gender, occupation and nationality (Pidgeon *et al.*, 1992). Where relationships have been found, little consideration is given to why certain people (e.g. women) perceived risks differently (Marris *et al.*, 1998). One notable study from Flynn *et al*, (1994), did identified gender differences in levels of perceived risk. Four categories of ethnicity and gender were considered; white males, non-white males, white females and non-white females. Here, the differences found were not that women were more sensitive to risk than men, but that a certain subset of men, namely white males, had particularly low levels of perceived risk compared to all other groups. Correlations in some societal characteristics were found amongst this sub-group of men. Generally they were found to be better educated, had higher incomes, where politically more conservative and more likely to express trust in official institutions (Boholm, 1998). This indicates that it was perhaps these attributes of the individuals driving their levels of risk perception, rather than their 'maleness'. In recognition of the differences between people in their reaction to risk, and that risk perception may be more related to the characteristics of a individual and notions of trust and accountability, the Cultural Theory of risk perception was developed (Marris *et al.*, 1998).

2.6.1.3. Cultural Theory

Along with the Psychometric Paradigm, Cultural Theory is one of the main models in the study of risk perception, and was developed by sociologists and anthropologists to address some of the criticisms of the psychometric model. This approach proposes that risks are perceived according to the beliefs and attitudes which arise from the social groups or communities that people identify with. According to Cultural Theory, risk perception in culturally constructed, based upon the general orientations or world views people hold (Boholm, 1998). Distinct ways of looking at the world, termed *cultural biases* are generated by the social relationships experienced by an individual, and adherence to a particular world view legitimises a corresponding type of social identity (Marris *et al.*, 1998), in this way providing a positive reinforcement for ones beliefs and values. Further, it has been suggested that underlying constructs can be used to understand why certain individuals perceive risk in a certain way, by using a typology of outlooks (Gerrard, 2000). Two typologies were developed by Douglas (1985) based on the degree to which an individual interacted with, identified with and bonded with others in a community. These were termed *grid* and *group*, where *group* refers to the extent to which an individual interacts, through a shared identity with members of a community, i.e. the degree of social contact. The *grid* spectrum refers to the extent to which external structures of authority influence individual norms, i.e. the degree of social regulation (Gerrard, 2000). This approach attempts to provide a framework for identifying underlying patterns of perception which go beyond standard socio-economic variables. The four 'ways of life' arising from the variable strengths of these *grid* and *group* characteristics are shown in Figure 2.5.

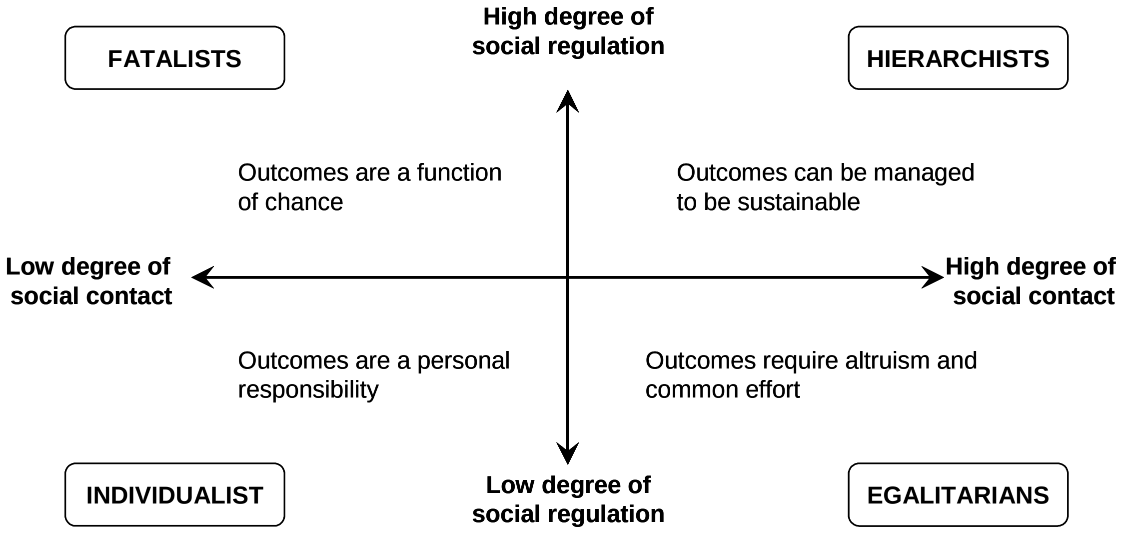

Figure 2.5 Framework of social control showing the principle social groups proposed by Cultural Theory which influence risk perception. These are based upon patterns of beliefs and values, and solidarities in shared social settings (modified from Gerrard, 2000, p.460).

Several criticisms against Cultural Theory have been published (see Boholm, 1996; and Sjoberg, 2000). These largely centre around the lack of empirical evidence, based on rigorous and replicable methodological approaches. One of the problems with testing the theory empirically, arises because even amongst cultural theorists, different versions of the theory exist, based upon whether the unit of analysis should be individuals or institutions (Marris *et al.*, 1998). In studies that have utilised the approach, Boholm (1998) argues there is little information provided about how the four 'ways of life' are defined, or how these are influenced by the patterns of social relations identified within the grid-group structure. Sjoberg (2000; 2002) in his critique of several works, notes the very low levels of variance in perception explained by cultural bias scales (around 5%). Work by Marris *et al.* (1998) confirmed that the amount of variance explained was no more than that found by using standard socio-economic variables (< 12%). Although the psychometric model explains a higher percentage of variance in risk perception (between 20-30%) (Sjoberg, 2000), and between them the two models begin to explore the individual characteristics and social contexts in which perceptions are bounded, a more complex matrix of additional factors must be implicit in the formulation of risk judgements.

2.6.1.4. Social Amplification of Risk

In an effort to bridge the gap between the psychological, social and cultural approaches to risk perception, and to integrate alternative rationales within hazard decision-making processes, Kasperson *et al.* (1988) developed an integrated model relating to the social amplification of risk. The model attempts to systematically link the psychological, sociological and cultural aspects of risk perception using a 'source-signal-receiver' model (Gerrard, 2000). Here communications of risk pass from a sender, through intermediate stations to a receiver, and in the process serve to amplify or attenuate perceptions of risk (Kasperson et al., 1988). The model attempts to consider how these individual, social and cultural factors interact to either increase or decrease public perceptions of risk (Pidgeon *et al.*, 1992). An important aspect of social amplification is that direct impacts need not be too large to trigger major indirect impacts (Slovic and Weber, 2002).

Multiple mechanisms or signals contribute to the social amplification of risk. An individual or group can be seen as the receiver of these signals, whilst the media, scientists or government agencies, for example, can be considered the stations through which these signals are filtered (Pidgeon *et al.*, 1992). The magnitude of an event, or its signal potential, and thus its potential social impact appears to be systematically related to the perceived characteristics of the hazard. For example, a large event that takes many lives may produce few higher-order impacts if it occurs as part of a familiar, well understood system. Whereas a smaller incident may have a significant social impact, if it occurs within an unfamiliar system (Slovic and Weber, 2002).

Social amplification is triggered by the occurrence of an adverse event, and through the process of risk amplification, adverse impacts can sometimes extend far beyond the direct damage of victims and property. Largely based upon research exploring technological, man-made hazards, the model predicts a ripple effect, resulting in higher-order impacts. These encompass firstly the direct victims, then the responsible company, and in the worst cases, other companies, agencies or industries (Slovic and Weber, 2002). This ripple effect is the result of changes resulting from the initial hazard event, which are perceived and reacted to, resulting in higher order impacts. Whilst traditional risk analyses ignore these ripple effects, and therefore underestimate the adverse effects from some risk events, society assesses a fuller determination of the risk and its impacts, and may therefore have more accurate perceptions (Kasperson and Kasperson, 2005).

Pidgeon *et al.* (1992) details several criticisms of the social amplification of risk model. Firstly, the approach appears to be too general to allow direct empirical testing. Secondly, it sees communication as a one way process flowing from the risk event, through the filtering stations, to the receivers. Risk perception is likely to be the product of more interactive processes, or feedbacks between the source and receiver than implied by this model.

2.6.1.5. Protection Motivation Theory

In an attempt to examine the link between risk perception and the adoption of protective behaviour, the Protection Motivation Theory (PMT) was proposed by Rogers (1975). This investigated the effects of fear arousal upon attitude change, in relation to health threats. Applied successfully in the context of health threats (Wurtele & Maddux, 1987; van der Pligt, 1996), PMT also appears to provide useful insight into human behaviour in relation to natural and technological hazards, although studies remain rare (see Lindell & Perry, 2000; Neuwirth *et al.*, 2000; Grothmann & Reusswig, 2006; Martin *et al.*, 2007). The PMT health behaviour model attempts to identify a set of stimuli for fear appeal (e.g. methods of persuading people to act in their own best interests when faced with a threat, i.e. to stop smoking), and the cognitive processes through which a communicators recommendations are accepted or rejected. The theory attempts to understand the role of risk communication in mediating attitudes and behaviour, and why when faced with persuasive information regarding the dangers associated with a particular practice, some people continue with maladaptive behaviour (Rippetoe & Rogers, 1987). The theory identifies three cognitive appraisal processes emphasised in risk communications; (i) perceived severity of the depicted harmful event, (ii) perceived vulnerability to the threat, and (iii) response efficacy, or perceived effectiveness of alternative responses in preventing the occurrence of the threat (Wurtele & Maddux, 1987). In a revision of the theory, Rogers (1983) added self-efficacy as a fourth cognitive mediator. Self-efficacy is defined as the strength of a person's conviction in their own effectiveness to cope in a given situation (Bandura, 1977), and in turn this belief in ones own abilities influences whether protective behaviour is adopted (Wurtele & Maddux, 1987).

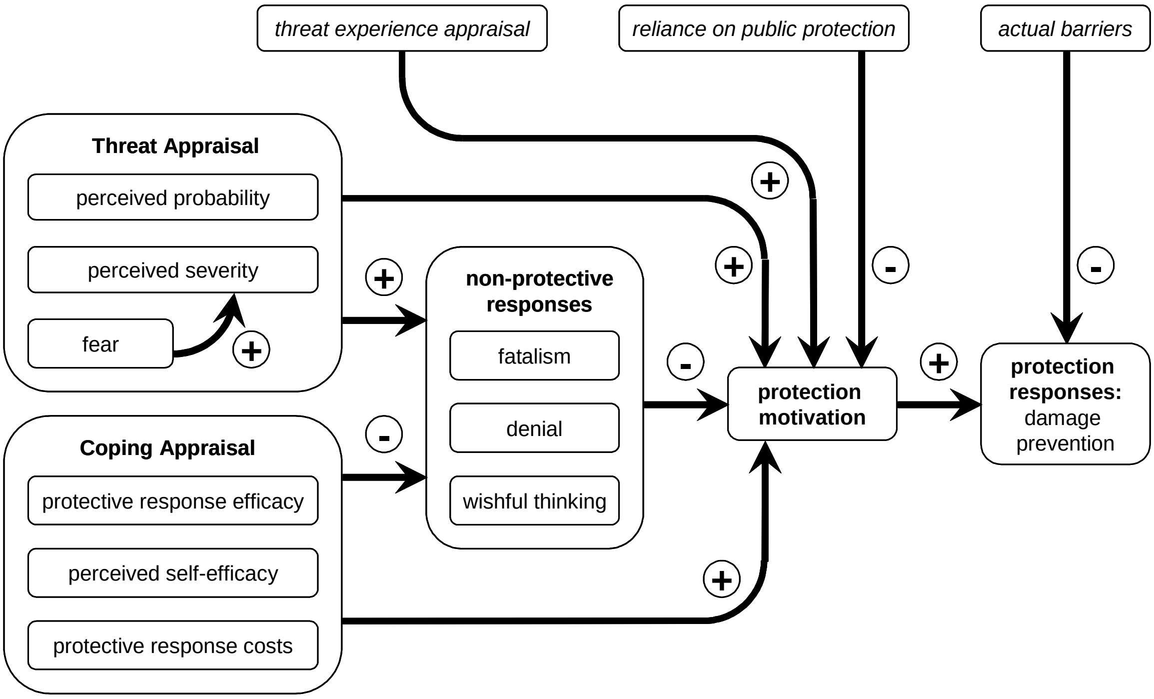

Figure 2.6 Flow diagram showing two key perceptual processes important in the motivation of protective responses to risk; threat appraisal and coping appraisal, and their cognitive components (modified from Grothmann & Reusswig, 2006).

A key feature of PMT suggests that communicated information regarding a threat initiates two different perceptual processes; *threat appraisal* and *coping appraisal* (Rippetoe & Rogers, 1987). Figure 2.6 provides a schematic of the perceptual processes associated with the threat and coping appraisal factors within the PMT model. These include for threat appraisal, also known as risk perception, how a person assesses; (i) the perceived probability of being exposed to a threat, (ii) the damage potential or consequences of a threat, or the perceived severity of the threat, assuming no adaptive behaviour is undertaken, and (iii) fear, which indirectly effects threat appraisal by affecting the estimate of the severity of danger. Coping appraisal is initiated following the threat appraisal process, but only commences once a specific threshold of threat appraisal has been reached. It is the process by which a person evaluates; (i) their own ability to carry out the necessary protective response; (ii) how effective protective measures will be at limiting harmful effects to themselves, and; (iii) the cost of carrying out protective behaviour in terms of money, time and effort (Grothmann & Reusswig, 2006).

Exposure to knowledge about a potential threat initiates the threat appraisal process, if during this process the threat is deemed insignificant, no further action will be taken. If the threat is deemed to represent a sufficient danger, the coping appraisal process is initiated. At this stage, if self-efficacy, and the other subcomponents of coping appraisal are low, maladaptive, or non-protective responses will be adopted, such as denial of the threat, wishful thinking or fatalism. These will not protect from harm, but may help to reduce the negative emotional consequences induced by the high levels of perceived risk which initiated the coping appraisal process. If self-efficacy is sufficiently high, the individual will be motivated to take protective action (Grothmann & Reusswig, 2006), or rather be stimulated into a willingness to adopt preparedness strategies. PMT distinguishes between intention to act and actual behaviour, as *protective motivation* may not lead to actual behaviour, due to unforeseen barriers, e.g. lack of resources, knowledge or social support (Hurnen & McClure, 1997).

Barriers to action, and the role of self-efficacy in mediating the effects of risk perception on behaviour, may help explain why some studies have failed to find an explicit link between risk perception and the adoption of self-protective behaviour (Lindell & Whitney, 2000; Rimal & Real, 2003). Other psychological factors which may influence levels of preparedness are summarised by Hurnen & McClure (1997). Firstly, stimulation to prepare for a hazard, and accurate estimates of the probability of a hazard occurring, may be hindered by a propensity to take risks. Secondly, overly optimistic belief in personal immunity to a hazard or denial of the risk, may also inhibit willingness to prepare. Thirdly, people with an internal 'locus of control' see damage from natural hazards as more preventable, and are more likely to take precautionary action. Those with an external locus have less belief in their own ability to prevent damage, thus conferring responsibility onto an outside agency, e.g. the government, or NGOs. Additional research relating to earthquake hazard has demonstrated that people often know about the risks and how to prepare, but have failed to do so, believing sufficient warning would be provided by scientists (Valery, 1995).

Another important barrier to the acceptance of risk communication, and hence the stimulation of preparedness activities, is trust, not only in the message but also in the sources of information, and the credibility of the media used to convey the message (Slovic, 1993). Where trust in formal communication sources is lacking, informal sources of information are often utilised (Haynes *et al.*, 2008a). Trust in the individuals, industries and institutions responsible for risk management is particularly important where there is limited or no personal experience of the hazard (Renn, 1998). This is especially relevant in relation to volcanic activity, which is often characterised by long periods of quiescence.

A similar theory proposed by Paton (2003), expands on health and natural hazards research relating to protective behaviour, to develop a model specifically related to disaster preparedness. Previous work by Paton *et al.* (2001a; 2001b) and Bishop *et al.* (2000) utilised a model of social-cognitive variables (coping, self-efficacy and sense of community) to predict preparedness and resilience to natural hazards. Psychological Sense of Community (PSOC) is thought to be an important component in the formation of an individual's self-definition. It has been described as:

> *"...the feeling that members have of belonging, a feeling that members matter to one another and to the group, and a shared faith that members' needs will be met through their commitment to be together."* (McMillan & Chavis, 1986 p.7)

The socio-cognitive model of protective behaviour from natural hazards proposed by Paton (2003) built on previous work, and integrated aspects from theories relating to health protective behaviour, but includes a wider range of variables. It describes how intentions mediate the relationship between motivating factors and risk reduction behaviour, through a three step process. The first concerns factors that motivate people, the second describes the variables that link these initial motivations with the formation of intentions, and the third phase describes the relationship between preparatory intentions and actual preparation. However, little empirical work has been conducted to explore the usefulness of this model.

2.7. SUMMARY

In this review, the literature and research relating to natural hazards, risk management and assessment, and the social, cultural and psychological determinants of vulnerability have been explored. An evaluation of both quantitative and qualitative approaches to risk evaluation has highlighted some methodological problems associated with applying these techniques to volcanic activity. The long return periods, variations in eruptive style and hazard phenomenon, as well as knowledge gaps regarding casual mechanisms lead to epistemic uncertainties in quantitative risk assessments. Qualitative risk evaluations provide a more simplistic method for assessing risk, but have been criticised for their lack of scientific rigour and subjectivity. However, the extent to which the quantitative approach can be said to be purely objective is questionable. Ultimately the choice of whether to conduct a quantitative or qualitative risk assessment will depend upon the aims and objectives of the study, the quantity and quality of accessible data, and the time and resources available.

Other research and academic literature focused on social vulnerability to natural hazards and suggests that the relationship is complex, but incorporates at its most basic level, exposure to a geophysical or meteorological process. The consequences of the spatial interaction between this process and a community at risk, are determined in part by the magnitude of the natural event. But, as has been revealed by the increasing trends in natural disaster occurrence, the social, cultural and economic fabric of the affected community, plays a much larger role in determining whether a disaster unfolds. The importance of this sociological context has only recently been recognised in the formulation, development and implementation of strategies aimed at mitigating the losses from natural hazards. However, there still appears to be an over reliance on the use of technological mechanisms to reduce potential impacts, and international relief aid to deal with the consequence once a disaster has occurred. These approaches will always remain important, but a shift in focus onto what can be modified within a society to reduce its vulnerability, should provide an approach to hazard management that is proactive rather than reactive.

One possible mechanism that has been identified as an important step towards this is understanding the vulnerability of individuals and groups within a society. Particularly the social and economic context in which they live, as well as the beliefs and attitudes that shape their behaviour. Although previous work has identified specific demographic groups as being at increasing risk, they often do not explicitly indicate how or why these groups are more vulnerable. Being old may indicate reduced income, frailty, and limited mobility and such factors could be more relevant for emergency managers. Whilst psychological dimensions, such as the knowledge gained from previous experiences, which may attenuate risk, or the beliefs one holds about their own ability to access the resources necessary for preparation, may amplify risk, and it may be these facets of an individual that are most amenable to mitigation through education and communication strategies. As noted by Buckle *et al.* (2000), an important element in reducing vulnerability and increasing resilience is the communication to exposed groups of the importance of self-reliance, individual preparedness and awareness of the risks.

Choice amongst a range of alternatives in dealing with a hazard is based on the individuals perception of them, which is conditioned by environmental, social and psychological factors (Warrick, 1979). An importance psychological factor is the way in which individuals respond to risk; the ways in which that risk is perceived, their beliefs about their own abilities to deal with the risk, and how (or if) this transforms into self-protective behaviour. Some research has identified specific socio-economic groups that may be more vulnerable than others, e.g. the aged, women, the very young, those living in poverty. Whilst others highlight the importance of psychological factors that may attenuate or amplify vulnerability, specifically risk perception. Several interesting and relevant models of these concepts highlight possible theoretical approaches for the study of vulnerability, particularly Protection Motivation Theory as modified for flood risk by Grothmann & Reusswig (2006).

However, the concept of vulnerability remains mired in semantic debate between the interdisciplinary actors involved in its study, and this divide reflects a continuous theme throughout the literature reviewed here. Two very distinct disciplines, natural science and social science, are involved in studying the issues surrounding risk from natural hazards and each makes an important contribution towards developments within the field. However, rather than expect each to adopt the language and methodological approach of the other, perhaps a third integrated discipline is required that can bridge the gap.

CHAPTER 3: METHODOLOGY

3.1. RESEARCH DESIGN

The wider social context is often ignored within traditional scientific research disciplines (Lawrence & Depres, 2004) but should form a fundamental component when the field of study intersects the human/environment interface, such as risk research and assessment. Where populations are at risk from natural hazards, e.g. in settlements located within the hazard zones of potentially active volcanoes, consideration of the social context is essential. To address this issue, this research utilised an interdisciplinary approach, which drew on the natural and social sciences, combining theory from psychology and social geography, along with the researcher's own background in environmental sciences. Quantitative and qualitative methods were employed to assess both risk and human vulnerability to volcanic activity at the two case study volcanoes in Ecuador and the USA. A comparative cases methodology allowed the research to explore the different social, cultural and demographic characteristics which shape vulnerability in communities at varying levels of risk from volcanic activity.

A two phase research design was devised to address the assessment of both risk and vulnerability. The aim of the first phase of the project was to develop a simplified approach to risk assessment that utilised existing data sets from the available literature and current hazard management reports. The intention was not to assess the risk associated with a given volcano but to evaluate the threat presented by that volcano to a specific town or community. The objective was to develop a methodology applicable to any community located within proximity of the volcano, allowing relative threat levels between communities to be assessed, and the most vulnerable to be identified. Within the wider hazard management context this approach would aim to enable judgements to be made regarding the most cost-effective use of limited resources for the mitigation and management of volcanic hazards, by directing it to those communities identified as most vulnerable. To achieve this, a semi-quantitative assessment tool was developed to assess volcanic risk based on work by Ewert *et al.* (2005) and Ewert (2007). Using a systematic review methodology of secondary data (comprising peer reviewed journal articles, emergency management reports and conference proceedings) combined with personal field observations, a threat assessment tool was developed and completed for several communities situated within the hazard zones of each case study volcano. The same procedure was applied in both Ecuador and the USA and is detailed in section 3.2.

Phase two of the research aimed to explore whether widely available pre-existing measures of socio-economic variables, e.g. census data, could be integrated within the phase one risk assessment to identify specific groups within a community that may be more vulnerable. To achieve this, it was necessary to determine whether socio-economic variables were important predictors of vulnerability. The relationships between various 'vulnerability indicators' were explored, and the relative importance of each in determining an individual's level of vulnerability were accessed. This vulnerability assessment took the form of a comparative case study survey design, with the results analysed using various quantitative statistical techniques.

Although a comparative approach was used and applied to the three communities studied in the United States, it was deemed inappropriate to draw comparisons between the questionnaire survey results from Ecuador and the United States due to the methodological constraints associated with cross-national studies. As far as possible, research subjects should be similar in all other aspects apart from the variables forming the focus of study (Van de Vijver & Leung, 1997). As noted by Boholm (1998, p. 135) *"actions and understandings about risks…are informed by socially and culturally constructed conceptions and evaluations…"*. Therefore, information about different events or phenomena are socially processed (Rappaport, 1996), and human social existence is culturally variable. This makes it problematic when drawing conclusions if similarities are found in studies across national or cultural boundaries, as these may not result from common processes or structures but rather from specific historical, social or cultural circumstances (Boholm, 1998). As well as these theoretical limitations, methodological procedures for comparative studies require the use of the same survey instrument, i.e. containing the same questions with identical wording (Enders, 2001). For the vulnerability assessment conducted at Mount Rainier, adjustments were made to improve the questionnaire, as a result of the experience gained during the fieldwork season in Ecuador. For clarity, the two different methodologies used in each country are outlined separately.

Although statistical comparisons across national boundaries were contraindicated, cross-community comparisons were drawn between the three locations surveyed at Mount Rainier. Additionally, one of the aims of this research was to develop a methodology for assessing risk and vulnerability that could be applied in both developed and developing countries, justifying fieldwork in two different global regions.

3.2 THREAT ASSESSMENT

As discussed in the preceding chapter, various different methodologies exist for the assessment of risk, but at the most basic level it can be expressed through the equation:

$$\textit{Risk} = \frac{\textit{Hazard (probability) x Loss (expected) x Vulnerability}}{\textit{Resilience (preparedness and loss mitigation)}}$$

Increasingly, quantitative risk assessments have built upon this equation with progressive complexity in an attempt to control for multiple additional variables. This requires comprehensive data on all aspects of volcanic activity, including identifying specific hazard types associated with volcanism, estimating the likelihood of an eruption and whether the specific hazards identified will occur, as well as evaluating the possible extent and scale of impact. Having explored the relative merits and disadvantages of various quantitative and qualitative risk assessment methodologies, a semi-quantitative, ranking methodology was selected based on; (i) the availability of secondary data, (ii) the limitations in time and resources, and (iii) the ability to addressing the overarching aims and objectives of the project.

Firstly, the long return periods often associated with volcanic activity, sometimes hundreds or thousands of years, seldom provide sufficient data on which to base a quantitative risk assessment (Crandell *et al.*, 1984; Bell, 1999a). Although considerable work on reconstructing past activity has been conducted at both Tungurahua (Barberi *et al.*, 1988; Hall *et al.*, 1999; Le Pennec *et al.*, 2004; Jaya *et al.*, 2006; Le Pennec *et al.*, 2006c; Le Pennec *et al.*, 2008) and Mount Rainier (Crandell, 1971; Mullineaux, 1974; Swanson *et al.*, 1989; Scott & Vallance, 1993; Sisson, 1995; Vallance & Donoghue, 2000; Byman & Vallance, 2001; Vallance, 2001; Sisson & Vallance, 2009), neither record can be considered complete, when many small but more frequent eruptions leave no evidence in the stratigraphic record (Crandell *et al.*, 1984). This lack of data regarding historical activity results in irregular eruption recurrence intervals, and presents problems when attempting to calculate the full range of outcomes and the likelihood of each; a crucial element of quantitative risk assessments (Kates, 1987; Bell, 1999a; Lee & Jones, 2004). Indeed this uncertainty regarding probability estimates results in what Lee & Jones (2004, pg. 11) termed "*…[a] graduation from quantitative estimations of risk to qualitative estimations…based more and more on expert judgement and informed guesswork.*" By utilising a semi-quantitative approach, this research attempts to strike a balance between the need for comprehensive data, and an over-reliance on more subjective judgements.

As well as epistemological constraints, the large quantities of data and complex calculations required for a traditional risk estimation at two volcanoes were felt beyond the scope of this project, particularly as this aspect of the research formed only one half of the project. Additionally, it was felt unnecessary to carry out a comprehensive quantitative risk assessment in order to meet the aims and objectives of the project. The aim here was to develop a simplistic approach to volcanic risk assessments that allowed the *relative* risk of different *communities* to be quantified and to compare these with residents' perceived risk, as well as to integrate a measure of social vulnerability within the assessment tool in order to explore *within* community vulnerability. The objectives of phase one were to assess the risk for each of the communities studied and determine which were most at risk. This was opposed to determining the overall risk presented by each volcano. In order to clarify this point, and following Ewert *et al.* (2005) the term 'risk assessment' was replaced by 'threat assessment', where threat is defined as *"…the qualitative risk posed by a volcano to people and property"* (Ewert, 2007, pg. 112).

3.2.1 Development of Assessment Tool

A simple methodology that allowed risk to be quantified on a scale that would enable comparisons to be drawn between communities, and between measures of perceived risk and actual risk, was devised based on the work of Ewert *et al.* (2005) and Ewert (2007). This work details a system for ranking the relative threat from the 169 volcanoes of the United States, based on the combined scores for fifteen hazard factors and nine exposure factors. Combining the scores from these factors, an overall threat score was calculated, allowing the volcanoes to be ranked and categorised from very high threat to very low threat. The overall objective was to prioritise the most threatening volcanoes for monitoring and mitigation efforts.

Whilst the focus of the system developed by Ewert was the volcano, the approach developed for this research considered the communities around each volcano as the focus of study. The aim was to assess the relative threat to different settlements around each volcano, from an eruption as a whole and from different volcanic and post-volcanic products. This allowed the ranking of settlements at each volcano in order to identify the most vulnerable communities from those studied. Considering each volcano separately, the approach allowed the overall threat between communities to be compared, as well as the relative threat from different hazard types to be quantified, and allowed comparisons with residents perceived risk to be made. The changes made to the original Ewert work to adjust the focus of study to a community approach is detailed below, along with how different sources of data were utilised.

3.2.2. Secondary Data Collection

A systematic review methodology was utilised, which involved locating and selecting relevant previous research into the historical activity, eruptive behaviour and hazards associated with volcanism at Tungurahua and Mount Rainier. As well as journal articles, the review considered emergency management reports, conference proceedings, hazard maps and the applicable volcano reference file from the Smithsonian's GVP database. From this literature, comprehensive assessments of each volcano were compiled, and are detailed in sections 4.1 (Tungurahua) and 5.1 (Mount Rainier). Additionally, a comprehensive review of the 1980 Mount St Helens eruption was undertaken. A sister volcano to Mount Rainier, the 1980 event is used as the basis for the official hazard assessments, as well as mitigation planning and emergency management at Mount Rainier. A comprehensive knowledge of this event was required to fully understand the published work on Mount Rainier, and a summary is provided for the reader in Appendix 4. This includes a review of the specific volcanic phenomena that occurred, along with their magnitude and extend, a timeline of events and details of the impact on surround communities.

The threat assessment developed for this research utilised Ewert's hazard and exposure factors as a starting point, and developed a methodology for ranking settlements around each volcano based on their likely exposure to specific hazards. These hazards were selected based on the work detailed in the comprehensive assessments, and included; (i) for Tungurahua, work by Hall *et al.* (1999) and Le Pennec (2006a), with the hazards identified being ash/tephra fall, pyroclastic flows, lava flows, lahars/mudflows, debris avalanches and earthquakes, and (ii) the current USGS hazard assessment report for Mount Rainier (Hoblitt *et al.*, 1998), with the hazards identified being ash/tephra fall, pyroclastic flows, lava flows, lahars/mudflows, debris avalanches and lateral blasts. The information gleaned from these sources included details of the likelihood and possible extent of each hazard type. Based on the known characteristics for each of these hazards, both generally but more specifically at each volcano (based on the systematic review of the secondary data), a metric was developed that related to each hazard's likely extent. The hazard factor metric for Tungurahua is shown in Table 3.1 and for Mount Rainier in Table 3.2.

Table 3.1 Hazard factors for threat assessment of communities around Tungurahua.

Hazard Factors	***Score***
Ash/tephra:	
If located ≤ 100km from volcano: score = 1	
If yes to above, located within ashfall Zone 1: score = 1	
If yes to above; located in prevailing wind direction = 1	
Pyroclastic flows:	
If located ≤ 10km from summit cone: score = 1	
If yes to above; located on or near river valley: score = 1	
If located in area associated with geological feature, e.g. deep/steep-sided river valley that protects town: score = 0, if not score = 1	
Lava flows:	
If located ≤ 7km from summit cone: score = 1	
If located ≤ 7km below north flank (active fumaroles): score = 1	
Lahars/mudflows:	
If located on or near river which heads on volcano: score = 1	
If yes to above; ≤ 80km downstream from volcano: score = 1	
If located in area associated with particular geological feature, e.g. deep/steep-sided river valley protects town: score = 0, if not score = 1	
Debris avalanche:	
If located ≤ 30km downstream/slope to the north, northwest or west of the volcano: score = 1	
If yes to above, located in area associated with particular geological feature, e.g. caldera scar that provides protection from debris hazard: score = 0, if no such features: score = 1	
Explosions/Earthquakes:	
If located ≤ 10km from volcano: score = 1	
Total of Hazard Factors (max. score 14)	

Each metric took the form of a series of questions, which comprised the hazard factors aspect of each threat assessment, and were tailored to the specific hazard types and geological setting at each volcano. Each question could attract either a yes (score = 1) or no (score = 0) answer, and in this way quantified the hazard threat. The maximum score obtainable at each volcano was 14, with the number of questions weighted towards more likely and serious hazard types.

Table 3.2 Hazard factors for threat assessment of communities around Mount Rainier.

Hazard Factors	***Score***
Ash/tephra:	
If located ≤ 100km from volcano: score = 1	
If yes to above; located in prevailing wind direction = 1	
Pyroclastic flows:	
If located within boundaries of National Park: score = 1	
If yes to above; within main river valleys: score = 1	
Lava flows:	
If located within 4km of summit vent: score = 1	
Lahars/mudflows:	
If located on or near river which heads on the volcano: score = 1	
If yes to above; ≤ 60km downstream from the volcano: score = 1	
If located in area associated with particular geological features, e.g. town protected as river runs through deep/steep-sided valley: score = 0 If town located on flood plain: score = 1	
If located at the confluence of two or more rivers that head on the volcano: score = 1	
Debris avalanche:	
If located ≤ 30km downstream/slope from the volcano: score = 1	
If yes to above; to the north west of the volcano: score = 1	
If located in area associated with particular geological features, e.g. mountain ridges upstream provide some protection from avalanche hazard: score = 0, if no such features: score = 1	
Lateral blast:	
If located ≤ 50km from volcano: score = 1	
If yes to above; located to the north west of volcano: score = 1	
Total of Hazard Factors (max. score 14)	

Exposure factors were derived directly from Ewert (2007), with five factors relevant to the assessment of a specific city or town, rather than the volcano, retained. The same measures were used at both case study volcanoes. The first exposure factor was the

$\log_{10}$ of the city or town's population, giving a measure of the population that could be exposed in the event of an eruption. Population data for each community surveyed was obtained from the last national census conducted in each country (US Census Bureau, 2000; INEC, 2001). Local aviation exposure was included in the assessment, and was scored based on the sighting of an airport within 10 km of the town. Power infrastructure included power generation, transmission or distribution facilities. This included major power lines within the settlements. Transport infrastructure covered ports, rail lines, and major roads, where major roads were defined as state or interstate highways. Major development or sensitive areas included economically important places or activities, such as industrial centres. Field observations were carried out in each community to complete an assessment of the latter four exposure factors. A maximum exposure score of four plus the $\log_{10}$ of the settlement's population could be obtained, weighting the ranking towards larger settlements (Table 3.3.).

Using the secondary evidence from past volcanic activity, the specific geological setting and the current hazard assessments detailed in the systematic review, as well as the researchers own field observations, threat assessments were completed for five communities; two at Tungurahua and three at Mount Rainier. The individual scores for the hazard factor and exposure factor elements were multiplied to calculate the overall threat assessment score. This allowed the communities at each volcano to be ranked from most threatened to least threatened. By maintaining a maximum hazard factor score of 14 across the two volcanoes and utilising the same exposure factors, it was possible to compare the relative threat to communities around both volcanoes.

Table 3.3 Exposure factors for threat assessment of communities around both case study volcanoes.

Exposure Factors	***Score***
Log$_{10}$ of city population:	
Derived from census data (total population of town/city)	
Local aviation exposure:	
If there is a jet-service airport within 10km of the city: score = 1, if none: score = 0	
Power infrastructure:	
Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	
Transportation infrastructure:	
Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	
Major development or sensitive area:	
Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	
Total of exposure factors	

The settlements at each volcano were selected to provide a representation of communities based on their distance from the volcano, e.g. relatively close, mid-distance and most distal, as well as their exposure to different types of hazard, e.g. downwind, increased exposure to ashfall, or downstream, increased exposure to lahars/debris avalanches. This was particularly relevant at Mount Rainier, were the majority of risk assessments have concentrated on communities at risk from lahars, i.e. those located to the north and west of the volcano (see (Scott *et al.*, 1995; Inverson *et al.*, 1998; Vallance *et al.*, 2003; Davis *et al.*, 2006; Johnston *et al.*, 2006; Wood & Soulard, 2009). This study is unique in that no previous risk studies have been conducted in communities to the east of the Cascade Mountains, where the major hazard would be ashfall.

By conducting a systematic review of the secondary data and compiling a comprehensive assessment for each volcano, the reasoning behind each score can be justified. This follows the recommendations of Lee and Jones (2004) and Cox *et al.* (Cox *et al.*, 2005), when relying on expert judgement for more qualitative risk assessments.

3.3. VULNERABILITY ASSESSMENT

The varying levels of risk different individuals or community groups may be exposed to in the event of a volcanic eruption are determined by the proximity and nature of the physical hazards, as well as the social, cultural and economic context within which they live. This underlying social fabric interacts with the potential hazard to create vulnerability. The characteristics of this social fabric include socio-economic features such as gender, age and income, and psychological factors such as perceptions of and experiences of risks and hazards, and overall capacity to respond (Cutter *et al.*, 2000). By investigating these characteristics, it should be possible to identify those groups who are at greatest risk. Mitigation and management techniques can then be tailored specifically to target the most vulnerable members within a community.

The theoretical underpinning of this research suggests that individuals with certain socio-economic characteristics may incur greater losses during a disaster. Whilst perceptions of risk, levels of trust, information seeking and preparedness, as well as previous experience, may influence how an individual responds or behaves during future hazardous events, thereby increasing or decreasing their vulnerability. By exploring these psychological qualities and how they differ between individuals who exhibit different socio-economic and economic characteristics, the relationships between these factors and vulnerability can be explored.

The threat assessment tool, which formed the first phase of this research, incorporates exposure factors to provide a measure of the 'macro-scale' vulnerability *between* communities. The vulnerability considered relates mainly to infrastructure and economic activity, with human vulnerability measured only in terms of the total number of residents at risk. The main focus of the second phase of this research was to explore the importance of socio-economic variables in determining vulnerability *within* communities. The aim being that should these variables prove important predictors of vulnerability, readily available information (e.g. census data) could provide an additional measure for incorporation within the threat assessment metric to provide an further level of complexity. Identifying this 'micro-scale' vulnerability at the individual level would allow strategies for risk management, education and communication programmes to be targeted towards particular groups within a community, which have been identified as more vulnerable. The objective here was to examine the relationships amongst selective socio-economic and psychological characteristics, and protective behaviours, rather than to build a comprehensive model of vulnerability.

3.3.1. Ecuadorian 'Pilot' Study

In order to investigate these issues, a questionnaire survey was conducted in the city of Baños, which nestles in the foothills below Volcan Tungurahua, Ecuador. Given the limitations within the data obtained as a result of the problems encountered during this fieldwork season (see Chapter 1), the results are presented as a descriptive study that aimed to explore the relationships amongst selective personal characteristics and socio-economic features, whilst forming an initial study on which to base the more comprehensive survey conducted in the United States.

3.3.1.1. Survey Method

In order to explore issues of vulnerability within the selected community, a structured questionnaire was designed for completion by members of the public. Devised to document the demographic and socio-economic characteristics of an individual, as well as their attitudes and beliefs regarding volcanic risk at Tungurahua, the survey aimed to explore the relationships between socio-economic status and various facets of risk perception, as well as the current knowledge environment amongst participants. A number of social scientists were consulted regarding the questionnaire content and structure (personal communications: L. Hayes, University of Exeter, Oct 2005; G. Tobin and L. Whiteford, University of South Florida, Jan 2006; M. Mowforth, University of Plymouth, Nov 2005;), and the final questionnaire was constructed with their assistance (see Appendix 5). The choice of variables used in the survey was also guided by the theoretical work of Paton (2003), and past empirical work on perceptions of natural hazards (Lindell & Whitney, 2000; Becker *et al.*, 2001; Paton *et al.*, 2001b; Tobin & Whiteford, 2001; Whiteford *et al.*, 2002). Wording for the socio-economic section reflected that used in the last national census carried out in Ecuador (INEC, 2001).

It was not possible to conduct a formal pilot phase. As well as political unrest, this was in part due to the necessity of delaying the translation of the questionnaire into Spanish until arrival in Baños (for Spanish version of questionnaire see Appendix 6). It was felt that local knowledge and experience was vital to ensure the intended meaning of each question was retained during the translation process. This was carried out at a language school in the town with assistance from a local teacher, who had experience of the volcano and the 1999 evacuation (personal communications: M, Sanchez, Raíces Spanish School, Baños).

The survey comprised a total of 56 questions, both multiple choice and open-ended, and included sections designed to assess various attitudes and beliefs regarding volcanic risk from Tungurahua, as well as to establish the demographic profile of participants. Demographic characteristics included; gender, age, occupation, household income, property ownership and household composition (household size and number of children aged 16 and under). Survey items designed to elicit the perceptual beliefs and attitudes regarding hazard and risk at Tungurahua, included those addressing (i) risk perception - rating levels of concern regarding the volcano and the risk to oneself and ones family, and knowledge about specific volcanic hazards; (ii) preparedness – knowledge of personal mitigation plans and evacuation procedures; (iii) information – assessing the types of information sources accessed and the providers of this; (iv) trust – levels of trust in various agencies to provide accurate information regarding future volcanic eruptions; (v) previous experiences – whether respondents evacuated during the 1999 eruption of Tungurahua and an assessment of their feelings regarding this, both at the time and now; and (vi) a measure of the existence and strength of informal social networks.

A purposive, convenience sampling methodology was employed. Specifically, residents of Baños were selected through local contacts and a resulting snowball effect attracted additional participants. Although this excluded complete randomness of the sample, an apparent cross-section of the local population was achieved. The aim of the sampling strategy was not to obtain a statistically formal representative sample of the population, but rather to seek sufficient variation on a number of socio-economic characteristics, for reliable between-group comparisons to be made. The majority of surveys were completed during face-to-face interviews with the researcher, whilst approximately 10% were self-completed by participants. The questionnaire took approximately 30 minutes to administer during interviews.

3.3.1.2. Sample Characteristics

A total of 47 questionnaires were completed by residents from Baños, these were evenly split between men (48.9%) and women (51.1%). The age of respondents ranged from 18 to 62, with a mean of 36.6 (*SD* = 10.3). Marital status included those who were married (72.3%), single (19.1%) and widowed (6.4%). Of the 93.6% employed, 10.6% worked in agriculture,14.9% worked in or ran an independent store, 23.4% worked in business, 10.6% were employed in a café/restaurant, 10.6% worked in or ran a hotel/guesthouse, 14.9% were employed as teachers (both at the local school or within a language school) and 8.5% (*n* = 4) either did not state their employment or were students (*n* = 2). Annual household income ranged from $1,800 per year (6.4%) to $36,000 per year (2.1%), with a mean of $8,132 (*SD* = 7,756). The majority of respondents lived in houses (70.2%), whilst 23.4% lived in apartments and 6.4% lived in a room. Home ownership comprised; 42.6% home owners, 23.4% family owned home, 29.8% rented and 4.3% lived with friends. Households ranged in size from single occupiers (8.5%) to 2 nine person households (4.3%), whilst the average was 4.4 (*SD* = 1.9). Of the sample as a whole 68.1% included children aged 16 years or younger. Just 12.8% (*n* = 6) of households had residents aged 65 years or over, all of whom resided with a grown-up son or daughter and their families.

The demographic characteristics of the questionnaire sample do not correspond exactly with the INEC (2001) data for the town of Baños (details of which are provided in Table 3.4). However, limitations due to the small sample size already precluded the possibility of drawing inferences about the wider population from the results obtained.

Table 3.4 Questionnaire survey sample characteristics compared to Baños census data.

	Baños	
Population (total)	16,112	47
Gender (%)		
Male	49.9	48.9
Female	50.1	51.1
Age (%)		
Under 20 years	42.1	2.1
20 to 24 years	9.3	6.4
25 to 34 years	15.7	38.3
35 to 44 years	12.3	34.0
45 to 54 years	9.1	12.8
55 to 64 years	5.7	6.4
65 years and over	5.8	0.0
Employment (%)		
Agriculture	28.7	10.6
Manufacturing	7.1	14.1
Construction	3.8	9.3
Trade	12.1	14.9
Education	4.3	14.9
Other	33.8	23.4
Unemployed	10.7	12.8
Annual household income ($)		
Average	5,376	8,132
Marital Status (%)		
Married	45.7	72.3
Single	37.9	19.1
Widowed	4.9	6.4
Divorced/separated	4.7	2.1
Other	6.8	0.0
Property ownership (%)		
Own	64.7	66.0
Lease	24.8	29.7
Free	7.1	4.3
Service	2.2	0.0
Other	1.2	0.0

3.3.1.3. Data Analysis

Question responses were inputted and analysed using SPSS (Statistical Package for the Social Sciences). Answers to open ended questions were assessed for similarities, and where responses fell into clearly identifiable categories were assigned codes to allow quantitative analysis. The raw data and descriptive analysis from both questionnaires is provided on the disc (inside back-cover). Statistical analysis was largely confined to basic descriptive techniques due the small sample size, but these are detailed where used. Some interesting contextual details were uncovered and are presented in the results section of Chapter 4.

3.3.2. US Case Study

Building on the work conducted in Ecuador, the survey instrument was refined to better address the aims and objectives of the research. Considerably improved fieldwork conditions allowed three different communities to be surveyed, and a much larger sample size was obtained. This in turn increased the available statistical analysis techniques which could be employed. The results of the survey were addressed in relation to differences between the three communities for specific measures of key psychological variables indicated by the literature to be important in motivating protective response towards a hazard. These included hazard salience[3], risk perception, self-efficacy, trust in official institutions, access to information and perceived preparedness. Additionally, two novel issues were considered. Firstly, respondents' perceived risk of the six hazards highlighted in the phase one threat assessment for Mount Rainier were compared with the 'objective' risk rating from the threat assessment, giving a measure of the accuracy of lay judgements. Secondly, an individual's planned protective response to volcanic activity was compared to the 'appropriate' response for each community. This appropriate response was determined

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[3] Hazard salience is defined as the extent to which a particular hazard plays upon the mind relative to other concerns. It is measured by whether the hazard is spontaneously mentioned when an individual is asked to list factors they are concerned about and by how frequently they think about the hazard. It forms a facet of a persons perception of risk (Johnston *et al.*, 1999; Lindell & Perry, 2000; Barberi *et al.*, 2008).

from current published guidelines issued by the USGS, Pierce County Department of Emergency Management and Mount Rainier National Park Service. Following on from the comparison of these variables by location, variations due to socio-economic differences were explored. Finally, the relative importance of socio-economic factors versus psychological characteristics in predicting protective response were considered.

3.3.2.1. Theoretical Framework

Survey work conducted during the fieldwork phase in Ecuador, identified some correlations between certain socio-economic variables and risk perception. However, as summarised by Lindell & Perry (2000) and Rimal & Real (2003), the link between perceived risk and the adoption of preparedness behaviour, which may be important for reducing overall vulnerability, is not clear. To address this issue and to build on the work of the previous case study, the questionnaire utilised for this fieldwork season was revised to include additional questions regarding perceived preparedness, and precautionary adaptation.

Precautionary adaptation (e.g. planning an evacuation route, assembly of an emergency pack, or purchasing breathing equipment to avoid ashfall) may reduce the effects of an eruption on an individual or their household, thereby reducing vulnerability. The approach adopted in this study to explain variance in individual vulnerability to volcanic hazards, utilised a socio-psychological model of precautionary adaption based on Grothmann & Reusswig's (2006) modified Protective Motivation Theory model (see Chapter Two for details). Many potential factors influence why people take precautionary action such as past experience, lack of reliance on government protection, or strong emotions, i.e. fear (*ibid*). Self-protective behaviour may therefore be influenced by beliefs about self-efficacy, and be associated with higher perceptions of risk. To compare the ability of a perceptual approach to assess vulnerability to volcanic activity at Mount Rainier, this research aimed to compare a socio-psychological model of vulnerability (which included risk perception, self-efficacy, preparedness etc) with a socio-demographic model of vulnerability (including age, gender, income etc). To measure the former perceptual variables requires extensive work developing and administering questionnaires, whereas socio-economic factors are readily available via census data. Therefore, determining the best model for predicting volcanic hazard adaptation has important implications for future risk mitigation research, and for helping to identify the most important individuals/groups within a community to target with education and communication strategies.

Several additional psychological variables were included in the Mount Rainier study, specifically questions regarding hazard salience, optimistic bias[4] and sense of community. Previous work has indicated the relative importance of hazard salience in stimulating preparedness (Davis *et al.*, 2005; Paton *et al.*, 2005), whilst the roles of optimistic bias (van der Pligt, 1996) and sense of community (Davis *et al.*, 2005) in moderating risk perception suggests they may be import barriers in promoting self-protective behaviour.

3.3.2.2. Survey Method

In order to explore issues of vulnerability within the three selected communities, a structured questionnaire was designed for completion by members of the public. Devised to elicit an individual's beliefs and attitudes towards volcanic risk at Mount Rainier, the survey aimed to explore the relationships between socio-economic status and key psychological characteristics. Modified from the original survey tool used in the initial Ecuador study, measures of several additional psychological variables were incorporated. A number of risk perception practitioners were consulted regarding the questionnaire content and structure (personal communications: M. Davis, Dominican University of California, Jun 2007; D. Johnston, Joint Centre for Disaster Research, Massey University, New Zealand, Aug 2007; H. Crosweller, University of Bristol, May

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[4] Optimistic bias is the tendency of individuals to exhibit unrealistic optimism regarding their level of risk to a negative event by rating their risk as lower than average when compared to others (Weinstein, 1980; van der Pligt, 1996).

2007) and several aspects from their volcanic risk perception studies were incorporated (Davis *et al.*, 2005; Davis *et al.*, 2006; Johnston *et al.*, 2006; Barberi *et al.*, 2008; Crosweller, 2009). The choice of variables used in the survey was also guided by the theoretical work of Paton (2003) and that relating to PMT (Rogers, 1975, 1983; Mulilis & Lippa, 1990; van der Pligt, 1996; Grothmann & Reusswig, 2006; Martin *et al.*, 2007) and past empirical work on perceptions of natural hazards (Lindell & Whitney, 2000; Becker *et al.*, 2001; Paton *et al.*, 2001b; Tobin & Whiteford, 2001; Whiteford *et al.*, 2002; Grothmann & Reusswig, 2006). Wording for the demographic questions were taken from the last national census in the United States (US Census Bureau, 2000). It was not possible to conduct a formal pilot phase, however, during the initial stages of the study, two problematic questions were identified and these were adjusted in order to clarify their meaning (these adjustments are highlighted on the questionnaire shown in Appendix 7, and relate to questions 18 and 19).

The survey comprised a total of 39 questions, both multiple choice and open-ended, and included sections designed to assess psychological attitudes towards Mount Rainier, and to determine the key demographic characteristics of participants. Demographic characteristics were; gender, age, household income, educational attainment, property ownership, household composition (number in household, number of children/number of elderly), location and psychological sense of community (PSOC). A modified version of the 12 item Sense of Community Index (SCI), adapted for the purposes of this research from Obst & White (2004), was included within the questionnaire to measure PSOC. Questions relating to psychological variables included; (i) hazard salience: time spent thinking about the hazard, level of concern about future volcanic activity and concern relative to other hazards, (ii) risk perception: rating the likelihood and severity of a future eruption, how this would effect oneself and family, and rating the seriousness of specific volcanic products, (iii) self-efficacy: feelings of control regarding the ability to protect oneself and family, (iv) trust: confidence in officials' level of preparedness and their ability to provide accurate information about future eruptions, (v) information: assessing the types of information sources and the providers of this, (vi) preparedness: adoption of hazard adjustment behaviour and knowledge of appropriate responses in the event of an eruption.

A selective, purposive, convenience sampling methodology was employed. As before, the aim of the sampling strategy was not to obtain a statistically formal representative sample of the population, but rather to seek sufficient variation on a number of socio-economic characteristics, for reliable between-group comparisons to be made. The method employed specifically selected only residents of the three case study locations. Door-to-door interviews were conducted in Carbonado, both during the day, and in the evening to try and ensure a representative sample of both employed and unemployed members of the community. Additionally, the local school was approached and asked to distributed questionnaires to members of staff for self completion. To try and maximise the number of surveys completed, face-to-face interviews in Sumner and Ellensburg were conducted at local libraries, with both patrons and members of staff. Additionally, an explanatory information board and drop-box were set up at a local community hall in each town with questionnaires supplied for self-completion (see photographs, Appendix 9). Other questionnaires were left at a number of local schools, a university and civic offices, for completion by staff members following an information campaign conducted by senior teaching and administrative staff, using instructions provided by the researcher. The questionnaire took approximately 30 minutes to administer during face-to-face interviews, and approximately 75% of the 242 completed surveys were obtained in this way.

3.3.2.3. Sample Characteristics

A total of 242 questionnaires were completed by residents from the three survey sites: Carbonado; 38 (15.7%), Sumner; 94 (38.8%) and Ellensburg; 110 (45.5%). More women (69.5%) were surveyed than men (30.5%). Ages ranged from 18 to 87 years, with a mean of 51.73 years (*SD* = 17.51). Ethnicity was predominantly white (92.9%).

Educational attainment included those who had no formal schooling or had not obtained a high school diploma (5.5%), high school graduates (29.0%), those with some college or an associate degree (19.7%), those with bachelor's degrees (28.6%) and those with post-graduate degrees (17.2%). When asked their approximate annual household income, 23 people (9.5%) declined to respond. For those who answered, incomes ranged from less than $20,000 per year (13.2%) to $100,000 and over (14.2%). Median income was $40,000 to $59,999. Home ownership comprised; 76.8% home owners (31.7% mortgage free, 45.3% mortgaged) and 18.9 % renter-occupied housing. Property type was dominated by detached homes (78.7%), with 12.1% living in apartments, 6.3% in mobile homes and 2.9% in attached homes. Property value ranged from less than $100,000 (5.2%) to over $500,000 (11.7%). The percentage of households with one or more children under 18 was 30.5%, whilst 32.2% had one or more people aged 65 years or older in residence. Other household composition data included; 23.0% single- person households, 31.4% couples, 35.1% married-couples with children, 2.5% single-parent families, and 7.9% non-family households (e.g. co-habiting friends).

The demographic characteristics for the questionnaire sample do not correspond exactly with US Census Bureau (2000) data for Washington State, or the three case study cities (Table 3.5). The largest discrepancies were in three key characteristics; (i) gender - many more women completed the questionnaire than men, (ii) age - where the sample contained an appreciably higher percentage of respondents over the age of 60, and (iii) education - where the sample appeared more highly educated than the wider population. Despite these disparities, the sample did provide a fairly representative profile of the major social groups, allowing some tentative generalisations to the wider population to be made. More importantly, though some differences in educational attainment and household composition exist between the three study sites (specifically a higher level of schooling completed by Sumner and Ellensburg respondents than Carbonado residents, who have a larger number of households with children), generally the three samples have similar demographic profiles, allowing comparisons between locations to be drawn.

Table 3.5 US questionnaire survey sample (in blue) and US census characteristics.

	Washington		Carbonado		Sumner		Ellensburg	
Population (total)	5.8m	242	621	38	8504	94	15414	110
Gender (%)								
Male	49.8	30.5	52.5	29.7	48.4	36.2	48.7	25.9
Female	50.2	69.5	47.5	70.3	51.6	63.8	51.3	74.1
Age (%)								
Under 20 years	28.6	2.9	37.1	8.1	28.9	2.1	25.7	1.9
20 to 24 years	6.6	4.2	5.6	0.0	6.3	2.1	29.3	7.4
25 to 34 years	14.3	10.9	13.7	16.2	14.2	11.7	13.8	8.3
35 to 44 years	16.5	17.2	16.1	27.0	16.2	17.0	8.9	13.9
45 to 54 years	14.4	20.9	13.5	16.2	12.7	22.3	7.9	21.3
55 to 59 years	4.8	7.1	5.0	8.1	4.7	8.5	2.9	5.6
60 to 64 years	3.6	10.9	1.9	5.4	3.7	7.5	2.1	15.7
65 to 74 years	5.7	13.8	3.5	13.5	6.6	14.9	3.6	13.0
75 to 84 years	4.1	10.5	2.6	5.4	4.8	12.8	3.7	10.1
85 years and over	1.4	1.7	1.0	0.0	1.9	1.1	2.1	2.8
65 years and over	11.2	25.9	7.1	18.9	13.4	28.7	9.4	25.9
Male	4.8	10.4	2.6	10.8	5.2	13.8	3.5	7.4
Female	6.4	15.5	4.5	8.1	8.2	14.9	6.0	18.5
Educational attainment (%)								
Less than 9th grade	4.3	1.7	4.2	5.3	4.3	0.0	5.8	1.9
12th grade, no diploma	8.6	3.8	15.1	0.0	9.8	4.3	8.4	4.7
High school graduate	24.9	29.0	42.7	50.0	31.8	31.2	24.0	19.6
College, no degree	34.3	19.7	26.5	26.3	34.4	18.3	29.8	18.7
Bachelor's degree	18.4	28.6	8.2	10.5	15.4	36.5	19.4	27.9
Graduate or prof. degree	9.3	17.2	3.3	7.9	4.3	9.7	12.6	27.2
% high school grad or higher	87.1	94.7	80.6	94.7	85.8	95.7	85.8	93.4
% bachelor's degree or higher	27.7	45.7	11.6	18.4	19.6	46.3	32.0	55.2
Household income (%)								
Less than $14,999	13.1		12.6		13.0		41.6	
$15,000-$24,999	11.7	13.2	9.8	3.0	13.0	18.5	15.5	12.0
$25,000-$34,999	12.5	21.0	11.0	24.2	18.5	15.1	12.7	25.0
$35,000-$49,000	17.1	21.9	16.1	24.2	20.2	19.8	11.5	23.0
$50,000-$74,999	21.4	20.1	32.3	18.2	21.0	18.6	11.6	22.0
$75,000-$99,999	11.6	9.6	16.5	12.1	8.4	14.0	4.6	5.0
$100,000 or more	12.6	14.2	1.6	18.2	5.9	14.0	2.5	13.0
Property ownership (%)								
Owned mortgage free	15.9	32.2	17.8	21.6	15.3	29.8	12.3	38.0
Mortgaged	48.7	45.6	72.7	70.3	37.2	41.5	22.3	40.7
Renter-occupied housing	35.4	22.2	9.5	8.1	47.5	28.7	65.4	21.3
Household type (%)								
Living alone	26.2	23.0	17.5	13.5	30.7	25.5	35.5	24.1
Nonfamily household	7.8	7.9	3.5	2.7	6.3	9.6	22.1	8.3
Couple	33.3	31.4	31.0	18.9	31.0	27.7	21.6	38.9
Married-couple family	26.2	35.1	46.0	62.2	22.6	34.0	14.8	26.8
Single parent	6.5	2.5	2.0	2.7	9.4	3.2	6.0	1.9
With children <18 years	35.2	30.5	51.0	43.2	35.0	32.9	22.2	23.1
With elderly >65 years	20.4	32.2	16.5	27.0	23.7	33.0	16.4	33.3

3.3.2.4. Data Analysis

Questions were pre-coded to assist data entry, and inputted and analysed using SPSS. Answers to open ended questions were assessed for similarities, and where responses fell into clearly identifiable groups, were coded to allow quantitative analysis. The first stage of the analysis involved conducting a series of descriptive statistical tests on each question to summarise the data (Appendix 10). This included calculating the frequencies of categorical data, and the mean, variance, standard deviation and distribution of interval data. From this initial analysis the data was found to be generally normally distributed. The statistical approaches utilised in psychological research recognise that data in psychology is rarely perfectly normally distributed, but states that parametric tests are sufficiently robust to cope with small violations of this assumption (Langdridge & Hagger-Johnson, 2009). Further analysis was therefore conducted using the statistically more powerful parametric tests, unless other assumptions were violated, and these are stated where applicable. Following the initial descriptive exploration of the survey results, a comprehensive analysis of the questionnaire data was conducted. Correlation tests were used to assess associations between variables and tests of significance were used to assess whether the results from the sample could be applied to the wider population. Finally multiple regression analysis was employed in an attempt to determine which variables were important predictors of vulnerability. The inferential statistical techniques used to identify patterns, relationships or differences within the data, are detailed where used within the results. The interdisciplinary techniques and methodologies employed within social science research and psychology, do not adhere to the same principles which govern more quantitative disciplines, but these are considered standard within social science research (Howitt, 2005; Ruane, 2005). Several texts were consulted in the design, execution and analysis of the questionnaire results to ensure appropriate disciplinary methods were employed (Field, 2005; Howitt, 2005; Ruane, 2005; Langdridge & Hagger-Johnson, 2009).

The results of the two phases of research carried out following the methodologies outlined above are detailed in the following two chapters. These are presented by case study country, beginning with Ecuador, and for each country give details of the systematic review and results of the threat assessment, followed by the results of the statistical analysis of the questionnaire survey used for the vulnerability assessment. After each research phase the results are discussed, whilst in the concluding chapter the results from each phase and case study country are summarised and overall conclusions drawn. These findings are considered in light of their relationship with the existing literature, the original research aims and objectives, and any contributions they make to the wider field, as well as implications for policy and practice. Limitations with the methodologies are also discussed in the final chapter, along with recommendations for future work.

CHAPTER 4: ECUADOR CASE STUDY

4.1. INTRODUCTION

The central aim of this case study based research was to examine the vulnerability of local residents to eruptions at Volcán Tungurahua. Two phases of research were completed. Firstly, a threat assessment was conducted using personal field observations, combined with a systematic review of existing published literature, including peer reviewed journal articles, current emergency management reports, conference proceedings and hazard maps. This comprehensive assessment of the secondary data is presented in the following section, and was used to complete the devised threat assessment tool for two communities identified as being at varying levels of risk from different volcanic hazards associated with eruptive activity at Tungurahua.

The second phase of research considers the human context of the volcanic threat, explored using a questionnaire survey of local residents. This addressed issues of perceived risk from specific volcanic phenomena, and how these may alter depending on the socio-economic status of the individual. Although field conditions prohibited access to a sufficiently broad sample of public opinion, the approach provided a useful 'pilot' for the more comprehensive study conducted during the subsequent fieldwork season in the USA.

4.2. TUNGURAHUA THREAT ASSESSMENT

4.2.1. Comprehensive Review of Secondary Data

A systematic review of the historical activity, eruptive behaviour and hazards associated with volcanic activity at Tungurahua volcano was used in an effort to quantify, in a broad manner, the threat posed to residents living in two communities at different distances, and subject to different risks from the volcano. As recommended in relation to more qualitative risk assessments, this information is provided in detail below in order to document fully the criteria upon which the judgements used to complete the threat assessment are based.

4.2.1.1. Regional Setting and Volcano Type

One of the world's highest mountain ranges, the Andes are a 9,000 km long orogenic feature forming the South American section of the circum-pacific 'Ring of Fire'. This volcanic belt is dominated by large, often glacier clad stratovolcanoes and has the largest number of volcanoes of any region on earth with 204, and is second only to Japan for the number of volcanoes with dated eruptions. It has the highest number of documented eruptions measuring four or more on the VEI during the past 200 years, and accounts for 15% of the worlds mudflow-producing eruptions. Some of South America's earliest documented eruptions were recorded in Ecuador during the early 1530s. The region's smallest country in terms of population and area, Ecuador has the second highest number of historically active volcanoes with sixteen. However, twenty volcanoes are listed as having been active during the Holocene period on the GVP database (Siebert & Simkin, 2002-). Formed by the subduction of the eastern Pacific's Nazca Plate beneath the continent of South America at a rate of 7.5cm/year (Trenkamp *et al.*, 2002), the Ecuadorian Andes comprise a procession of active volcanoes, which straddle the country and are known locally as "La Avenida de los Volcanes" (The Avenue of Volcanoes). The morphology of the main orogenic belt comprises two north-south trending cordilleras stretching 400 km from Cerro Negro de Mayasquer on the country's border with Columbia in the north to Peru in the south. Separated from the Western Cordillera by the 30 to 50 km wide Inter Andean Valley (Le Pennec *et al.*, 2006a), the Eastern Cordillera comprises, amongst others, the volcanoes of Sangay, Cotopaxi, Antisana and Tungurahua (Figure 4.1).

Volcan Tungurahua is one of Ecuador's most active volcanoes and, at 5,023m, the countries tenth highest mountain. It is located just south of the equator in central Ecuador, and 120km south of Quito, the country's capital. Local population centres include Ambato, the capital city of Tungurahua Province, situated 31 km to the northwest, with a population at the last census of 354,095, and the city of Riobamba 32 km to the southwest (population 124,807). Approximately 1,800m below the volcano's summit and 8 km to the north is the small thermal springs town of Baños, an important tourist destination with a population of around 16,000 (Whiteford *et al.*, 2002).

Figure 4.1 Map of Ecuador showing Tungurahua and other significant volcanoes of the Ecuadorian Andes (modified from Topinka, 2003).

Many smaller villages and settlements surround the lower slopes of the volcano. The fertile volcanic soils combined with the area's mild climate provide a highly productive farming region, supplying crops and livestock to the markets in Ambato and Riobamba, and this agricultural production is the main economic activity of the area.

Tungurahua is a steep-sided andesitic-dacitic stratovolcano. It is notable for its extreme relief, reaching 3,200m above its northern base and, prior to the commencement of the current eruptive episode in 1999, had a small summit glacier. Since the mid Pleistocene, three major volcanic edifices have been sequentially constructed over a basement of metamorphic rocks. Following the collapse of the initial edifice, Tungurahua II developed within the past 30,000 years. This collapsed approximately 3,000 years ago, producing a large debris avalanche deposit and a horseshoe-shaped caldera open to the west. Inside this the modern stratovolcano (Tungurahua III) was constructed. Historically, eruptions have originated from the summit crater and have been characterised by strong explosions, lava flows, lahars and pyroclastic flows that have reached populated areas at the volcano's base. Since 1999, the volcano has been in a state of near continuous eruption. Prior to this period, the last major documented eruption occurred between 1916 and 1918 and measured 4 on the VEI. Minor activity continued until 1925, and smaller episodic events were recorded several times prior to 1999 (Siebert & Simkin, 2002-).

4.2.1.2. Eruptive History

The process of building and destruction at Tungurahua extends back around 700,000 years (Barberi *et al.*, 1988; Whiteford *et al.*, 2002). Various studies indicate there have been three main constructional phases followed by major flank collapses (see Hall *et al.*, 1999; Molina *et al.*, 2005; Le Pennec *et al.*, 2006a). The constructional period of Tungurahua I was characterised by andesitic lava flows and tephra fall (Hall *et al.*, 1999), culminating with large debris avalanches associated with a major sector collapse around 30,000 years ago (Le Pennec *et al.*, 2006a). The current northern, eastern and southern flanks of the edifice are what remain from Tungurahua I following these flank failure events and are characterised by deeply incised canyons.

Evidence for Tungurahua II is found in a series of lava flows exposed on the upper southern flank and in the Patate River valley (Figure 4.2), as well as tephra deposits to the southwest of the volcano. Exposures to the south of the volcano indicate that three or four major eruptions took place between 30,000 years BP and 9,000 years BP . A particularly large eruption took place around 9,700 years BP. Scoria clasts ejected at this time are found 10-15 km to the southwest of the volcano, whilst concomitant pyroclastic surges travelled 15 to 20 km to the southwest, reaching the southern margins of the area now occupied by the town of Guano (Le Pennec *et al.*, 2006a).

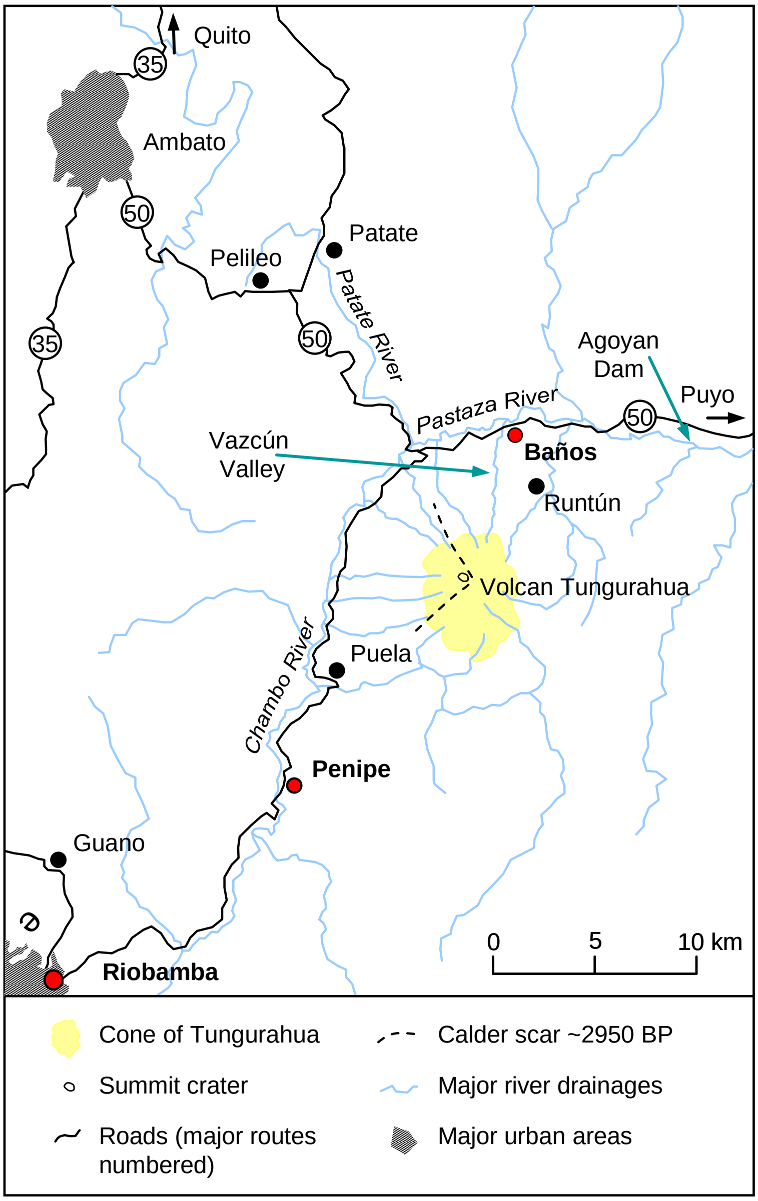


Figure 4.2 Map showing the regional setting of Tungurahua with volcanic features, major drainages, local towns and cities, and main road links (modified from Hall *et al.*, 1999; Le Pennec *et al.*, 2006a).

Evidence suggests that prior to its collapse this intermediate edifice reached a similar elevation to Tungurahua I; around 3,000m, and was centred on the same conduit as today's cone (Hall *et al.*, 1999).

Tungurahua II collapsed around 2,950 years BP (Hall *et al.*, 1999; Jaya *et al.*, 2006), with avalanches destroying the steep western flanks and forming a large amphitheatre, preserved in the caldera scar on the south-western flank (Figure 4.2). This edifice failure was accompanied by a large eruption producing a volcanic blast and sub-plinian column, estimated to have reached a height of 25 km above the summit, with tephra fallout mainly to the north. The volume of ash erupted during this period has been calculated at approximately 1.3 km^3, indicating a VEI of 5, making this the largest eruption at Tungurahua during the Holocene (Le Pennec *et al.*, 2006a). The collapse of Tungurahua II was followed by the extrusion of large dacitic lava flows up to 6 km long and debris flows, both related to the emplacement of a lava dome within the amphitheatre and the growth of present-day Tungurahua III.

The present Tungurahua III edifice developed during two distinct periods of activity, one approximately 2,300 – 1,400 years BP, the second beginning 1,200 years BP (Hall *et al.*, 1999). Occupying the western third of the older volcanic complex, this edifice forms a nearly symmetrical cone, which erosion has deeply incised with steep-sided gorges up to 70m deep in places (Le Pennec *et al.*, 2006a). During the past 2,300 years, the growth of Tungurahua III has been characterised by almost continuous eruptive activity, generating lava flows, pyroclastic flows and debris avalanches, principally descending the cone's western and northern flanks. Eruptions have also ejected moderate amounts of ash, scoria lapilli and pumice lapilli, transported by prevailing winds predominantly to the west and southwest (Hall *et al.*, 1999). Most eruptions appear to have been accompanied by the emplacement of andesitic lava flows, many of which have reach 5-7 km from the crater (Le Pennec *et al.*, 2006a).

Historic eruptions at Tungurahua have been characterised by explosive activity accompanied by lava flows, lahars and pyroclastic flows that have reached populated areas at the volcano's base (Hall *et al.*, 1999). Archaeological evidence, historical archives, stratigraphic analysis, radiocarbon dating and dendrochronology suggest that a particularly large eruption occurred in 1640 (Le Pennec *et al.*, 2004; Le Pennec *et al.*, 2006c; Le Pennec *et al.*, 2008). This eruption was associated with pyroclastic surges, lava flows, block and ash flows and several debris flows, some of which may have descended the northern flank down the Vazcún valley (Figure 4.2) (Le Pennec *et al.*, 2006a; Le Pennec *et al.*, 2008). The destruction of a village and the loss of its 5,000 inhabitants at this time is thought to be the result of a landslide triggered during this eruption (Le Pennec *et al.*, 2006b). It is now thought that descriptions in early historical archives for an eruption at Tungurahua in 1534 actually correlate with an eruption of Cotopaxi (Le Pennec *et al.*, 2006b), and therefore the 1640 eruption is the oldest event for which historical evidence exists.

A VEI 3 eruption occurred during 1773 and was accompanied by pyroclastic flows and surges down the north and west flanks. Lahars and pyroclastic flows descended the Vazcún valley, reaching the town of Baños, although no casualties were reported. Andesitic lava flows reached the north-western foot of the volcano, temporarily damming the Pastaza River (Hall *et al.*, 1999; Le Pennec *et al.*, 2006a). This eruption was followed in 1886 by a VEI 4 magmatic eruption associated with pyroclastic flows and surges down river drainages, lava flows on the western flank and significant ashfall to the west (Le Pennec *et al.*, 2006a). Prior to the current eruptive phase, the last major eruption occurred from 1916 to 1918 (Siebert & Simkin, 2002-). This was associated with several VEI 3 explosions forming pyroclastic flows, which descended all flanks of the volcano. These explosions were associated with ash plumes, ballistic ejecta and a small lava flow, as well as phases of Strombolian activity. Waning in 1919, the activity ceased in 1925 (Le Pennec *et al.*, 2006a).

Current activity began following the detection of volcanic tremor in January 1993, with a small phreatic eruption occurring in May of that year. Intermittent elevated seismic activity was detected between 1994 and 1997, becoming more frequent and intense from September 1998. Increased fumarolic activity began in July 1999 with the release of steam and gas from the summit crater. This and the continuing increase in volcanic tremor prompted authorities to raise the alert level to Yellow in September 1999. Between October and November 1999 a series of explosive eruptions occurred, including a phreatic eruption which injured two people close to the summit (Hall *et al.*, 1999; Le Pennec *et al.*, 2006a). Elevated SO_2 output (Arellano *et al.*, 2008) and glowing material in the crater during the middle of October resulted in a Red alert being issued and the evacuation of 26,000 inhabitants from Baños and the surrounding villages (Hall *et al.*, 1999; Tobin & Whiteford, 2002a; 2002b; Le Pennec *et al.*, 2006a). Almost continuous vapour and ash emissions were observed, accompanied by audible explosions, with 1,400 recorded during November alone. Heavy rains during this time triggered the first of a series of lahars down the western flanks. Strombolian-vulcanian activity continued over the next few months but the predicted pyroclastic flows did not occur prompting the return of most residents (Le Pennec *et al.*, 2006a). Since this time activity has waxed and waned in intensity. During pulses of increased ‘explosive degassing activity’ (Arellano *et al.*, 2008), significant ash fall has covered the region to the west of the volcano. Numerous lahars have been generated, severely disrupting transportation by blocking the Baños-Penipe road. Intermittent Strombolian activity has continued characterised by gas and steam emissions, audible explosions and ash plumes rising from 10 to 14 km above the summit.

Activity increased in 2006 to levels similar to that seen in 1999. Pyroclastic flows were generated for the first time and vibrations and the sound of ‘roaring’ prompted some residents to voluntarily evacuate. Pyroclastic flows in mid-August destroyed several small villages and hamlets on the slopes of the volcano, killing at least five people and prompting the evacuation of around 3,200 residents from the “at risk” areas, including the hamlet of Runtún. These incandescent flows travelled down the west, northwest and northern flanks of the volcano at speeds of up to 40 km/hour and were sufficiently mobile to reach the Baños-Penipe road (Wunderman *et al.*, 2006). Block and ash deposits from a pyroclastic flow that travelled down the west and southwest flank were an estimated 50m thick (Wunderman *et al.*, 2006). As well as settlements, pastures, livestock and basic infrastructure were affected. The Agoyan hydroelectric dam, situated downstream to the east of Baños, was shut down for a period of several days and air traffic across the country was disrupted due to ashfall at a number of airports (Wikinews, 2006). Ash plumes reached an estimated height of 10 km above the summit and covered the central part of Ecuador (Wunderman *et al.*, 2006). The provinces of Chimborazo, Tungurahua, Cotopaxi and Bolivar were declared disaster areas, and damage due to loss of agriculture following ash fall was estimated at US$150 million (Wikinews, 2006). This particular eruptive episode was a moderately sized event, and rated 3 on the VEI (Siebert & Simkin, 2002-; Barba *et al.*, 2008; Hanson *et al.*, 2009). Following a reduction in volcanic activity, and a return to a ‘passive degassing’ phase (Arellano *et al.*, 2008), evacuated residents returned home.

Since the end of 2006 activity has been characterised by variable eruptive behaviour, many rain-induced lahars, continuing explosions and ash plumes (Siebert & Simkin, 2002-). The most recent Volcanic Activity Report from the GVP indicates the continuation of steam emissions, ash plumes rising 6 to 10 km above the summit, the ejection of incandescent blocks from the crater and ashfall reported to the west and southwest of the volcano (Kuhn-Sennert, 2010).

4.2.1.3. Hazards

The study of historical activity at the current Tungurahua III edifice can provide an indication of likely future eruptive behaviour. For clarity, a summary of the discursive history provided in the previous section is chronicled in tabular form in Appendix 2. Past activity has predominantly been characterised by emissions of lava, pyroclastic flows and air-fall tephra. Secondary hazards include lahars, caused by the re-mobilisation of ash and tephra deposits on the volcano's steep slopes by frequent heavy rainfall. Lava flows, pyroclastic flows and lahars are generally hazards proximal to the volcano and are confined by several deep gorges and valleys that radiate from the summit cone. These include the valleys of the Puela, Vascún and Ulba rivers. The Río Vascún flows through a steep sided gorge on the northern flanks of the volcano, bisecting the western edge of the town of Baños, and flows into the Pastaza River upstream from the Agoyan Hydroelectric Dam. The Pastaza river valley has long been the main communication route between the inter-Andean valley and the Amazon basin (Le Pennec *et al.*, 2006a), but has been rendered impassable for extended periods following major eruptions (Hall *et al.*, 1999). The main Ambato to Baños road circles the northwest base of the volcano and is frequently inundated by lahars. Many small to medium size villages and towns more distal to the volcano have been affected by airfall tephra and ashfall. The predominant wind direction carries the majority of this to the west and southwest of the volcano (Whiteford *et al.*, 2002).

Additional hazards include intermittent small volcanic tremor and explosions from the summit crater. The latter hazard represents a risk only to anyone venturing to the summit crater, as large rock fragments ejected from the volcano typically fall close to this area. In recognition of this, the upper flanks and summit region of the volcano have been closed to public access since the current period of activity commenced in 1999. Earthquakes associated with volcanism occur at or near volcanoes, generally within 10 km, and often precede increased volcanic activity (McNutt, 2000), as occurred prior to the current eruptive phase at Tungurahua. Volcanic seismicity has continued throughout this period, often associated with audible explosions from the summit crater, but has generally been at relatively low magnitudes, and has been insufficient to cause direct damage to buildings or infrastructure (Siebert & Simkin, 2002-). It has been suggested that edifice stability at Tungurahua may presage a major flank collapse as a direct result of seismic activity (Jaya *et al.*, 2006), and this is discussed further in relation to the debris avalanche hazard.

Lava flows have commonly occurred during eruptive phases at Tungurahua. Deposits indicate that most have originated from the summit crater and are characterised by thicknesses of 10 to 25m and maximum lengths of about 5 to 7 km (Le Pennec *et al.*, 2006a). However, during the constructional phase of the current edifice, large lava flows issued from a lateral vent on the northern flank, flowing 25 km along the Pastaza River, and it is on this lava bench that the town of Baños is constructed (Hall *et al.*, 1999; Le Pennec *et al.*, 2006a). Current hazard assessments indicate that lava flows are most likely to travel down the northern and western flanks, and will generally be confined within local river valleys. Hall *et al.* (1999) suggests that lava flows do not represent a major hazard to populations living at the foot of the volcano due to the relatively high viscosity of magmas limiting the velocity potential of any lava flows generated from the summit crater.

As indicated by the exploration of past volcanic activity detailed above, pyroclastic flow forming eruptions are a common feature of volcanic activity at Tungurahua. Work by Le Pennec *et al.* (2008) suggests the eruption recurrence rate for pyroclastic flow-forming events is one every one hundred years since the 13th century. The town of Baños and several villages on the northern and western flanks would be directly threatened, with the Ulba and Vazcún valleys descending towards Baños and the Agoyan dam most at risk (Hall *et al.*, 1999). Flow simulations quoted in Le Pennec *et al.* (2006a) suggest that due to the steep topography of the northern flank, a pyroclastic flow could attain speeds of up to 100 km/hr and would reach Baños in less than 5 minutes. The climate of the region frequently renders the summit region obscured by clouds, preventing warnings being issued should a pyroclastic flow be generated. During the current eruptive episode, pyroclastic flows were not generated until the period of increased activity in 2006 when several small, relatively slow moving (40 km/hr) flows travelled down the north, northwest and western flanks (Siebert & Simkin, 2002-).

Hall *et al.* (1999) states that along with pyroclastic flows, lahars represent the greatest hazard at Tungurahua and remain so long after an eruption has ceased. Lahars originating on the volcano may be generated by torrential rains, particularly during the rainy season in October/November, debris avalanches or earthquakes (Sorensen & Jaya, 2003). The humid, sub-tropical climate of the region can generate significant rainfall, e.g. >100mm in a 24 hour period (Sorensen *et al.*, 2003), sufficient to remobilise loose pyroclastic material from the slopes of the volcano. Frequent small lahars have been generated during the ongoing eruption, and between November 1999 and March 2002, 59 lahars were recorded in drainages around the volcano (*ibid*).

Figure 4.3 Photograph of a lahar channel in the La Pampa sector of Tungurahua to the north of the volcano, showing an active, steep sided erosion channel (photograph authors own, 2006).

These have principally occurred on the western and north-western flanks and also in the Vazcún gorge. The highway between Baños and Riobamba has been covered by lahars on several occasions, disrupting one of the major economic routes between the Ecuadorian Andes and the Amazon region. Livestock has been killed and several vehicles were trapped in mudflows prior to the installation of a number of Acoustic Flow Monitoring (AFM) devices by the IGEPN, which allowed warning alerts to be issued to the La Pampa area (at the confluence of the Pastaza, Patate and Chambo Rivers) and Vazcún valley (Le Pennec *et al.*, 2006a).

Since the start of eruptive activity, a number of channels have been dug at various locations around the foot of the volcano. These allow lahars to be redirected either under roads which have been elevated above the river channels (Figure 4.3) or into ponding areas, which capture lahar runoff. Particularly at risk in the Vazcún gorge is the El Salado hot springs spa, situated on the banks of the Vazcún river in the eastern suburbs of Baños. During heavy rainfall in February 2005, recent ashfall deposits on the steep upper slopes of the volcano were remobilised. The resulting lahar was channelled down the narrow Vazcún valley, travelling its 10 km length before spilling into the Pastaza River. The El Salado Baths came within centimetres of being inundated by this relatively small lahar, whilst boulders measuring more than 1m in diameter were deposited against the supports of the main bridge of the Baños highway (Williams *et al.*, 2008). The AFM system installed in the Vazcún valley detected the approaching lahar, allowing sufficient time for the baths to be evacuated. However, during late August 2008, heavy rainfall and the subsequent rupture of a natural dam that had formed across the Vazcún Valley resulted in a flood containing volcaniclastic material. The flood water reached the El Salado Baths within 5 minutes of breaching the dam, and destroyed most of the buildings and a retaining wall (Figure 4.4). Travelling on, the flood overtopped the Baños-Penipe highway bridge, and destroyed two homes in the Las Ilusiones district of Baños where two people were reported injured, whilst two children were reported missing and subsequently presumed killed

(i) Photograph authors own (2006).

(ii) Photograph courtesy of IGEPN (2008).

Figure 4.4 Two photographs showing the El Salado Baths, a hot springs bathing complex situated on the western edge of Banos in the Vazcun Valley. (i) The baths in use, January 2006, (ii) The baths following their destruction during August 2008 from a volcaniclastic loaded flood.

(Siebert & Simkin, 2002-). Much larger lahars and debris flows have been generate at Tungurahua when drainage areas have been blocked by debris avalanches causing lakes to form. Even a small volume collapse (<1 km^3) could fill the narrow Chambo valley to the northwest of the volcano, damming it, creating the possibility of a lake-breakout debris flow of significant proportions. Deposits up to 120m thick are observed at the confluence of the Pastaza and Topo rivers, 30km downstream from Baños, emphasising the catastrophic nature of such a laharic event, which occurred following the 3,000 year BP sector collapse (Hall *et al.*, 1999).

There have been two major sector collapses associated with the destruction of Tungurahua I and II, the most recent occurring 3,000 years BP. The largest event, during the collapse of the original edifice occurred 30,000 years ago and produced a massive debris avalanche, filling the Chambo river valley with up to 300m of volcanic debris and breccias. Smaller scale events have occurred more frequently during the last 2,000 years. During the AD 1640 eruption, the north-western part of the summit cone collapsed generating a debris flow that blocked the Patate river valley, forming a lake measuring 6 km in length. The dam was subsequently breached creating a lake-breakout debris flow (Le Pennec *et al.*, 2006a). Work by Jaya *et al.* (2006) suggests that the current Tungurahua III edifice has a high probability of flank collapse in the event of significant localised seismic activity or the intrusion of a cryptodome within the volcano. The occurrence of such a collapse event represents a significant threat to inhabitant around the volcano (Hall *et al.*, 1999; Jaya *et al.*, 2006; Le Pennec *et al.*, 2006a).

Tungurahua is considered a moderate tephra producer and deposits from past eruptions are generally characterised by a limited distribution. At distances of between 10 to 15 km from the crater, maximum deposit thicknesses of 30cm have been associated with major eruptions, whilst smaller events rarely exceed 5cm at similar distances (Hall *et al.*, 1999). However, relatively small volumes of ash can be sufficient to severely impact the local population and agricultural activities, as occurred during the 2001 strombolian phase of the current eruptive episode, where compacted ash deposits ranged in thickness from just 1 to 2cm to the west of the volcano (Le Pennec *et al.*, 2002). The continuation of intermittent activity over the past decade, although failing to produce the initially predicted catastrophic eruption that prompted the original evacuation in 1999, has resulted in a more pervasive problem with the periodic deposition of ashfall over a wide area, mainly to the west of the volcano. It has been estimated that between October 1999 and December 2004, the total accumulation of ash 4 km downwind of the crater measured 30 to 40cm in thickness (Le Pennec *et al.*, 2006a). Long term health impacts and the curtailment of economic activity have resulted for the many small agricultural communities and peasant farmers in the region due to this ongoing hazard (Tobin & Whiteford, 2002a; 2002b; Lane *et al.*, 2003).

The case study sites selected for this research are potentially at risk from a number of the volcanic hazards originating on Volcán Tungurahua. These are discussed in further detailed below, and include the current hazard maps produced for the area.

4.2.2. Population, Infrastructure and Potential Hazards in Baños

With a population of around 16,000 but often swelled by the large number of tourist visitors, and situated just 8 km and 1,800m below the summit crater, Baños is the largest town in close proximity to the volcano. Along with several small villages located on the western and northern flanks of the volcano, the town is directly threatened by pyroclastic flows and lahars (Hall *et al.*, 1999) and frequently experiences minor ashfall. Communication lines through the town are frequently threatened by lahars inundating the single highway providing access to the wider region. Economically, the town is dependent on tourism, and to a lesser degree agricultural production. The service industry based in hotels, restaurants and tour operators provides many employment opportunities, and although these were severely disrupted following the period of enforced evacuation in 1999, the glowing volcanic crater and ash cloud have since become a tourist draw in themselves.

4.2.2.1. Earthquakes

A minor hazard associated with volcanism in the region comes from the frequent but low magnitude earthquakes (<4.0 on the Richter scale), and explosions. Explosions have occurred with varying frequency throughout the current eruptive phase beginning in 1999. The IGEPN has reported 10s of explosions per day during particularly active periods. Associated with the ejection of blocks of rock and ash from the summit crater, these are generally deposited onto the upper flanks of the volcano. The explosions are often heard by resident in Baños and the surrounding villages, and have been reported to have shook buildings and rattled windows at the OVT in Guadalupe village, situated in the Pastaza River Valley approximately 11km to the northwest of the crater. During especially intense activity in 2006, particularly large explosions were heard up to 40km away, and in settlements near the volcano's foot, glass windows shattered (Siebert & Simkin, 2002-). Earthquakes associated with volcanism at Tungurahua are equally frequent, with 100s of event recorded each month. Different types of seismicity have been recorded and are associated with the emission of steam, gas and ash from the volcano, or the movement of magma within the volcano. Although large earthquakes have occurred in the region, most notable the 1949 Ambato earthquake, which measured 6.8 on the Richter scale and killed 6,000 people and injuring a further 20,000, earthquakes directly related to volcanism are generally very much smaller in scale. One of the most notable events of recent years was recorded on the 12th January 2008, and measured 3.7 on the Richter scale, and was reported by residents of Baños (Instituto Geofisico, 2004-). Although alarming, such earthquakes would be insufficient to cause any significant damage to local property (McNutt, 2000).

4.2.2.2. Lava Flows

Hall et al. (1999; 2002) and (Sorensen *et al.*, 2003) have produced comprehensive hazard maps indicating the likely inundation zones for the most serious volcanic products. Lava flow inundation zones in Hall *et al.* (1999) are indicated for the length of the Vazcún Valley, the Ulba Valley, and subsequently feeding into the Pastaza River and additionally for the upper reaches of a single river valley on the eastern flank (Figure 4.5 – area 5 on map). The IGEPN hazard map (Hall *et al.*, 2002) more clearly defines the river valleys as high hazard zones, and also indicates historical lava flows concentrated on the west and north-western flanks (Figure 4.6). Lava flows would need to be of sufficient volume and viscosity to travel down the Vazcún Valley an estimated 9 km from the crater to reach the western edge of Baños. Lava flows during historical times have largely been confined to within 5 to 7 km of the summit and are generally more viscose in nature, and therefore do not represent a significant threat to people living at the foot of the volcano (Hall *et al.*, 1999). Evidence does exist in the geological record, during the more violent activity associated with the constructional phase of the current edifice, that much larger lava flows have occurred. This included issues from lateral vents on the northern flank above the current location of Baños (Le Pennec *et al.*, 2006a). Given the likely precursory activity to such a large eruption, residents would most likely have been evacuated prior to any inundation of the town from lava flows. However, the discovery in late 2000 of new fumaroles at an altitude of 4,400m on the northwest flank in the main drainage above Baños, suggests some topographic movement along fractures in this area. Associated bulging of the north flank was also recorded. These fumaroles have been observed emitting plumes of gas and steam continuously since this time (Siebert & Simkin, 2002-; Instituto Geofisico, 2004-), and indicates there remains the potential for lateral flank vents issuing lava in closer proximity to the town than that associated with central vent lava flows.

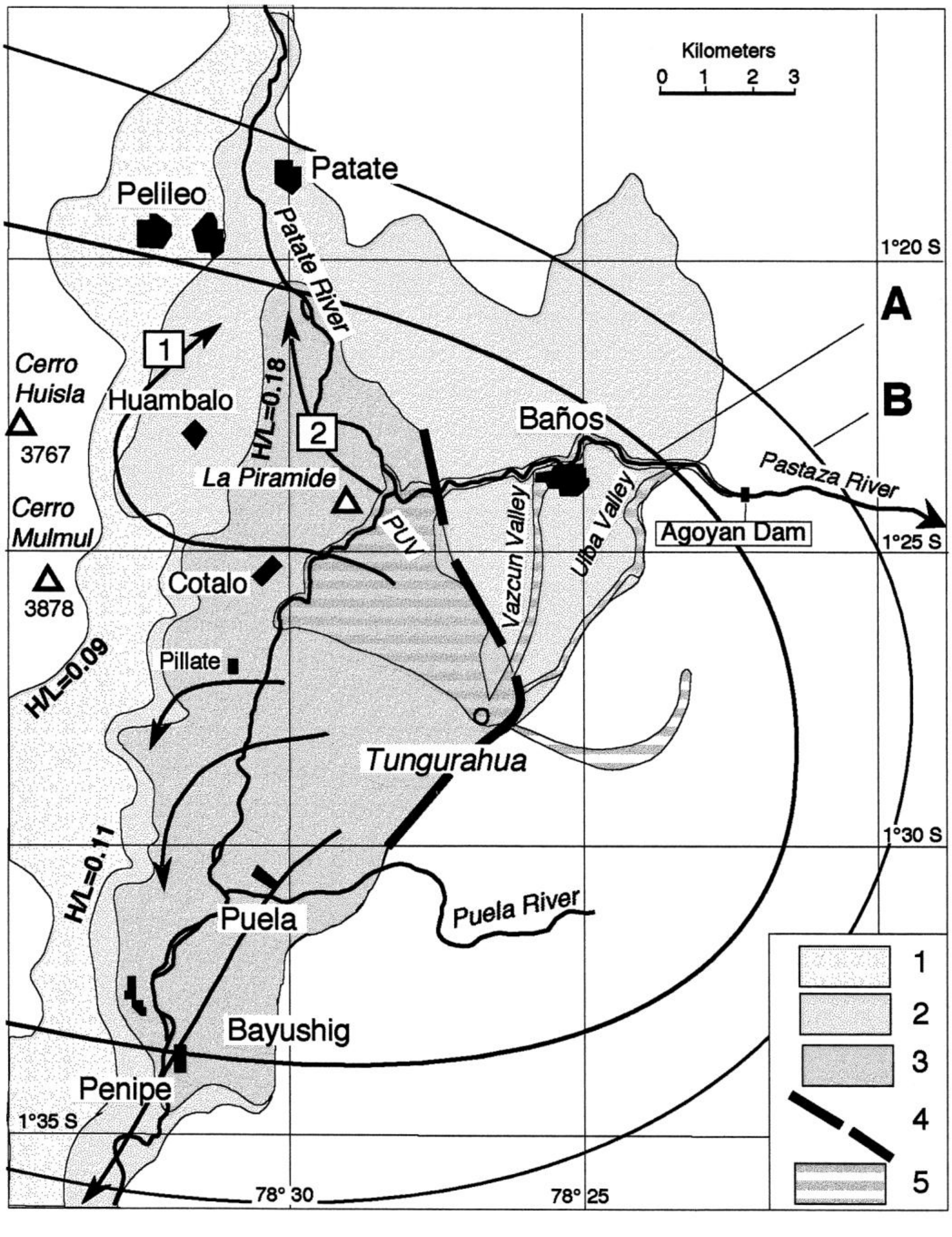


Figure 4.5 Hazard map for lava flows, ashfall deposits and sector collapse events at Tungurahua volcano (Hall *et al.*, 1999).

Key: 1 = distribution of hypothetical large volume debris avalanche, worse case event (> 10 km^3), 2 = distribution of hypothetical debris avalanche similar to 3000 year BP event (estimate 5 km^3), 3 = distribution of hypothetical small volume avalanche (1-3 km^3), 4 = caldera limits which would control the distribution of small to medium size avalanches in future events, 5 = most probable paths of future lava flows. Expected ash distributions: A < 10 cm; B < 5 cm (ibid).

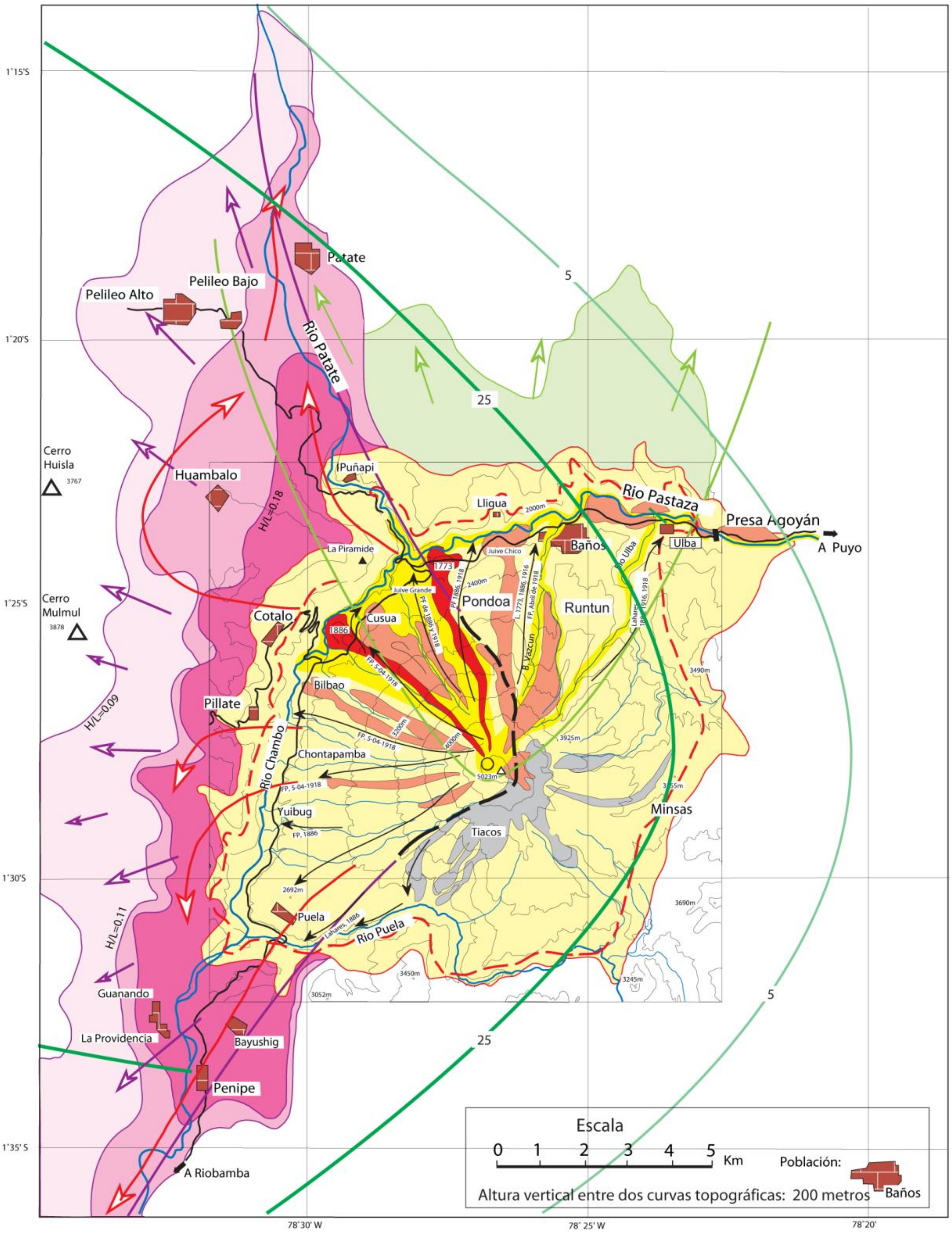


Figure 4.6 Map of the potential hazards associated with future eruptions of Tungurahua volcano (Hall *et al.*, 2002).

Key to Figure 4.6:

🟨	*Lava flow hazard zone – confined within valleys to the north and northwest, due to current crater shape.*
◪ ↗ L.1773,	*Lava flow hazard zone – creeks and river valleys on the north and west flanks. Yellow areas indicate likely areas of inundation. Black arrows indicate path of mudflows during eruptions of 1773, 1886, 1916-1918 and 1999-2000.*
↗ FP.1918,	*Pyroclastic flow hazard zone – red dashed line indicates area at highest risk from pyroclastic flows and surges, the latter of which can pass over topographic relief. Shape of current crater likely to focus future flows towards northwest. Black arrows indicate areas inundated during historical eruptions.*
🟥	*Pyroclastic flow and lateral blast hazard zone – low risk area.*
25 5	*Ash and pumice fall hazard zone – (1) high risk area; possible accumulation >25cm, (2) intermediate risk; possible accumulation between 5 and 25 cm, (3) low risk; possible accumulation <5 cm.*
🟪	*Debris avalanche hazard zone - possible western extent of small volume debris avalanche (≤1 km³).*
🟪	*Debris avalanche hazard zone – possible western extent of large volume debris avalanche (~5km³), e.g. 3000 year BP event.*
↗	*Arrow indicates direction of debris avalanche which occurred 3000 years ago.*
🟪	*Debris avalanche hazard zone – possible western extent of very large volume debris avalanche (≥ 10 km³).*
← ←	*Direction of lateral blast in relation to collapse of west flank.*
🟩	*Northern extent of debris avalanche that accompanied western flank collapse 3000 years ago. Green arrows indicate area that would be affected by any associated lateral blast.*
1886	*Historical extent of lava flows during 1773 and 1886 eruptions.*
🟧	*Lava flows prior to sixteenth century, majority of which produced between 1400 and 2200 years BP.*
▬ ▬	*Caldera scar from 3000 year BP collapse.*
⬜	*Exposed lava flows from construction of current cone.*

4.2.2.3. Debris Avalanche

Sector collapse and associated debris avalanches are rare events at Tungurahua but the geological records indicate they have occurred at least twice, most recently associated with the collapse of Tungurahua II ~3,000 years BP, the extent of which is shown in Figures 4.5 and 4.6. Historically, smaller debris avalanches have occurred within the last 400 years during the 1640 eruption, and resulted from the collapse of the crater rim. Jaya *et al.* (2006) suggests there are two scenarios which could precipitate a flank collapse in the future, the intrusion of magma within the volcano and an earthquake induced collapse. The former situation would most likely provide sufficient warning from precursory activity to allow evacuation, whilst the later could occur without warning. The map produced by Hall *et al.* (1999) shows the likely distribution of three different sized debris avalanches (Figure 4.5). These are; (1) a very large volume avalanche more typically associated with a massive flank collapse (>8 km^3); (2) a large volume avalanche, similar in size to the 3,000 years BP event (~5 km^3); (3) a small volume avalanche (<1 km^3). Hall *et al.* (1999) suggests the conditions of the current cone favour a future collapse generating an avalanche 1 to 3 km^3 volume with a distribution similar to that shown in Case 3. The prominent caldera scar, a remnant of Tungurahua II, would in this instance protect Baños, directing the avalanche to the west. The recurrence interval of this phenomena at Tungurahua is measured in thousands of years (Hall *et al.*, 2002). Figure 4.6 shows more clearly the same three zone extent for debris avalanche hazard at the volcano, as well as the extent of deposits from the 3000 year event.

4.2.2.4. Pyroclastic Flows and Lahars

Historical eruptions and the current period of activity suggest that pyroclastic flows and particularly lahars are common hazards associated with volcanism at Tungurahua. Pyroclastic flows and surges, which can ascend over topographic features and may be caused by the collapse of the eruptive column, could impact any sector of the volcano's flanks (Figure 4.7). Both pyroclastic flows and lahars directly threaten Baños and several villages located on the western and northern flanks of the volcano. The risk from pyroclastic flow and debris flow hazards are particularly high in the valleys that head on the volcano, especially for the Vazcún and Ulba valleys, which descend towards Baños and the Agoyan dam (Figure 4.6). During both current activity and recent historical activity, lahars and pyroclastic flows have descended the Vazcún valley towards Baños (lahars during the 1886 and 1916 eruptions, and pyroclastic flows during 1918) (Hall *et al.*, 2002). The IGEPN map (Hall *et al.*, 2002), also indicates that sufficiently mobile lahars could inundate areas up to 80km downstream of the volcano along the Pastaza River, placing these regions in the high risk 'yellow zone'.

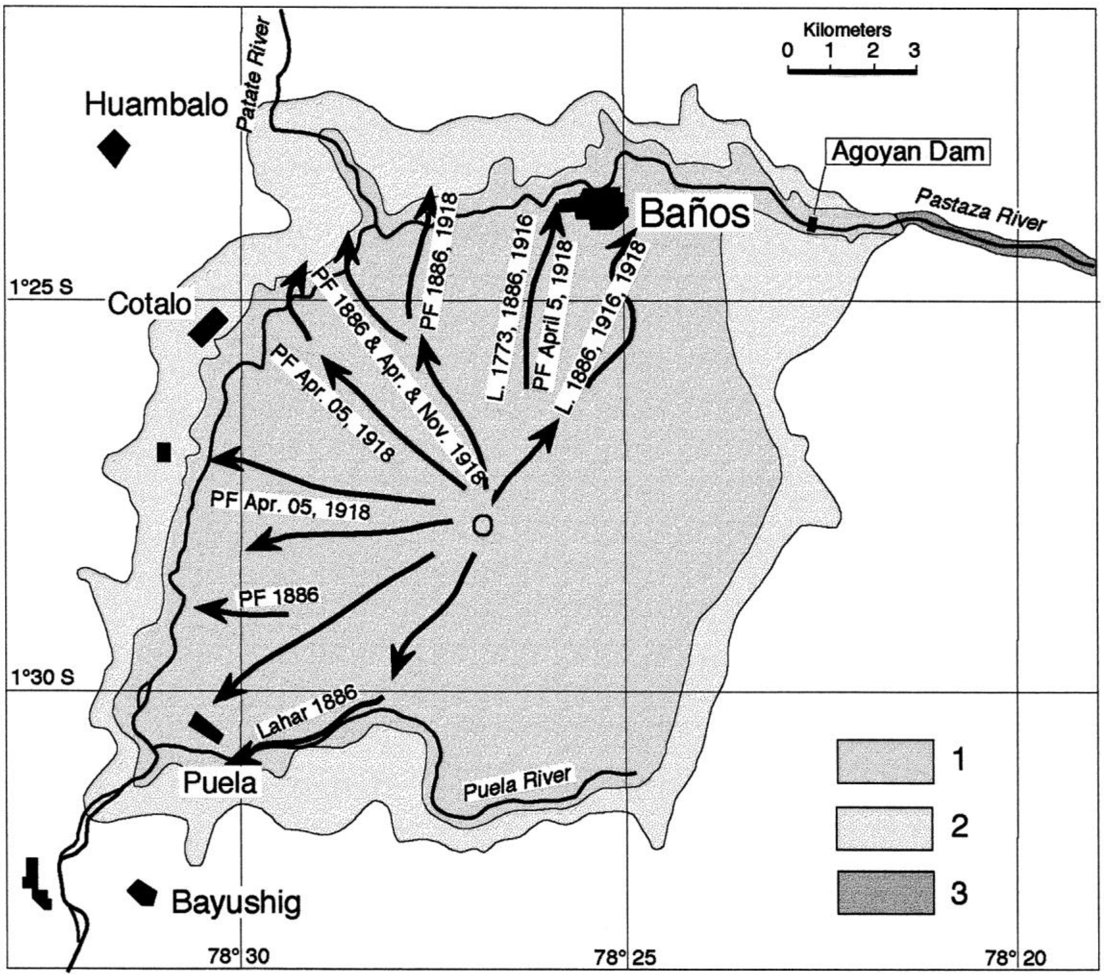


Figure 4.7 Hazard map for pyroclastic flows and lahars, showing main routes followed by historic flows (PF = pyroclastic flows). (1) High hazard for laterally direct blast and column collapse pyroclastic flows over whole area, and lahars in valleys, (2) Minor hazard area for pyroclastic flows, (3) High hazard for lahars in lower Pastaza valley (Hall *et al.*, 1999).

Baños' location, elevated above the valley floor, places it in the slightly less hazardous 'red zone' (Figure 4.6). The greatest risk to Baños residents would be if they were unable to evacuate should lahars or pyroclastic flows destroyed the bridges carrying the Ambato-Puyo highway across the Vazcún and Ulba rivers, the only means of escape from the most endangered areas.

Further work by Sorensen & Jaya (2003) established two hazard zones using Digital Elevation Models (DEMs) of Tungurahua volcano and the surrounding area; (i) the proximal and (ii) the lahar hazard zones (Figure 4.8). The proximal hazard zone is subject to slope failures, debris avalanches and lahars. Debris avalanches, lahars and pyroclastic flows that originate in the proximal zone are likely to travel further downstream beyond the limits of this zone. The lahar hazard zone has been subdivided into three divisions based on a series of hypothetical lahar volumes. These are 1×10^6 m^3, 4×10^6 m^3 and 16×10^6 m^3. As would be expected, smaller low impact lahars are likely to occur more frequently than larger high impact events. Baños is placed in the proximal hazard zone, and its western and northern edges would be inundated to a lesser or greater extent by intermediate (4 x 106 m^3) and larger (16 x 106 m^3) lahars. The more frequent smaller (1×10^6 m^3) lahars would generally be confined to the Vascún River valley before flowing into the steep sided Pastaza River up to 80m below the town (*ibid*).

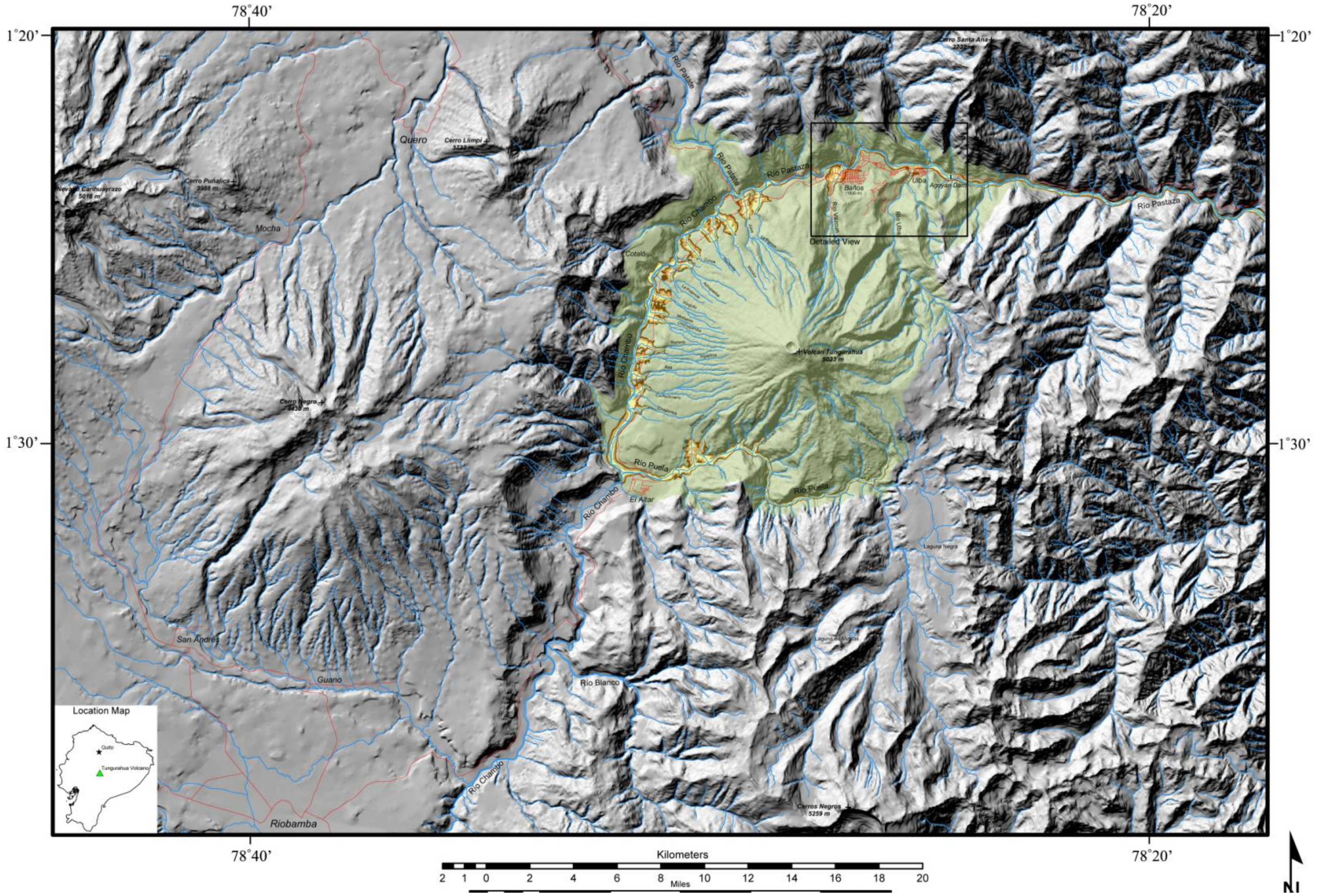
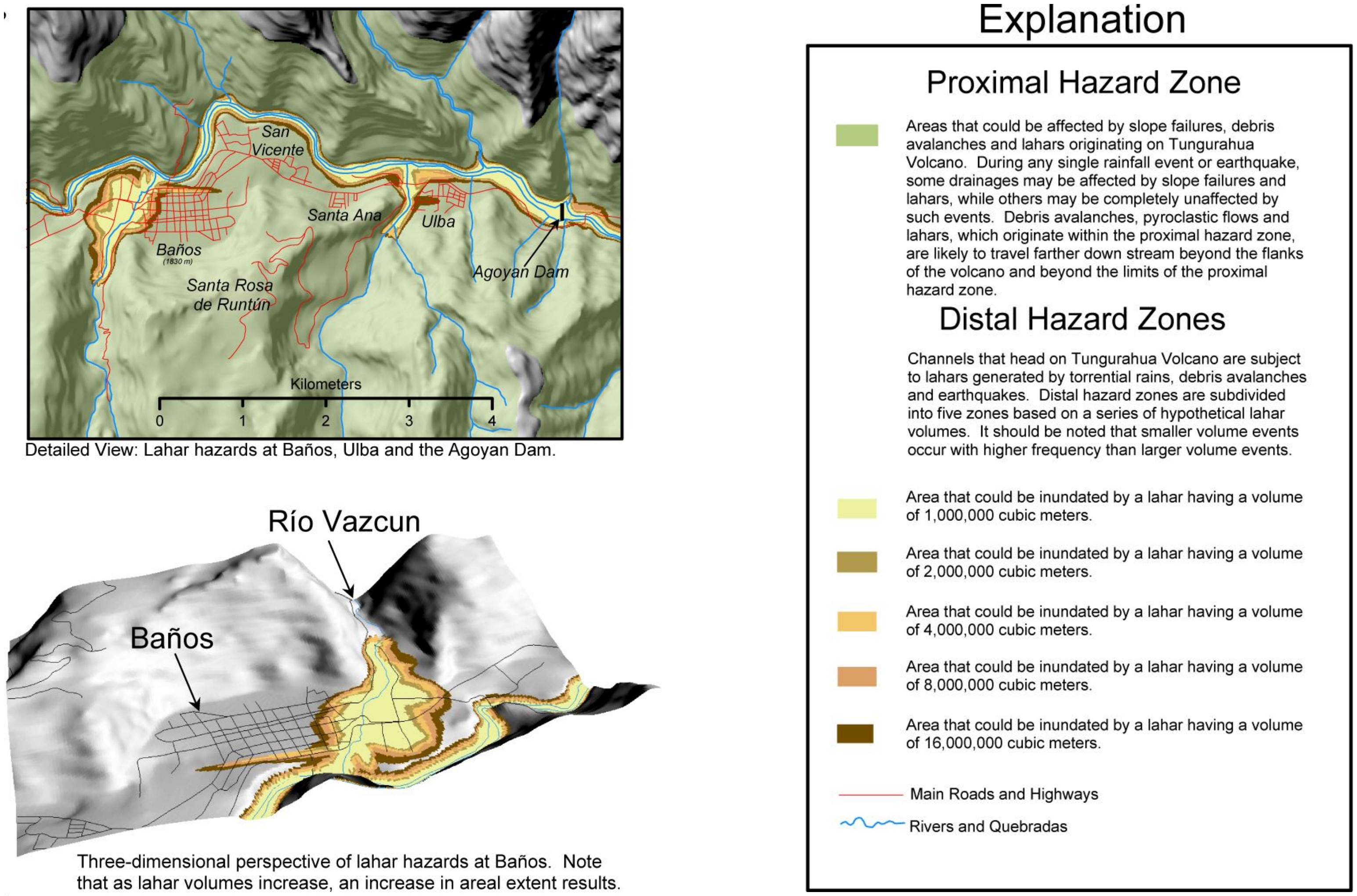


Figure 4.8 Lahar hazard zonation map, Volcán Tungurahua, Ecuador (Sorensen & Jaya, 2003), for key see following page.



Detailed View: Lahar hazards at Baños, Ulba and the Agoyan Dam.

Three-dimensional perspective of lahar hazards at Baños. Note that as lahar volumes increase, an increase in areal extent results.

Explanation

Proximal Hazard Zone

🟩 Areas that could be affected by slope failures, debris avalanches and lahars originating on Tungurahua Volcano. During any single rainfall event or earthquake, some drainages may be affected by slope failures and lahars, while others may be completely unaffected by such events. Debris avalanches, pyroclastic flows and lahars, which originate within the proximal hazard zone, are likely to travel farther down stream beyond the flanks of the volcano and beyond the limits of the proximal hazard zone.

Distal Hazard Zones

Channels that head on Tungurahua Volcano are subject to lahars generated by torrential rains, debris avalanches and earthquakes. Distal hazard zones are subdivided into five zones based on a series of hypothetical lahar volumes. It should be noted that smaller volume events occur with higher frequency than larger volume events.

🟨 Area that could be inundated by a lahar having a volume of 1,000,000 cubic meters.

🟫 Area that could be inundated by a lahar having a volume of 2,000,000 cubic meters.

🟨 Area that could be inundated by a lahar having a volume of 4,000,000 cubic meters.

🟧 Area that could be inundated by a lahar having a volume of 8,000,000 cubic meters.

🟫 Area that could be inundated by a lahar having a volume of 16,000,000 cubic meters.

— Main Roads and Highways

〰 Rivers and Quebradas

Figure 4.8 cont…/ Detail from lahar hazard zonation map showing Baños and the Vazcun valley, with explanatory key (from Sorensen & Jaya, 2003).

4.2.2.5. Ashfall

The monthly activity reports provided by the GVP website (Siebert & Simkin, 2002-), indicate that at times during the current eruptive episode, ashfall has been reported as affecting towns up to 100 km to the west of the volcano. These same reports indicate numerous instances of ashfall in Baños, and during the period of increased activity in August 2006, ash deposits > 1 mm were reported in the town (*ibid*). The current hazard map (Figure 4.6) places Baños in zone 1, an area that "*…would be affected by falling ash and tephra. The thickness of deposits that might be expected are greater than 25 cm*" (Hall *et al.*, 2002). This is predominately due to the towns proximity to the summit crater. However, during the current eruptive period, ash fall in Baños, although frequent, has been measured in millimetres and the prevailing wind direction generally carries ash plumes towards the west, and it is here that the most significant ashfall has been experienced.

4.2.3. Population, Infrastructure and Possible Hazards in Riobamba

Forming the capital city of the Chimborazo Province and the main urban centre of the Riobamba Canton, the city of Riobamba is located approximately 190km south of Quito. Situated at an elevation of 2,754 m, the city is surrounded by volcanoes. Chimborazo dominates the skyline to the northwest, whilst the nine jagged peaks of El Altar can be seen to the east and the smoking summit of Tungurahua is visible to the northeast. One of the largest cities of the Sierra region (and the 10th largest in the country), Riobamba's population at the last census was 124,807, and the city has one of the highest urban concentrations of indigenous people (INEC, 2001). These mainly Quechua speaking communities contribute to the local economy through the sale of textiles, handicrafts and leather goods at the city's large artisan market. The other main economic activity is focused on agricultural production in the surrounding countryside, whilst the city is also an important trading centre for cattle-ranching.

Riobamba moved to its current location after the original city was destroyed by an earthquake in 1797. The most destructive historical earthquake in Ecuador, with an estimated magnitude of 7.6, was associated with a fault rupture (Beauval *et al.*, 2010) rather than volcanic activity, although crater explosions at Tungurahua coincided with the earthquake (Hall *et al.*, 1999). Relocated 20 km to the northeast, the modern city is characterised by historical buildings, wide avenues and cobblestone streets. There are several theatres, museums, cinemas, the town hall and provincial government buildings, a cathedral, churches, police station, fire service, several hospitals and clinics, a number of schools and two universities, as well as numerous banks, hotels, restaurants and stores. The city forms an important stop on the main Pan-American highway between Quito and major southern cities such as Guayaquil and Cuenca. An intermittent train service also runs from the city, north to Ambato and south to Guayaquil, as well as the tourist Nariz del Diablo (Devil's Nose) route. To the northwest of the city is a small airfield.

4.2.3.1. Ashfall

The city is located approximately 32 km to the southwest of Volcan Tungurahua. Due to this distance, and because the rivers that head on the mountain drain into the Amazon basin to the east, Riobamba is at risk from a single hazard originating from an eruption of the volcano. Ashfall is mainly dispersed by the prevailing winds towards the west and southwest, and during the current eruptive period has frequently been recorded in the city of Riobamba (Hall *et al.*, 1999). Current satellite imagery from Google Earth clearly shows an ash plume extending approximately 40 km from the volcano's summit reaching the city of Riobamba and beyond (Figure 4.9). However, it is difficult to determine the geological or historical extent of ashfall across the region as studies have not been conducted at any distance from the volcano. Ongoing reports from IGEPN, issued via the GVP monthly bulletins (Siebert & Simkin, 2002-), indicate the extent of ashfall in Riobamba for the current eruptive phase, beginning in 1999.

Figure 4.9 Satellite image of ash plume from Tungurahua covering the city of Riobamba (bottom left of image) over 30 km to the southwest (Image courtesy of Google Earth, 2005).

During both November and December of 1999, ash columns rose above the volcano and moved southwest, with ashfall deposited across Riobamba. In February of the following year ash deposits were sufficient to close the airports at both Ambato and Riobamba. Almost continuous gas and ash emissions during September 2001 caused ash plumes reaching between 0.6 and 2 km above the volcano, which drifted northwest to southwest, with ashfall reported in the city. Further ashfall was reported in September 2002, associated with strong explosions and ash emissions. The following June, Strombolian activity caused ash plumes that reached to an altitude of 2 km and ash accumulations of <1mm fell in Riobamba. Similar deposits where recorded in August 2003 and January 2004. The most significant ashfall was associated with the major volcanic activity that occurred in July 2006. During this event, five people were reported dead, two missing, thousands were evacuated from their homes, and ashfall caused damage to extensive areas of cultivated land. The eruptive column reached a maximum height of between 15 and 16 km during the eruption of 16th and 17th July (*ibid*). Tephra falls containing ash and scoria fragments affected the city of Riobamba and deposits of >30mm closed the local airport (Guffanti *et al.*, 2007). Activity decreased until 2008, since which time almost continuous steam and ash plumes have been generated to heights of up to 8 to 9 km, with light ashfall of <1 mm reported repeatedly in Riobamba (Siebert & Simkin, 2002-).

Figure 4.10 Photograph of Tungurahua viewed from the Pan-American highway between Ambato and Latacunga looking southeast, showing the eruption plume carried to the west (photograph authors own, Jan 2006).

Published hazard maps are restricted to the immediate area surrounding the volcano, excluding more distal communities such as Riobamba. However, using the Hall *et al.* (2002) map (Figure 4.6) and extrapolating the isopachs beyond the map boundaries suggests that Riobamba may fall within the intermediate risk zone; possible accumulation of ash and pumice of between 5 to 25 cm.

4.2.4. Threat Assessment Results and Discussion

Utilising the comprehensive review detailed in the previous sections, which provides a discursive assessment of Tungurahua volcanism, the eruptive history of the volcano (including the most recent activity), the potential hazards and a consideration of the population and infrastructure at risk from specific hazards in two communities, the threat assessment procedure developed using the methodology modified from Ewert was completed for the cities of Baños and Riobamba. Using this system, three separate scores can be calculated for; (i) hazards, (ii) exposure and (iii) overall threat. These scores are calculated according to the metric detailed in Chapter 3. The maximum score possible for hazard factors is 14, whilst the maximum score for exposure factors is 4, plus the $\log_{10}$ of the population of the community under assessment. The overall threat assessment score is derived by multiplying the hazard and exposure factors. The completed assessment metric for each community is provided in Table 4.1 for Baños and Table 4.2 for Riobamba, and discussed below.

4.2.4.1. Threat Assessment of Baños

The total hazard factor score for Baños is 9 out of a possible 14. Three hazard types contribute equally; most notably lahars, pyroclastic flows and ashfall, each rating 2 out of a maximum score of 3. This is largely due to the city's proximity to the volcano, and location relative to the Vazcún river valley. Although only 8 km north of the summit crater, the city is protected to some extent from the worst volcanic products because of the surrounding topography. Small to medium pyroclastic flows and lahars would be channelled around Baños via the Vazcún and Pastaza valley's, the latter flowing through a gorge some 80m below the city. Similarly, its location to the north of the volcano, spares it from the worst of the ashfall, due to the predominant wind direction carrying most ashfall to the west/southwest.

Two further hazards represent a lesser threat to the city, each scoring 1 of a possible 2. There is a small risk from particularly large debris avalanches, but this poses a lesser threat because debris avalanches of sufficient volume necessary to inundate the town have been rare events in the geological history of the volcano, the location of the caldera scar on the flanks of the volcano would direct avalanches to the west, and the construction of the current edifice lacks sufficient volume to produce an avalanche comparable in volume to the devastating 3000 year BP event (Hall *et al.*, 1999). Lava

Table 4.1 Completed Threat Assessment for Baños.

Hazard Factors	***Score***
Ash/tephra:	max. score = 3
• If located ≤ 100km from volcano: score = 1	1
• If yes to above, located within ashfall Zone 1: score = 1	1
• If located in prevailing wind direction = 1	0
Pyroclastic flows:	max. score = 3
• If located ≤ 10km from summit cone: score = 1	1
• If yes to above; located on or near river valley: score = 1	1
• If located in area associated with geological feature, e.g. deep/steep-sided river valley that protects town: score = 0, if not score = 1	0
Lava flows:	max. score = 2
• If located ≤ 7km from summit cone: score = 1	0
• If located ≤ 7km below north flank (active fumaroles): score = 1	1
Lahars/mudflows:	max. score = 3
• If located on or near river which heads on volcano: score = 1	1
• If yes to above; ≤ 80km downstream from volcano: score = 1	1
• If located in area associated with particular geological feature, e.g. deep/steep-sided river valley protects town: score = 0, if not score = 1	0
Debris avalanche:	max. score = 2
• If located ≤ 30km downstream/slope to the north, northwest or west of the volcano: score = 1	1
• If yes to above, located in area associated with particular geological feature, e.g. caldera scar that provides protection from debris hazard: score = 0, if no such features: score = 1	0
Explosions/Earthquakes:	max. score = 1
• If located ≤ 10km from volcano: score = 1	1
Total of hazard factors (max. score = 14)	**9**
Exposure Factors	
Log_{10} of city population:	
• Derived from census data (total population of town/city)	4.02
Local aviation exposure:	max. score = 1
• If there is a jet-service airport within 10km of the city: score = 1, if none: score = 0	0
Power infrastructure:	max. score = 1
• Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	1
Transportation infrastructure:	max. score = 1
• Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	1
Major development or sensitive area:	max. score = 1
• Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	0
Total of exposure factors (max. score 4 + log^{10} of population)	**6.02**
Sum of hazard factors x sum of exposure factors	**54.18**

flows at Tungurahua are typically produced from the summit vent, are of high viscosity and unlikely to reach Baños. However, geological deposits and recently discovered active fumaroles provide evidence for previous flank extrusions above Baños, and although lava may be sufficiently viscose to allow people to evacuate, buildings, infrastructure and agricultural land would be affected. The earthquake hazard is also rated one, due to the towns proximity to the volcano. This represents a minimal threat (hence its weighting of only one hazard factor question), as volcanically induced seismicity is generally low magnitude, and likely to result in only minor damage.

The total exposure score of 6.02 reflects the intermediate population of the town, sighting of nationally important transportation links, and the location of the hydroelectric Agoyan dam. The route through Baños provides one of the only communication links between the Andean highland area of Ecuador (including the capital Quito) and the Amazon basin to the east. The Agoyan hydroelectric dam was scored on the power infrastructure factor (electricity generation), but not on the sensitive development category. If Baños had been located downriver of the dam, it would be appropriate to score on both elements. Whilst inundation by a lahar, or damage due to an earthquake could disrupt electrical power supply to the town, the release of water held behind the dam would represent a significant additional threat only to communities situated downstream.

The total threat assessment score for Baños is 54.18. On its own, it is difficult to make any judgements about what this score means. In order to evaluate the relative threat to the city, it is necessary to compare this score with that for the threat assessment of Riobamba.

4.2.4.2. Threat assessment of Riobamba

The completed threat assessment for Riobamba is shown in Table 4.2. A total hazard factor score of 2 is due to the city's exposure to a single hazard from Tungurahua. Located 32 km to the southwest of the volcano, the city is within the identified 100 km

Table 4.2 Completed threat assessment for Riobamba

Hazard Factors	***Score***
Ash/tephra:	max. score = 3
• If located ≤ 100km from volcano: score = 1	1
• If yes to above, located within ashfall Zone 1: score = 1	0
• If located in prevailing wind direction = 1	1
Pyroclastic flows:	max. score = 3
• If located ≤ 10km from summit cone: score = 1	0
• If yes to above; located on or near river valley: score = 1	0
• If located in area associated with geological feature, e.g. deep/steep-sided river valley that protects town: score = 0, if not score = 1	0
Lava flows:	max. score = 2
• If located ≤ 7km from summit cone: score = 1	0
• If located ≤ 7km below north flank (active fumaroles): score = 1	0
Lahars/mudflows:	max. score = 3
• If located on or near river which heads on volcano: score = 1	0
• If yes to above; ≤ 80km downstream from volcano: score = 1	0
• If located in area associated with particular geological feature, e.g. deep/steep-sided river valley protects town: score = 0, if not score = 1	0
Debris avalanche:	max. score = 2
• If located ≤ 30km downstream/slope to the north, northwest or west of the volcano: score = 1	0
• If yes to above, located in area associated with particular geological feature, e.g. caldera scar that provides protection from debris hazard: score = 0, if no such features: score = 1	0
Explosions/Earthquakes:	max. score = 1
• If located ≤ 10km from volcano: score = 1	0
Total of hazard factors (max. score = 14)	**2**
Exposure Factors	
Log$_{10}$ of city population:	
• Derived from census data (total population of town/city)	5.10
Local aviation exposure:	max. score = 1
• If there is a jet-service airport within 10km of the city: score = 1, if none: score = 0	1
Power infrastructure:	max. score = 1
• Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	1
Transportation infrastructure:	max. score = 1
• Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	1
Major development or sensitive area:	max. score = 1
• Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	1
Total of exposure factors (max. score 4 + log^{10} of population)	**8.10**
Sum of hazard factors x sum of exposure factors	**16.20**

ashfall zone and located in the prevailing wind direction. The recent period of volcanic unrest has demonstrated the city's susceptibility to volcanic ashfall, with airport closures and health impacts reported. The city is protected from other hazards due to its distance from the volcano. Well-travelled hazards such as lahars, which could traverse the necessary distance, are carried away from the city, downstream towards the Amazon basin in the east. Riobamba rates highly on the exposure factor element, scoring 8.10. This is due to its large population (124,807), sighting of significant economic development, power infrastructure, major transportation links and its airport. The city provides a hub for the surrounding agricultural communities, with its artisan and cattle-ranching markets. Power generation is located within the city, and as well as supplying Riobamba and the surrounding communities, remote rural settlements also receive their electricity supply via the city. Riobamba is not situated on the Pan-Andean highway, the only route between the north of the country, e.g. the capital Quito and the southern city of Cuenca, but it does score on the transportation element as it provides the terminus for an intermittent train service. A small regional airport, located in the northern suburbs, serves internal flights, including from/to Quito and Guayaquil.

Despite Riobamba's high exposure factor score, its total threat assessment equals just 16.20. At risk from a single volcanic product, its hazard factor score has suppressed its overall threat score.

4.2.4.3. Discussion

The threat assessment scores for the two case study communities are summarised in Table 4.3, and this shows the importance of assessing both the physical hazard and the characteristics of the settlement at risk when determining overall threat. As would be expected, due to its location, size and economic importance, Baños may be said to be over three times more threatened by volcanic activity from Volcan Tungurahua than the city of Riobamba, despite its higher population.

Once the comprehensive review of the volcano has been completed, it would be a fairly simple process to extrapolate the information and apply the threat assessment protocol to other settlements around the volcano. In this way the threat relative to Baños and Riobamba could be measured and the various communities ranked according to their overall threat score. All towns and cities potentially at risk from the volcano could be assessed in this was, allowing a regional picture to be developed. This could provide a method of determining the most important focus for the limited hazard mitigation resources, ensuring they are directed to the most threatened communities. This simplistic approach is particularly well suited to areas where the more extensive data sets required to carry out the calculations used in quantitative risk assessments may be lacking.

Table 4.3 Hazard, exposure and overall threat assessment scores for Baños and Riobamba from volcanic hazards associated with volcanic activity at Tungurahua.

	Hazard Factors	Exposure Factors	Overall Threat Score
Baños	9	6.02	54.18
Riobamba	2	8.10	16.20

Once the initial comprehensive review has been completed, conducting an assessment of any well developed town or community using the threat assessment approach developed here is fairly straightforward. For the smaller settlements in the Pastaza River valley it could be more problematic. Little geophysical research on volcanic deposits in this area have been conducted, although current hazard maps indicate the area may be at risk from lahar inundation. This area is sparsely populated and communities and settlements are dispersed over a wide area, many lacking basic communication with the wider region. Assessing these communities would require significant fieldwork in order to evaluate exposure factors, which could prove prohibitively expensive.

The qualitative assessment used here to explore the threat from volcanic hazards for Baños and Riobamba takes no account of existing mitigation measures, which could act to reduce overall threat. Volcanic activity of sufficient magnitude to effect the two communities surveyed would, in most instances, be preceded by an increase in seismicity, and eruptive behaviour. Given the substantial monitoring system currently in place at the volcano observing the ongoing eruption, changes in behaviour or an increase in activity are expected to provide sufficient warning to the at risk populations, allowing protective action to be taken.

One of the objectives of this research was to develop an approach to volcanic risk assessments that could integrate the evaluation of both geophysical hazards and human vulnerability. This approach provides an intermediate step towards this by considering the exposure factors at each community. To expand this further, it was necessary to consider socio-economic and demographic factors that previous research has indicated as important drivers of vulnerability. The integration of an additional element within the threat assessment metric could be used to assess 'vulnerability factors'. Utilising census data, communities could be scored based on their income, age and/or gender profiles. Firstly, it was important to explore the significance of these factors in determining vulnerability before their inclusion within the assessment tool could be justified on methodological grounds. This was achieved during the second phase of the research using a survey of residents from Baños and the small hamlet of Runtún.

4.3 TUNGURAHUA VULNERABILITY ASSESSMENT

4.3.1. Introduction

The varying levels of risk different individuals or community groups may be exposed to in the event of a volcanic eruption are determined by the proximity and nature of the physical hazards, as well as the social, cultural and economic context within which they live. This underlying social fabric interacts with the potential hazard to create social vulnerability. The characteristics of this social fabric include socio-economic features, perceptions of and experience of risks and hazards, and overall capacity to respond (Cutter *et al.*, 2000). The aim of this phase of the research was to investigate these characteristics, in an attempt to identify those groups who may be at greater risk.

The theoretical underpinnings discussed in Chapter 2 suggest that individuals with certain socio-economic characteristics may incur greater losses during a disaster. Differences in an individual's perceptions of risk, levels of trust, information seeking and preparedness, as well as previous experience, may influence how they respond or behave during a hazardous events. By exploring these psychological qualities and whether they differ between individuals who exhibit different socio-economic characteristics, the relationship between these factors and vulnerability can be explored. In order to investigate these issues, a questionnaire survey was conducted in the city of Baños and the hamlet of Runtún, which nestles in the foothills below Volcan Tungurahua. Divided into several sections, the questionnaire sought responses relating to perceptions of risk, preparedness and hazard mitigation, access to information, trust in information sources, and previous experience. The results presented in this section are therefore split into these five factors. As well as exploring each question descriptively, patterns or relationships between the relevant questions and the individual and household demographic features are explored. The problems encountered during the fieldwork period in Ecuador have previously been discussed, and given the resulting limitations within the data set, this research is presented as a descriptive study that aims to explore the contextual relationship between selective personal characteristics and socio-economic features, and not to build a comprehensive model of vulnerability.

4.3.2. Questionnaire Results

4.3.2.1. Risk Perception

Risk perception is the subjective assessment of the characteristics and severity of risk by lay members of the public. An important component of this is an individual's level of worry or concern, termed hazard salience (Paton *et al.*, 2001a; Davis *et al.*, 2005; Barberi *et al.*, 2008). To evaluate levels of concern, respondents were asked to rate how worried they were about Volcán Tungurahua on a four point Likert scale[5]. Reported levels of concern for the sample as a whole were relatively low, with a large majority (93.6%) reporting they were 'not worried' (34.0%) or only 'slightly worried' (59.6%) about the volcano ($M = 0.72$, $SD = 0.56$). Only three people reported feeling 'quite worried' (6.4%), whilst no-one reported feeling 'very worried'. There was no difference in levels of concern between men and women, by age, occupation, household income, number of children in the home, or by number of social networks. There was a significant negative correlation between number of people in the household and levels of worry ($r = -.28$, $p < .05$). This suggests that those living in smaller households felt more concerned about the volcano than people who lived within larger family groups.

Respondents were then asked to rate whether they thought the volcano was a risk to themselves and their family (Figure 4.11). On a five point scale, participants on average felt the volcano was a 'moderate risk', with a mean rating of 1.64 ($SD = 0.94$). Almost half of respondents felt the volcano was either 'no risk' (10.6%) or a 'low risk' (34.0%) to themselves and their family, whilst 38.3% felt the risk was 'moderate'. Eight participants considered the risk to be more extreme, rating it 'high' (14.9%) to 'very

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[5] A Likert scale is a psychometric scale used in questionnaire surveys where respondents are able to express how much they agree or disagree with an attitude statement, or to rate their response to a question from a range of given options (Langdridge & Hagger-Johnson, 2009).

high' (2.1%). There was no difference between the various demographic groups and their rating of the risk except for household size. There was a significant positive correlation between the number of people living in the home and ratings of risk

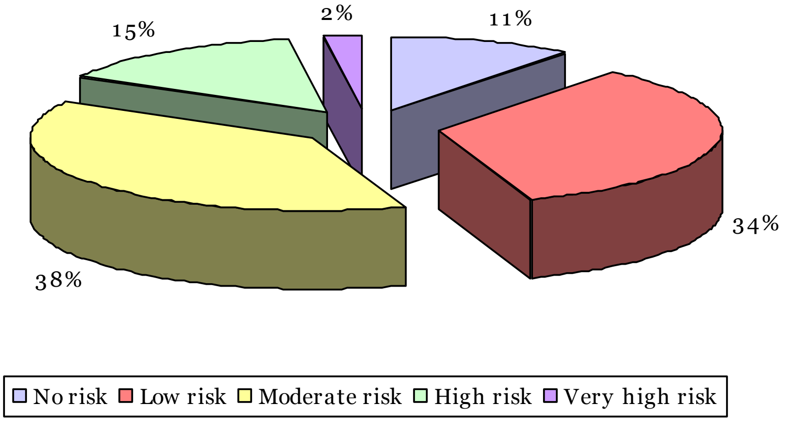


Figure 4.11 Pie chart showing the results of the survey question, *'Do you think that the volcano is a risk to you and your family?'*.

(r = .39, p <.01). This suggests that people living in larger households felt the risk was greater than did those living in smaller households. This is despite respondents from smaller households expressing higher levels of concern. By examining the household composition data, larger households tended to be those that not only had children aged sixteen years or under (not just their own children but in some cases nieces and nephews, as well as grandchildren), they also included those families that lived with their elderly parents. This compositional context, in which more vulnerable members of a family live together, may help explain why larger families feel more at risk, but are conversely less concerned, perhaps as a function of a perceived increase in the levels of support associated with living within a large family group. Previous research has indicated a strong positive relationship between hazard salience (worry/concern) and risk perception (Johnston & Benton, 1998; Paton *et al.*, 2001a; Davis *et al.*, 2006). However, the results of a correlation analysis indicate only a small positive but non-significant relationship ($r = .217$, $p = .07$) between the 'worry' and 'risk' questions, which may be explained by the influence of family size on responses.

At the time of the survey (March-April 2006), Tungurahua had been actively erupting, with varying intensity, almost continuously for nine years. This included a period of particularly intense activity where people were evacuated from Baños and the surrounding communities in 1999. Prior to the start of the current eruptive phase, a small phreatic eruption occurred in 1993 but more significant activity had not been recorded with certainty since the historically documented 1916 to 1925 eruptive episode. All but seven of the participants surveyed had lived in Baños prior to 1993, and all but three were evacuated during the 1999 eruption. In this context, it is interesting to note that when asked how often respondents thought Tungurahua erupted, almost three quarters said once a century, whilst less than 20% thought it erupted constantly. Similarly, when asked when they thought the next eruption would occur, almost 80% thought it would not be for years, whilst four people believed it would never erupt. On average people thought the next eruption of Tungurahua would be 'moderate' in size. Almost a third felt the next eruption would be large or very large, with the remainder believing it would be small or insignificant (Table 4.3).

Table 4.4 Results of three survey questions; (i) 'On average, how often do you think Tungurahua erupts?', (ii) 'When do you think Volcán Tungurahua will next erupt?', (iii) 'How big do you think the next eruption will be?'.

Eruptive Frequency	Next Eruption	Size of Next Eruption
Once a century – 74.5%	Never – 8.5%	Insignificant/small – 12.8%
Once a month – 4.3%	Not for years – 78.8%	Moderate – 57.4%
Constantly – 19.1%	Within months/days – 8.5%	Large/very large – 27.7%

These three questionnaire items relating to views about eruptive behaviour (frequency of eruptions; timing of next eruption; size of next eruption) were analysed by demographic factor and a single significant positive relationship emerged between household size and beliefs regarding the frequency of volcanic eruptions ($r = .31$, $p < .01$). This suggests that respondents from larger households felt the volcano would erupt with greater frequency than did those from smaller households. If they believe an eruption could occur more often, this may provide an additional explanation for why individuals living in larger households felt more at risk. Contrary to what might be expected, there were no significant correlations between the responses to these three questionnaire items. Generally it might be expected that those who think the next eruption will be large, may rationalise this belief by tempering it with the thought that an eruption is unlikely to occur in the near future, and that eruptions in general may be infrequent events. In this way beliefs regarding the risk are modified to reduce negative emotions.

When these results were compared with levels of concern and risk, there was a significant positive correlation between levels of worry and when respondents thought the next eruption would occur ($r = .27$, $p <.05$). This suggests that respondents who reported feeling most worried also believed that an eruption was likely to occur within a shorter timeframe. Also, as expected, level of risk was positively correlated with all three questions relating to beliefs about the volcano's eruptive behaviour: (i) eruption frequency; $r = .36$, $p <.05$, (ii) occurrence of next eruption; $r = .39$, $p <.01$, and (iii) size of next eruption; $r = .31$, $p <.05$. This indicates that people with higher perceptions of risk believe the volcano is more likely to erupt within a shorter timeframe (e.g. within their lifetime), that activity is generally more frequent and that an eruption is likely to be larger in size.

Two further questionnaire items asked participants to select which of six hazards they thought might occur during an eruption of Tungurahua, and which represented the biggest risk (Table 3.3). The hazards selected for inclusion in the questionnaire were those identified in the comprehensive review conducted during phase one as occurring in association with past activity at Tungurahua (Hall *et al.*, 1999; Le Pennec *et al.*, 2005). Respondents were asked to select all hazards they thought might occur during an eruption, with the mean number of hazards identified totalling 4.15 (*SD* = 1.96).

Ashfall was the hazard identified by the highest number of people (87.2%) as likely to occur during an eruption, but was only considered the greatest risk by 17% of respondents. Pyroclastic flows were identified as the greatest risk by the largest number of people (63.8%), having been identified by 66% of participants as a possible hazard associated with an eruption. Almost half of respondents felt that lava flows would be a significant risk (44.7%), whilst 31.9% identified earthquakes as the greatest risk. The hazard identified as most risky by the fewest number of people were lahars (8.5%). Although lahars associated with avalanches were identified by Hall *et al.*, (1999) as the greatest hazard at Tungurahua, the majority of Baños is protected by natural barriers due to the deep gorges which channel rivers to the north and west. Within the local area, lahars mainly pose a threat only to residents on the upper reaches of the Vascún and Ulba valleys, a number of homes on the western edge of Baños and on the main roads between Baños and the towns of Riobamba and Puyo. These results indicate that in general, residents correctly identified pyroclastic flows as the most threatening hazard.

Table 4.5 Results of the survey questions; (i) 'What types of hazards do you think might occur during an eruption?' and (ii) 'What do you think is the greatest hazard from an eruption?'.

	Hazard Type	
	Might Occur %	Greatest Risk %
Ashfall	87.2	17.0
Earthquakes	72.3	31.9
Lava flows	70.2	44.7
Pyroclastic flows	66.0	63.8
Lahars	61.7	8.5
Explosions	57.4	17.0

4.3.2.2. Preparedness and Hazard Adjustment

An individual's level of preparedness and hazard adjustment can directly influence their vulnerability, or more accurately help increase their resilience to the shocks of a volcanic eruption (Buckle *et al.*, 2000; Paton & Johnston, 2001; Tobin & Whiteford, 2002a; Manyena, 2006). Respondents were asked if they knew what to do if there were an eruption to assess their levels of preparedness. A majority of people felt they knew what they should do (93.6%). An open-ended question asked people to detail what they would do, and where the same responses were given, these were grouped and coded to allow quantitative analysis. Over two thirds of people said they would evacuate (74.5%), a further 8.5% said they would wait for instructions from the authorities, with some specifically mentioning 'the scientists' or the local civil defence agency. Three people (6.4%) said they would pray or put their trust in god to protect them. A single person mentioned storing emergency supplies, and one other stated they would do nothing (Figure 4.12). Participants were specifically asked if they knew their evacuation routes in the event of an eruption and all but four people responded positively (91.5%).

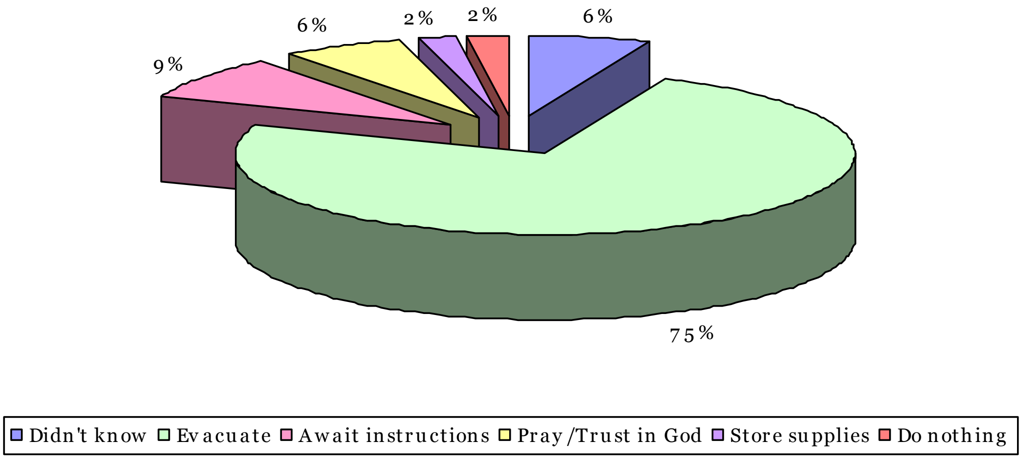


Figure 4.12 Pie chart showing responses to the survey question; '*Do you know what you should do if there is an eruption?*'.

To assess respondents' hazard adaption, a questionnaire item asked what plans they had made in case of an eruption, almost sixty percent reporting already having made plans (59.6%). Of the options provided, 29.8% said they had taken part in an evacuation drill, whilst 19.1% said they had stockpiled food, with the same number having planned where they would relocate if evacuated. There was no significant difference in socio-economic profile and either; (i) knowledge of what action to take in the event of an eruption, and (ii) preparedness measures adopted. However, when the number of plans people reported having already made were summed, men (M = 0.87, SD = 0.69) had on average adopted more preparedness measures than women (M = 0.54, SD = .59), but a t-test (a statistical test used to establish whether two means differ significantly) indicated that the difference was not significant (t = 1.75, p = .08).

4.3.2.3. Access to Information

Respondents were asked several questions about what types of information sources they had accessed regarding what action to take in the event of an eruption, who had provide this information and whether they had found it useful. Everyone questioned had seen at least one source of information, with the average number of items accessed 2.11 (SD = 1.07). The most popular information source was the radio (70.2%), followed by community meetings (53.2%) and maps (46.7%). Over three quarters of people said they found the information useful (76.6%). A single person, who had only accessed information about what action to take in the event of an eruption from a single source (attending a community meeting), did not find it useful. The most commonly cited provider of information was local officials with 83% of participants obtaining their information from this source. This was followed by radio and television programmes (53.2%) and scientists (34.0%). The number of different types of information sources accessed by each respondent were summed and compared by socio-economic group. There was no significant difference between the amount of information accessed by age, gender, income or other demographic factor.

4.3.2.4. Trust in Information Sources

Respondents were asked to rate how much trust they had in various different agencies to inform them about a possible eruption. Information providers included the national government, local officials, scientists, the media (newspapers, television, radio), and two unofficial sources; family and friends and the church or other social group. Levels of trust in each information source was rated on a four point scale; ‘not at all’; ‘somewhat’; ‘mostly’ or ‘completely’. Results are detailed in Table 4.6, and show that scientists were the most trusted source of information ($M = 1.70$, $SD = 0.93$), with the highest percentage of respondents saying they trusted them completely (23.4%). A series of t-tests indicate they were significantly more trusted than all other sources (national government; $t = 10.67$, $p < .001$, local officials; $t = 5.30$, $p < .001$, media; $t = 6.19$, $p < .001$, family/friends; $t = 3.20$, $p < .01$) except church/social groups ($t = 1.83$, $p = .08$). The next most trusted source of information was the church or other social groups ($M = 1.41$, $SD = 1.00$), followed by family and friends ($M = 1.28$, $SD = 0.89$). National government ($M = 0.66$, $SD = 0.67$) was seen as the least trustworthy source of information. With 42.6% of those questioned stating they did not trust them at all, and t-tests indicated they were trusted significantly less than all other sources ($p < .001$).

Table 4.6 Results of the survey question 'How much do you trust the following people to inform you about a possible eruption?'.

	Mean Level of Trust* (*SD*)	Percentage of Respondents			
		Not at all^0	Somewhat^1	Mostly^2	Completely^3
Scientists	1.70 (0.93)	8.5	36.2	31.9	23.4
Church/Social Group	1.41 (1.00)	17.0	31.9	23.4	14.9
Family/Friends	1.28 (0.89)	17.0	46.8	23.4	10.6
Local Officials	1.13 (0.74)	14.9	63.8	14.9	6.4
Media	1.06 (0.70)	19.1	57.4	21.3	2.1
National Government	0.66 (0.67)	42.6	51.1	4.3	2.1

* Mean level of trust on four point scale from O 'not at all' to 3 'completely'. Superscript figures indicate coding used in analysis.

Almost two thirds of respondents felt they had some trust in local officials. Trust in these officials may be particularly important in mediating communication, as over eighty percent of respondents indicated they had accessed information on what action to take during an eruption from this source. Additional, it is the responsibility of the local Civil Defence, in conjunction with the Mayor's office, to keep the community informed during a volcanic emergency about any preparedness and hazard adaption measures they should take. Information indicating the current alert status and details of present volcanic activity is provided by scientists from the local volcano observatory via a daily radio update. The high levels of trust in the scientists suggested by the survey results is encouraging for the success of this particularly communication tool.

4.3.2.5. Previous Experience

A section of the questionnaire focused on people's experiences during the period of increased eruptive activity in 1999. Questions included whether they had been evacuated, to where and for how long, their feelings about the evacuation at the time and how they felt about it now. Almost all those questioned had been evacuated (95.7%), and of these 57.8% said they had not gone voluntarily. A majority of respondents moved into rented accommodation (60%), whilst 35.6% stayed with relatives and the remaining 4.4% moved in with friends. On average respondents spent between three to six months away from home. However, two people said they and their families had returned home after less than two weeks. Both respondents were from the small farming settlement of Runtún, situated on the ridge above Baños in the high-risk zone. They described how they had returned home under cover of darkness, and spent the following months avoiding members of the military who were tasked with policing the evacuation zone. Both participants said they felt it was necessary to return home in order to protect their crops and livelihood. Respondents were asked what had prompted their return home and were asked to selected as many options from the list as were applicable. The most commonly cited reasons for returning home were economic (42.2%), or that family and friends had returned (44.4%). Other reasons for returning home were they no longer felt the volcano was a threat (24.4%), or because the official evacuation order was lifted (13.3%). Of those evacuated, 57.8% felt that at the time it had been necessary to evacuate.

An open-ended question asked how participants felt about the eruption now. Similarities between responses were studied and the groups identified were coded to allow quantification (Figure 4.13). Results indicated that 44.4% of those evacuated now felt the evacuation was not necessary (compared to the 57.8% who thought it was necessary at the time), 35.6% thought the information about the volcano had been inaccurate, and a further 15.6% said the evacuation was badly managed. Almost a quarter still felt the evacuation was necessary given what was known at the time (24.4%). A further, 17.8% felt the evacuation had been disruptive, in terms of their livelihood and lifestyle, whilst three respondents (6.7%) said they thought the evacuation had been politically motivated. Reasons for this were not expanded upon, but there remains a general lack of trust in officials, and government, particularly amongst the indigenous community, as demonstrated by the protests occurring at the time of the survey.

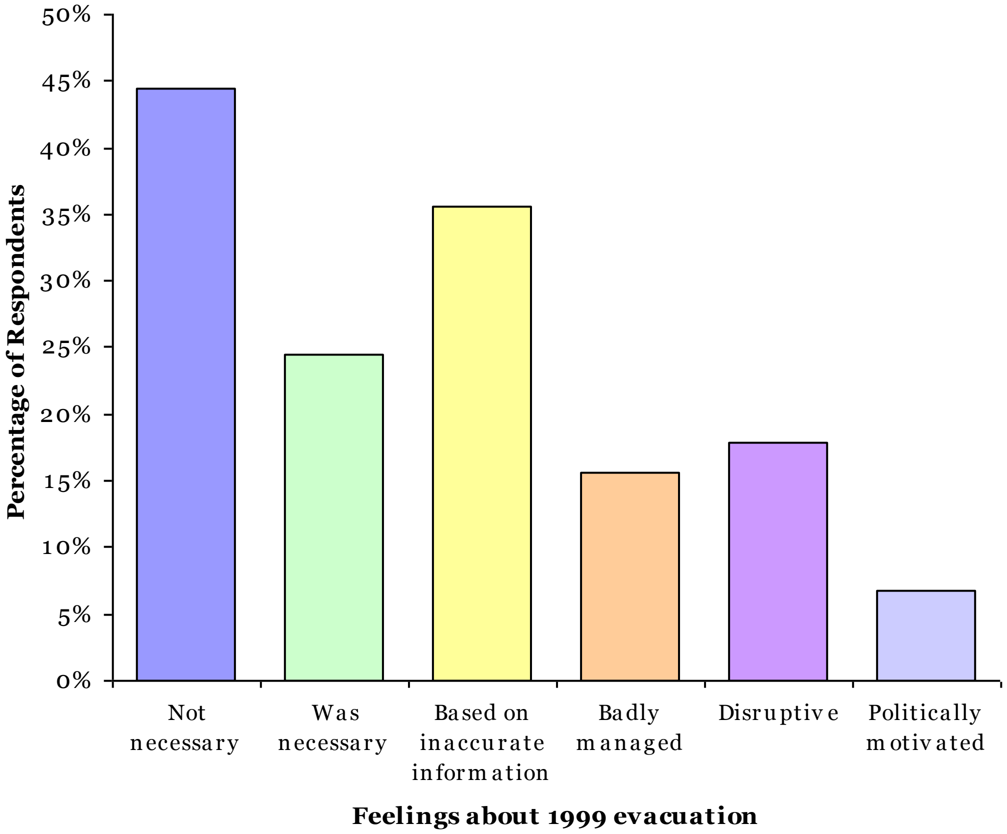


Figure 4.13 Bar chart of the results of the survey question; *'How do you feel about the* [1999] *evacuation now?'*.

The questions from the experience section were compared to the selected socio-economic characteristics, including (i) whether individuals had evacuated voluntarily and, (ii) whether they thought the evacuation was necessary at the time. Two significant correlations were found. There was a significant positive relationship between monthly income and whether an individual had evacuated voluntarily (t = 1.97, p <.05). This suggests that those who chose to evacuate voluntarily had, on average, higher incomes than those who evacuated against their wishes. There was a significant negative correlation between the number of informal social networks people identified and whether they thought the evacuation was justified at the time. This suggests that those who felt the evacuation was not necessary had a larger social network than those who felt the evacuation was necessary.

As would be expected, when the results of the two experience questionnaire items were compared there was a significant positive relationship between whether someone evacuated voluntarily and whether they thought the evacuation was necessary (r = .336, p <.01). Additionally, those who still felt the evacuation had been necessary five years after the event (e.g. at the time of this survey), were more likely to have thought the evacuation was necessary at the time (r = .351, p <.01), and to have evacuated voluntarily (r = .277, p <.05). In addition, a significant positive relationship was found between levels of worry (hazard salience) and whether the evacuation was considered necessary at the time (r = .301, p <.05), but there was no significant correlation between risk perception and past experience.

4.3.3. Discussion

Given the small size of the data set analysed above, only limited conclusions could be drawn about the relationships between the psychological beliefs and attitudes towards Volcán Tungurahua and the socio-economic characteristics of residents living in Baños. However, some interesting contextual results where found amongst the participants surveyed, and from these a profile of the respondents was constructed.

Of those questioned in Baños, levels of concern about the volcano appeared low, with almost 94% of people saying they were ‘not worried’ or only ‘slightly worried’ about the volcano, whilst almost 50% thought the volcano represented ‘no risk’ or only a ‘low risk’ to themselves and their family. This result was unexpected given the continuing activity of the volcano, and the evacuation of the town in 1999 (the second evacuation in 2006 of some of the villages around Baños occurred approximately two months after the survey was undertaken). Past experience of a hazard has been linked with higher perceptions of risk (Johnston *et al.*, 1999; Paton *et al.*, 2001a; Perry & Lindell, 2008). However, direct exposure to non-damaging effects, e.g. mild ashfall, may foster the perception that future activity will be similar to what has been witnessed in the past, creating what has been termed 'normalisation bias' (Johnston *et al.*, 1999; Gregg *et al.*, 2003). This suggests the at-risk population in Baños may have grown accustomed to the hazard, leading them to downplay its potential threat due to their continuing benign exposure. However, respondents did report high levels of knowledge about protective behaviour and high levels of preparedness, which past research has indicated may be associated with higher perceptions of risk (Rippetoe & Rogers, 1987; Grothmann & Reusswig, 2006; Martin *et al.*, 2007; Barberi *et al.*, 2008). It was not possible to explore these themes further because issues relating to self-efficacy, such as perceived levels of preparedness and ability to cope with the effects of an eruption, were not included within the survey instrument used in Baños. To explore the importance of these issues, questions to address them were subsequently included within the survey instrument developed for the second period of field work conducted in the US.

Level of worry represent hazard salience, which has been identified as an important component of an individual's overall risk perception (Becker *et al.*, 2001; Paton *et al.*, 2001a; Davis & Ricci, 2004; Davis *et al.*, 2005; Barberi *et al.*, 2008). We would therefore expect to see a relationship between these two variables. Although no significant correlation was found between levels of worry and perceptions of risk, results indicate a trend towards a positive relationship, consistent with the findings of others.

Some initially surprising results were found with regards to beliefs and attitudes relating to the behaviour of the volcano, specifically the frequency of eruptions, and the timing of the next eruption. Almost 75% of participants thought the volcano erupted on average once every hundred years, whilst almost 80% thought it would not erupt again for 'years'. This was despite almost all of those questioned having lived in Baños since before 1993, the last time the volcano erupted prior to its current activity (although this was only a minor event). Respondents should have been aware of at least two eruptions during the preceding fifteen years, and of the current period of on-going activity. There may be several possible reasons for the results obtained from these questionnaire items. Firstly, an individual's response to the question depends upon how they define an 'eruption'. It may be that the almost continuous light dusting of volcanic ash fall experienced in the town is not considered evidence of an eruption. Secondly, the summit of Tungurahua, and the visual spectacle of ash plumes and incandescent ejecta, are obscured from the town by a large ridge to the south, allied to which, the summit, viewable only from the extreme west of town is often obscured by clouds. Thirdly, perceptual biases may have resulted in non-protective responses being adopted, such as denial of the threat or wishful thinking regarding the ongoing activity, as suggested by PMT. These non-protective responses help reduce the negative emotional consequences of the perceived risk (Rogers, 1975; Grothmann & Reusswig, 2006; Martin *et al.*, 2007). If the latter hypothesis were true, we would expect a negative correlation between risk perception and the three volcanic behaviour questions (eruption frequency, size and timing of next eruption). However, results indicated a significant positive correlations, suggesting those with a higher perception of risk do not exhibit denial of the threat, rather they believe the volcano erupts more frequently, that the next eruption will occur sooner, and that it will be larger, than those people with lower perceived risk. Other mechanisms must be responsible for this apparent lack of knowledge, specifically regarding current activity at the volcano.

Despite the apparent lack of knowledge regarding the behaviour of the volcano, respondents' knowledge of the most risky hazards associated with volcanism at Tungurahua generally corresponded with those identified in the IGEPN hazard assessment. However, a significant number of respondents incorrectly identified lava flows as the greatest hazard. Work by Solana *et al.* (2008) and McGuire *et al.* (McGuire *et al.*, 2009) suggests there may be some confusion amongst lay people regarding the distinction between different products flowing from the volcano whereby pyroclastic flows may be incorrectly identified as 'lava flows'. Despite this potential error, the results indicate that pyroclastic flows were correctly identified as the most serious threat by almost two thirds of respondents, whilst ashfall and earthquakes were rated as the most likely hazards. Past experience of ashfall and earthquakes associated with volcanism, may explain the latter result. Whilst knowledge about the most serious hazards could be due to the daily bulletins, and weekly reports-broadcast which forms part of the wider communication strategy of the scientists and local authorities. Unfortunately, the wording of this question did not explicitly ask which hazards respondents felt they or their town were most at risk from. This point was addressed in the modified survey instrument used for the second field work period in the US.

Significant correlations were found between levels of worry and; (i) respondents who said they would evacuate (positive), and (ii) those who said they would wait to follow advice from the scientists (negative). The former could lead to self-evacuation, but without comprehensive knowledge about the behaviour of the volcano (a possibility given results regarding levels of knowledge relative to eruptive behaviour), evacuations may occur unnecessarily, causing needless disruption. However, this situation is preferable than one where the community is closed to the idea of evacuating, which might have been expected given some of the negative experiences suffered by residents during the 1999 evacuation, e.g. (see Tobin & Whiteford, 2002a; 2002b; Lane *et al.*, 2003). Much of the work conducted in these two studies focused on residents who were evacuated to official shelters, where conditions were described as particularly unpleasant. None of the survey participants questioned for the current research were evacuated to these sites. No significant correlations were found between knowledge of appropriate response or levels of preparedness and socio-economic factors.

It may have been hypothesised that beliefs and attitudes expressed in relation to the 1999 evacuation would have negatively impacted trust in the authorities and scientists. Results indicate that scientists are the most trusted source of information with over half of those questioned stating they trusted them 'mostly' or 'completely'. The most frequently mentioned source of information was the local authorities, who were felt less trustworthy, on average trusted only 'somewhat'. The least trusted source of information was the national government, which is unsurprising given the recent history of the country. Civil unrest is a common occurrence in Ecuador, particularly since the emergence of the indigenous population (approximately 25%) as an active constituency, adding to the democratic volatility. Since becoming a democracy in 1979, following the ousting of the dictator-led military government, Ecuador has had 12 different presidents, 6 of these in the last nine years. This almost constant state of political instability, combined with economic uncertainty following the period of hyperinflation which led to dollarisation in 2000, and a widespread (but not unfounded) belief in political corruption through all levels of government, unsurprisingly results in lower levels of trust.

Knowledge of appropriate protective response was very high, with almost all those questioned stating they knew what action to take, with over three-quarters saying they would evacuate. Hazard managers should take additional comfort in the knowledge that over ninety percent of those surveyed knew their evacuation routes. These high values are most likely due to past experience of evacuation, but everyone surveyed had also had access to at least one source of information about what action to take in the event of an eruption effecting the town. This included radio broadcasts, attendance at community meetings, and viewing hazard maps of the town. There was no significant difference between the number of sources of information accessed and socio-economic characteristics.

Several interesting correlations between experiences relating to the 1999 evacuation were found between a number of socio-economic variables. Firstly, there was a positive relationship between those who evacuated voluntarily and income. This suggests those on higher incomes were more likely to have left their homes willingly. Lower incomes within the survey sample were found to be associated with farming and agricultural employment. The economic activities of these people are closely tide to the land, and to leave would adversely impact not only their current income, but also their ability to maintain their income in the future. Those with higher incomes are perhaps better able to absorb the negative economic consequences associated with leaving home. Secondly, there was a negative relationship between social networks (close family members and membership of social groups) and whether the evacuation was thought necessary at the time, i.e. those with greater social ties were less likely to think the evacuation was necessary. This supports previous research into the strength of community bonds, which found PSOC was negatively correlated with heeding evacuation advice in relation to hurricane warnings (Riad & Norris, 1998). Although those people surveyed did not think the evacuation was necessary, they did evacuate (although this was achieved by military force).

Only a single socio-economic variable was found to correlate significantly with risk perception and levels of worry. Those survey participants who reported living in larger households were less worried about the volcano, but conversely they felt the volcano was a greater risk to themselves and their families, than did smaller households. Not withstanding the limitations of the data set discussed here, the lack of any relationships between socio-economic factors and psychological variables, implies that much of the theoretical assumptions that underlie discourse on vulnerability (Degg, 1992; Murck *et al.*, 1997; Corotis & Enarson, 2004; Wisner *et al.*, 2004), and cited by numerous empirical studies (e.g. Cutter *et al.*, 2000; King & MacGregor, 2000; Cutter *et al.*, 2003), are not supported by this phase of the research. Results relating to past experience and income seem to suggest that the psychological constructs of vulnerability affect behaviour pre-event, but that socio-economic factors determine post-event vulnerability. It is not that, for example, those with lower incomes adopt non-protective responses to risk, but rather that in adopting protective responses such as evacuating from their homes, they suffer adversely, whilst those on higher incomes are better equipped to absorb any adverse consequences, e.g. they have greater resilience.

In order to address this issue and several others raised during this study, a number of changes were made to the approach and methodology utilised in the field work conducted in the three communities surrounding Mount Rainier. Specifically an increase in the number of questions relating to risk perception and hazard salience, e.g. explicit questions were included that addressed perceived risk for both oneself and ones community, the inclusion of questions to explore issues of self-efficacy, additional questions regarding preparedness, and the inclusion of a specific scale to measure PSOC. The results of this modified approach are discussed in relation to the vulnerability assessment at Mount Rainier, detailed in the latter half of the following chapter.

CHAPTER 5: UNITED STATES CASE STUDY

5.1. INTRODUCTION

The overarching aim of this research was to examine the vulnerability of local residents to future volcanic activity. For this period of study the work focused on Mount Rainier, and three communities located within the identified hazard zones of the volcano. The objective of this case study was to build on the work conducted in Ecuador, refining the methodologies employed to address any shortcomings identified during the first period of field work.

Phase one of this case study involved conducting a threat assessment using personal field observations, combined with a systematic review of existing published literature, including peer reviewed journal articles, current emergency management reports, conference proceedings and hazard maps. The data obtained from this comprehensive review was used to complete the same semi-quantitative assessment metric utilised for quantifying volcanic threat at Volcán Tungurahua. This considered both the specific hazard factors and exposure factors that exist in the towns of Carbonado, Sumner and Ellensburg to calculate an overall threat factor score, with the objective of ranking the towns in order of most to least threatened. The comprehensive review of secondary data is presented in the following section, both generally in relation to the volcano, and specifically in relation to each of the case study communities, followed by the results of the threat assessment.

The second phase of this case study aimed to explore the human context of the volcanic threat by analysing statistically the results of a comprehensive risk questionnaire. Specifically, the aim was to address issues of vulnerability through measuring various psychological characteristics, including perceived risk, hazard salience and self-efficacy. These characteristics were identified in the social science and psychological literature as being important in the adoption of protective behaviour. A further objective was to explore how or if these characteristics altered in relation to differences in the socio-economic status of those surveyed. The more comprehensive nature of this questionnaire survey and the larger sample size (when compared to the work undertaken in Ecuador), allowed significantly greater scope for quantitative analysis of the results. Standard procedures used in psychological research guided the analysis, the results of which are presented in section 5.3.

5.2. MOUNT RAINIER THREAT ASSESSMENT

5.2.1. Comprehensive Review of Secondary Data

A systematic review of the historical activity, eruptive behaviour and hazards associated with volcanic activity at Mount Rainier was used in an effort to quantify, in a broad manner, the threat posed to residents living in three communities at different distances, and subject to different hazards from the volcano. As recommended in relation to more qualitative risk assessments, this information is provided in detail below in order to document fully the criteria upon which the judgements used to complete the threat assessment are based.

5.2.1.1. Regional Setting and Volcano Type

Together with the Aleutian Island arc and the volcanoes of Alaska, the Cascade Range of mountains form the North American section of the Pacific ‘Ring of Fire’, a chain of volcanic edifices associated with plate boundaries that encircle the Pacific Ocean basin. The Cascade Range stretches from southern British Columbia, in Canada, through the states of Washington and Oregon into northern California, and are characterised by around 15 major volcanoes among a total of almost 3,000 separate volcanic vents (USGS CVO, 2004-). The loftiest of the Cascade mountains at 4,392m, Mount Rainier is the highest peak in the contiguous United States. Located approximately 70km to the south-east of the Seattle/Tacoma metropolitan area, in Pierce County, Washington State, the volcano is the dominant feature of Mount Rainier National Park (Figure 5.1). Major settlements are concentrated to the west and northwest of the volcano in the

Puget Sound Lowland area. This topographic and structural trough, with elevations generally less than 300m, is bounded by the Olympic Mountains and Vancouver Island on the west, the Fraser Lowland to the north and the Cascade Range to the east.

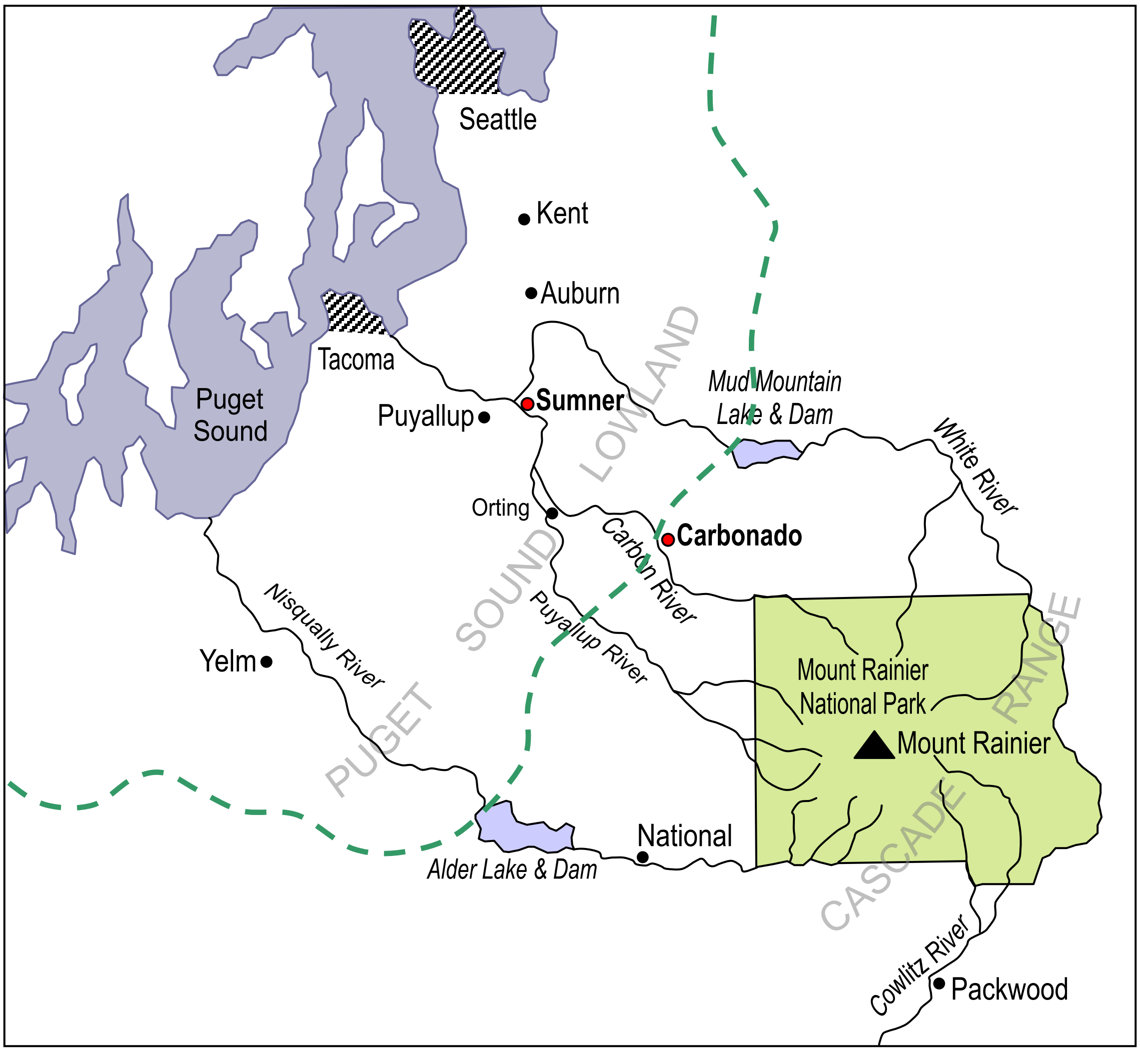


Figure 5.1 Map showing regional setting of Mount Rainier including National Park boundaries, major river drainages, key settlements, reservoirs and dams, and the extent of the Puget Sound Lowland area (modified from Scott *et al.* 1995).

Mount Rainier is a composite or stratovolcano, the volcanic form typical of convergent plate margins, and characterised by generally steep sided constructional cones, comprising layers of explosively erupted tephra and pyroclastic deposits interbedded with andesite and dacite lava flows (Davidson & De Silva, 2000). The summit area is almost completely covered in snow and ice, and with 23 major glaciers covering 92km^2, with a volume of 4.4km^3 (Driedger & Kennard, 1986), it is the most glaciated mountain of the conterminous United States. Areas of heated ground and acidic fumaroles with temperatures of up to 82°C (Frank, 1995) characterise parts of the summit cone and upper flanks of the volcano and help form the worlds largest volcanic ice-cave system (Zimbleman *et al.*, 2000). This active hydrothermal system has caused extensive alteration of the rocks forming the upper portion of the volcano, causing significant structural weakening (Finn *et al.*, 2001; Reid *et al.*, 2001; Siebert & Simkin, 2002-; John *et al.*, 2008). The substantial loading of snow and ice, and areas of hydrothermally altered rock which comprise the volcanic edifice have been responsible for some of the largest events in the volcano's history. These include periodic major flank collapses, debris avalanches and massive lahars, deposits of which underlie the now heavily populated Puget Sound lowland (Crandell & Mullineaux, 1978; Hoblitt *et al.*, 1998; Zimbleman *et al.*, 2000). These combine to make Mount Rainier one of the most dangerous volcanoes in the United States (Ewert *et al.*, 2005).

5.2.1.2. Eruptive History

The following section provides a discursive assessment of past volcanic activity at Mount Rainier, from 500,000 years ago to the present day, this information is summarised in tabular form in Appendix 3 for reference. The modern edifice of Mount Rainier began to develop approximately half a million years ago, and its growth has been characterised by periods of substantially variable effusion rates (Sisson *et al.*, 2001). For the first 80,000 years, effusion of widespread voluminous lava flows lead to rapid edifice growth. Sparse geological evidence exists for the period between 400ka and 300ka, which is thought to have been characterised by infrequent, small eruptions. This phase was followed by a highly effusive period of activity, lasting approximately 100,000 years from around 280ka, resulting in the rapid accumulation of pyroclastic deposits capped by lava flows. Intrusion of east-northeast-striking radial dykes occurred mainly during the two periods of high effusion (500ka to 420ka and 280ka and 180ka) (*ibid*). From around 180ka, eruption rates declined, although dikes and vents on the upper flanks continued to feed lava flows. During this time a number of vents opened on the lower flanks producing atypical basaltic lavas, these are not thought to have originated from the Mount Rainier magmatic system, but rather were fed from great depth (Driedger *et al.*, 2005). During this relatively quiet period of activity, erosion incised the upper edifice reducing the elevation of the summit. Around 40ka activity again increased, and hundreds of layers of lava, interbedded with breccia and tephra, reconstructed the upper flanks of the volcano, creating a cone 2,100-2,400 metres above its surroundings (Swanson *et al.*, 1989). This period of activity coincided with the development of present-day Mount St Helens (Driedger *et al.*, 2005). Activity waned around 15,000 years ago, before resuming again at the start of the Holocene.

The Holocene period is the most well studied of the volcano's history due to the extensive preservation of deposits. These indicate six eruptive episodes of varying lengths during which at least 11 explosive eruptions occurred (Driedger *et al.*, 2005). Other deposits indicate additional eruptions, but these are not well preserved (Crandell, 1971; Mullineaux, 1974). During this time (11,000 years ago to the present), as many as 60 debris avalanches and lahars (Crandell, 1971; Hoblitt *et al.*, 1998) occurred, some of which may have resulted from non-eruptive phenomena such as earthquakes, hydrothermal explosions or over-steepening of the volcano's flanks from erosion (Frank, 1995). More recent work indicates there may have been almost twice as many eruptions during this period than previously thought. Vallance and Donoghue (2000) suggest that Mount Rainier may have erupted as many as 20 times since around 9,700 BP, and it is therefore likely that more of the debris avalanches and lahars would have been eruptive in origin (Sisson *et al.*, 2001). During the earliest of the Holocene eruptive periods, approximately 11,000 years ago, an eruption deposited ash across much of the eastern part of the National Park (Layer R, Figure 5.2) and extended well beyond its boundaries (Mullineaux, 1974). A single lahar, possibly of landslide origin, is recognised in deposits from this period (Driedger *et al.*, 2005).

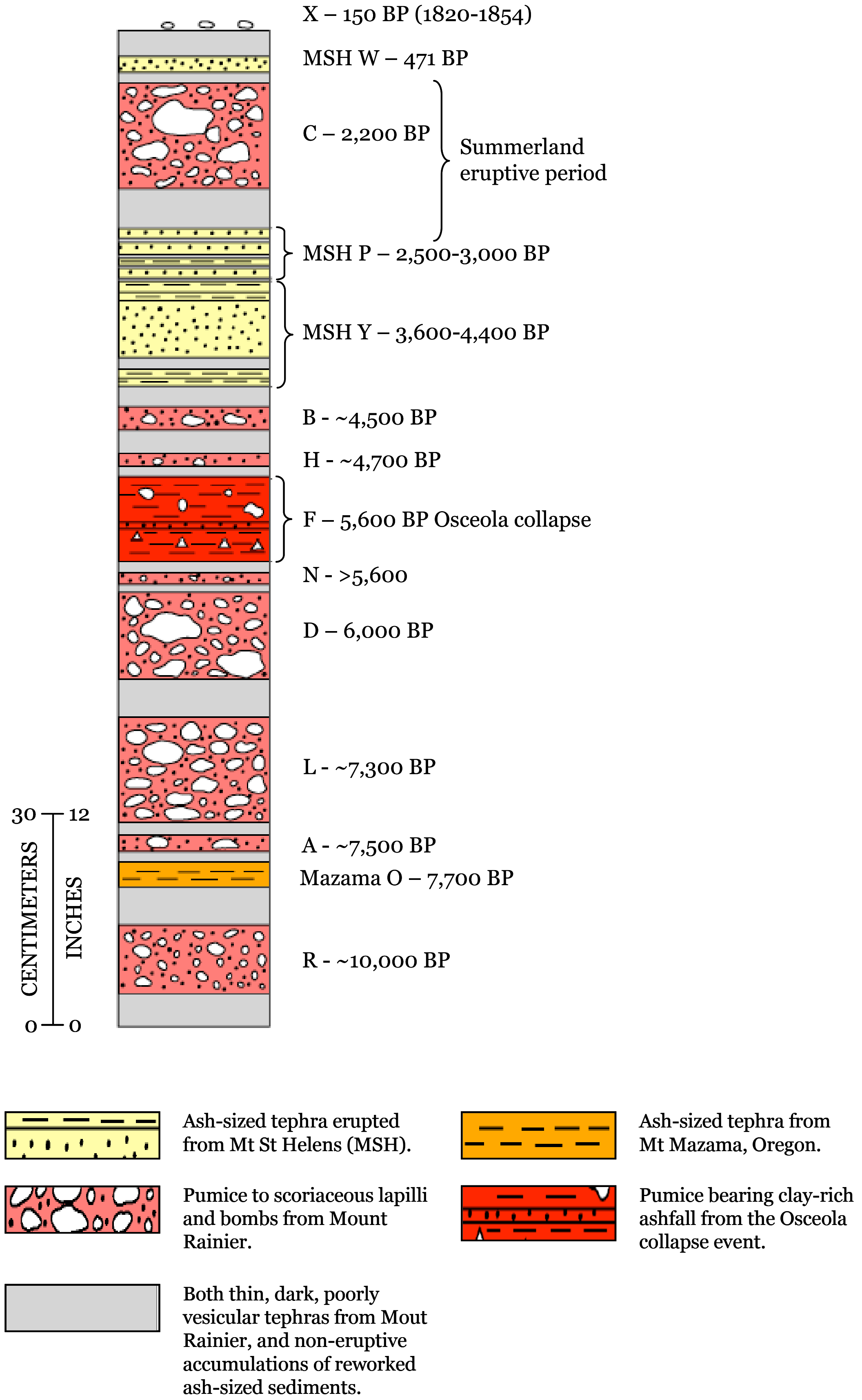


Figure 5.2 Stratigraphic section of prominent Holocene tephra deposits in sub-alpine meadows near Mount Rainier (modified from Mullineaux, 1974; Sisson & Vallance, 2009). Layer X is now considered to be non-eruptive (Sisson & Vallance, 2009).

Between approximately 7,400 to around 6,700 years ago, during the Cowlitz Park eruptive period, four distinct eruptive episodes produced subplinian falls, ash falls, pyroclastic flows and lahars (Byman & Vallance, 2001). During several eruptions, ash was deposited to the northeast, east and southeast well beyond the current boundaries of the national park (Layers A and L) (Mullineaux, 1974). A number of lahars occurred during this period, the largest of which travelled 70km down the White River to the Puget Sound lowland (Byman & Vallance, 2001; Driedger *et al.*, 2005). Another lahar, associated with a large avalanche, travelled down the Paradise valley (Driedger *et al.*, 2005) overtopping a ridge 60 metres above the valley floor and spilled into Reflection Lakes, raising its level by more than 6 metres (Crandell, 1971).

The Osceola eruptive period, approximately 5,600 to 4,500 years ago, was characterised by multiple eruptions (Vallance & Donoghue, 2000; Driedger *et al.*, 2005) and the largest lahar in Mount Rainier's post-glacial history; the Osceola Mudflow (Crandell, 1971). Around 5,600 years BP (Crandell, 1971; Dragovitch *et al.*, 1994; Vallance & Scott, 1997), explosive phreatic and phreatomagmatic eruptions triggered the collapse of the summit and north-eastern flank of the volcano (Vallance & Scott, 1997; Driedger *et al.*, 2005) initiating a landslide that removed between 200 metres (Dragovitch *et al.*, 1994) and 600 metres (Scott & Vallance, 1993) from the volcano's summit. This created a crater 1.8km wide, open to the northeast (Sisson *et al.*, 2001). The volume of material lost from the summit was calculated by Vallance & Scott (1997) at between 2 and 2.5km^3. Tephra deposits to the northeast of the volcano dated to this eruption (layer F), form a lobe that coincides with the outlet direction of the Osceola collapse scar (John *et al.*, 2008). This distribution and the deposit's composition, which is rich in hydrothermal minerals, suggest it resulted from a strong laterally directed blast (Mullineaux, 1974; Vallance & Scott, 1997), caused by explosive expansion of the interior hydrothermal system during failure and decompressive unloading (John *et al.*, 2008). The ensuing debris avalanche of hydrothermally altered rock, amalgamated with glacial ice and snow and mobilised into the massive Osceola

Mudflow (Crandell, 1971). This swept down the east and west forks of the White River and the lower parts of the Puyallup River, travelling to the present margins of the southern suburbs of Seattle and extending into Puget Sound (Crandell, 1971; Crandell *et al.*, 1979; Vallance & Scott, 1997) (Figure 5.3). It extended to a maximum distance of 120km downstream of Mount Rainier (Crandell, 1971; Dragovitch *et al.*, 1994; Vallance & Scott, 1997), and covered a minimum area of approximately 547km^2 (Vallance & Scott, 1997), with a total estimated volume of 3.8km^3 (Dragovitch *et al.*, 1994; Vallance & Scott, 1997). The difference in volume between the material lost from the volcano's summit and that of the mudflow was due to; '*…dilation of the original avalanche mass and bulking of exotic material…*' (Vallance & Scott, 1997, pg.149). Veneer deposits on steep-sided valleys are found as high as 200m above present river levels (Crandell, 1971; Vallance & Scott, 1997), whilst 5 to 20m thick deposits are found in valley bottoms (Vallance & Scott, 1997).

Thought to be synonymous with the Osceola Mudflow, the Paradise lahar resulted from the same edifice collapse but travelled down the Nisqually and Cowlitz river systems. It reached depths of more than 300m in some of the canyons on the volcano before rapidly thinning (Scott *et al.*, 1995; Vallance & Scott, 1997). Tephra deposits indicate that following the flank collapse a period of cone building ensued, after which activity waned (Mullineaux, 1974; Driedger *et al.*, 2005; Sisson & Vallance, 2009). The eruption which resulted in the Osceola Mudflow is rated as a VEI 3, whilst for comparison the 1980 Mount St Helens eruption is rated VEI 5. However, deposits indicate the former resulted in a much larger flank collapse, ensuing debris avalanche and lahar (Sisson, 1995).

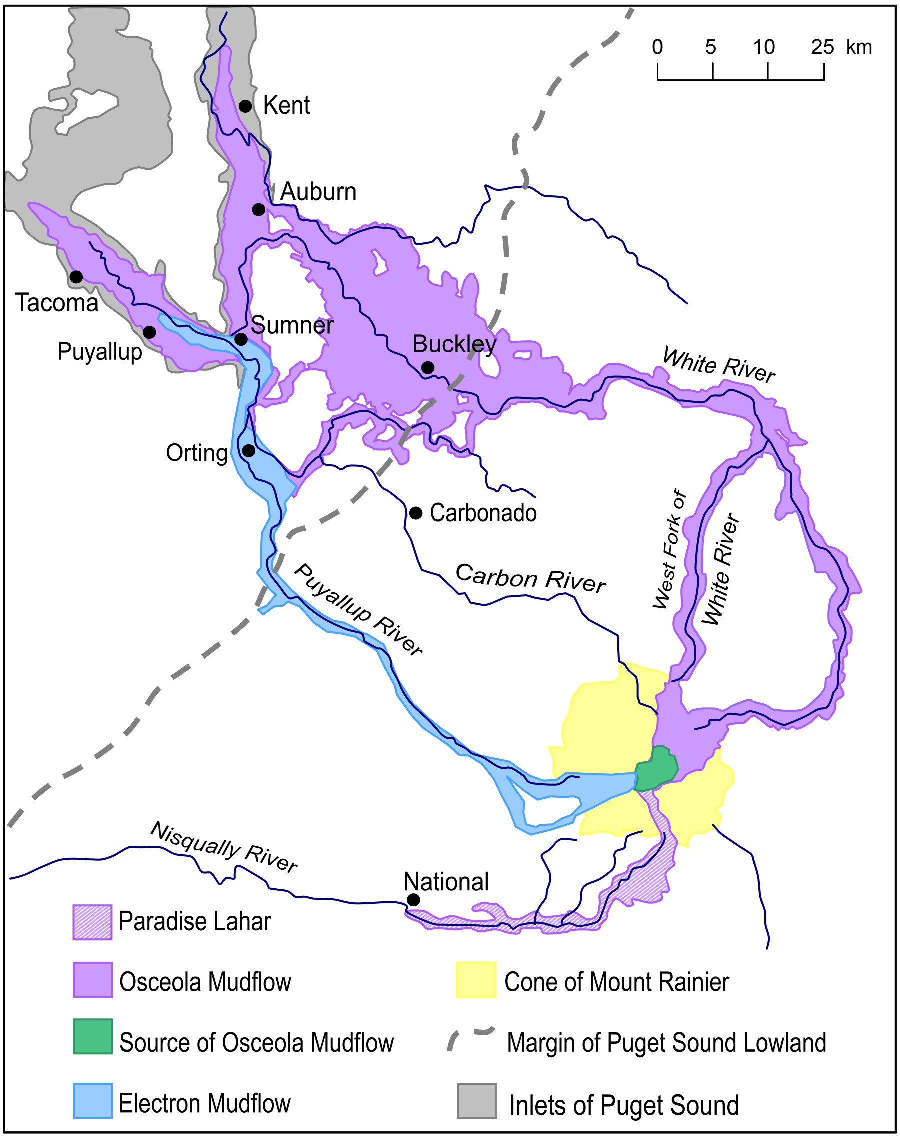


Figure 5.3 Map showing the extent of two of the largest mudflows to originate on Mount Rainier during the Holocene period; the Osceola Mudflow and the Electron Mudflow. Also shown is the upper reaches of the Paradise Lahar, which is thought to have occurred as a result of the Osceola collapse but travelled down the Nisqually and Cowlitz river systems (modified from Crandell, 1971, Vallance & Scott, 1997 and Driedger *et al*, 2005).

Following a period of dormancy, activity resumed around 2,600 years ago, and during a period of around 400 years (the Summerland eruptive period), as many as 8 eruptions occurred (Sisson & Vallance, 2009). These eruptions may have lasted months to possibly years and probably consisted of multiple explosive events, separated by intervals of up to a hundred years (Driedger *et al.*, 2005; Sisson & Vallance, 2009). Typified by ash fall, pyroclastic flows, lava flows and the further collapse of hydrothermally altered rock from the west flank, this period of activity included the generation of the Round Pass mudflow (Vallance, 2001; Driedger *et al.*, 2005; Sisson &

Vallance, 2009), which travelled down the Nisqually and Puyallup River valleys, reaching the Puget Sound lowland area (Scott *et al.*, 1995). Towards the end of the Summerland period around 2,200 years ago, a subplinian eruption occurred (Sisson & Vallance, 2009). Tephra deposits from this event (Layer C) cover a wide area of the national park trending north and east, extending beyond the park's boundaries and reducing in thickness from a maximum of 30cm to 8cm 15km from the summit. This represents the single largest Holocene tephra eruption from Mount Rainier, and has been estimated as a VEI 4 magnitude event, but is considerably smaller than similar events at other Cascade volcanoes (Mullineaux, 1974). During this period lava flows filled much of the summit crater, forming the present summit cone (Zimbleman *et al.*, 2000). Intermittent pyroclastic flows, ash falls and lava flows continued, and further lahars flowed south, southeast and west before activity declined (Vallance, 2001).

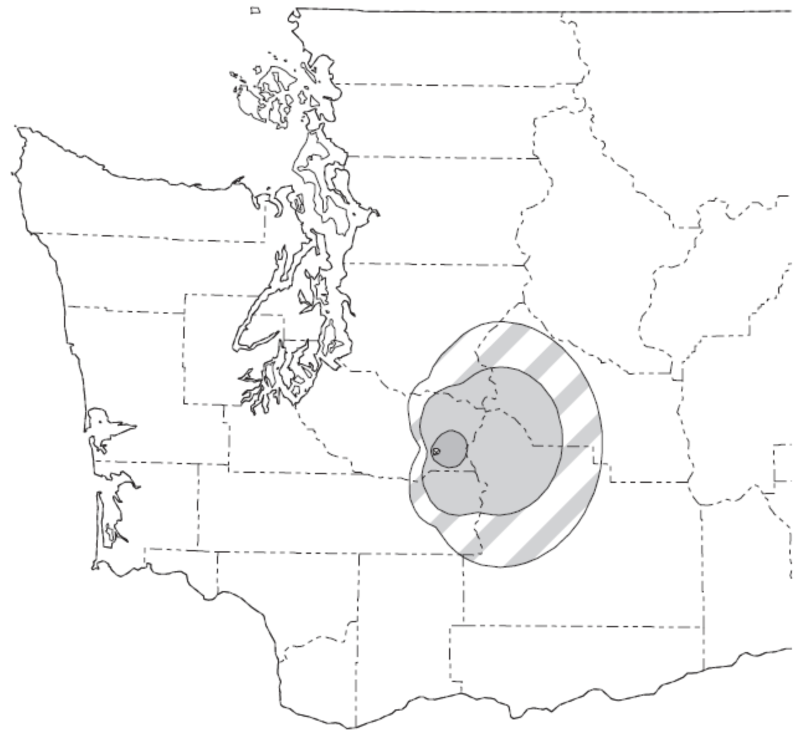
Around 1,500 years ago a number of small eruptions occurred with the formation of several far-travelled lahars. These may have negotiated up to 130km of river distance, reaching the location of the present day Port of Seattle (Vallance, 2001; Driedger *et al.*, 2005). Further large lahars occurred between 1,100 and 1,000 years ago and may have resulted from the melting of snow and ice high on the upper flanks of the mountain as a result of small scale pyroclastic flows or the deposition of tephra (Sisson & Vallance, 2009). These lahars descended valleys to the northeast and west of the volcano, and travelled down the White River as far as Auburn, and the Puyallup River to the tidal flats of the Puget Sound, which now form the southern suburbs of Seattle (Crandell, 1971; Vallance, 2001; Driedger *et al.*, 2005). The ~1,000 year BP White River event is the last confirmed magmatic eruption to have occurred at Mount Rainier (Sisson & Vallance, 2009).

The last major lahar, the Electron Mudflow, has not been correlated with volcanic activity due to a lack of tephra deposits dating to the same period, approximately 500 years ago (Crandell, 1971; Scott *et al.*, 1995; Hoblitt *et al.*, 1998). It is thought non-magmatic processes, e.g. an earthquake, may have triggered the collapse of a hydrothermally altered section of the northwest flank, resulting in a debris avalanche, which mobilised into a mudflow (Sisson & Vallance, 2009). The Electron Mudflow, although smaller than the Osceola, is still consider one of a group of 'large but infrequent' cohesive lahars at Mount Rainier (Scott *et al.*, 1995). Travelling down the Puyallup river, the mudflow was 30m deep where it entered the Puget Sound lowland and deposits up to 6m deep underlie the town of Orting (Hoblitt *et al.*, 1998) (see Figure 5.3).

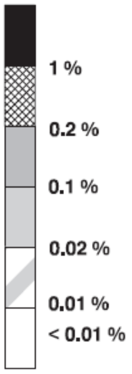
The occurrence of more recent volcanic activity has been disputed, with deposits initially attributed to a minor eruption dated between 1820 and 1854 (Mullineaux, 1974), now recognised as reworked tephra from the major subplinian event that occurred at the end of the Summerland period (Sisson & Vallance, 2009). Other historic eruptions between 1820 and 1894 have largely been discounted, although it is thought a small phreatic eruption took place in late 1894. No preserved deposits have been found to confirm this event but residents of Seattle reported seeing small, dark plumes rising from the summit (Driedger *et al.*, 2005; Sisson & Vallance, 2009).

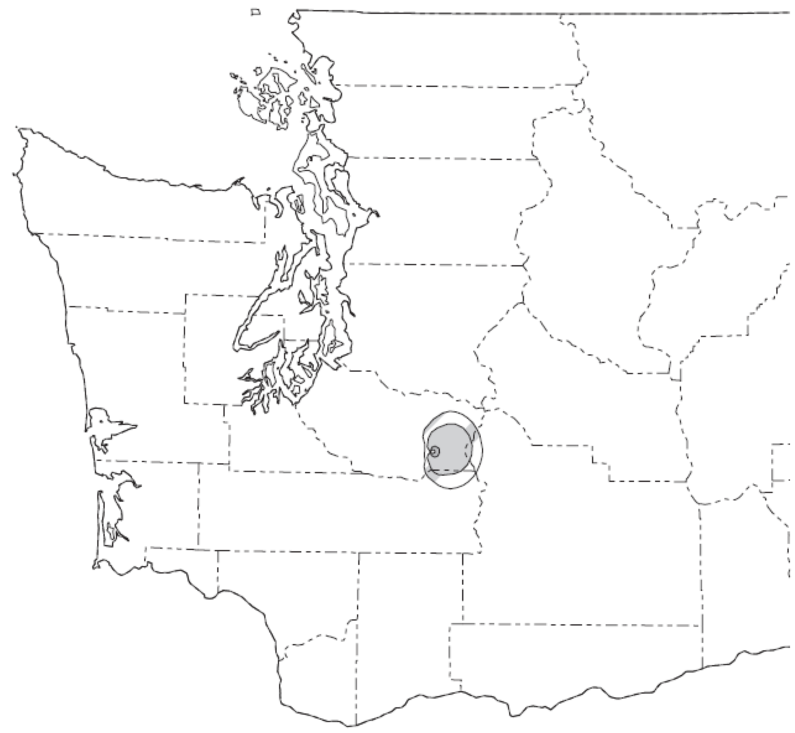
5.2.1.3. Volcanic Hazards

At least eight different volcanic phenomena are associated with periods of both activity and quiescence at Mount Rainier. During an eruption, primary hazards include lava flows, pyroclastic flows and surges, tephra, ballistic projectiles and lateral blasts. Significant secondary hazards include flank collapses, debris avalanches and the remobilisation of volcanic products into lahars. The latter can form from the eruption of hot tephra, lava, or pyroclastic flows onto the heavily glaciated summit, incorporating melted snow and ice. Primary hazards (excluding ashfall) are generally confined within or just beyond the boundaries of the national park, whilst ashfall and lahars could affect a much larger area at considerable distance from the volcano (Sisson, 1995; Hoblitt *et al.*, 1998). The tephra hazard has been mapped (Figure 5.4) using estimated annual probability of tephra accumulations of 1cm or more (Map 1)



(1) Annual probability of the deposition of 1cm or more of tephra from Mount Rainier.





(2) Annual probability of the deposition of 10cm or more of tephra from Mount Rainier.

Figure 5.4 Contour maps of Washington state showing the estimated annual probability of tephra accumulations of 1cm or more and 10cm or more from Mount Rainier (Hoblitt *et al.*, 1998).

and 10cm or more (Map 2). This takes into account the probability that the volcano will erupt, that the specific tephra thickness will occur at the specified distance, and that the wind will be blowing in a specific direction (Hoblitt *et al.*, 1998). Wind directions are expected to carry ashfall mainly to the east of the volcano.

A number of hazards may occur without an eruptive trigger. Fumarole measurements taken within the summit ice caves indicate episodic venting of magmatic gases (Zimbleman *et al.*, 2000), and the potential risk from asphyxiation and carbon dioxide poisoning should be considered by climbers who use these caves for shelter (Hoblitt *et al.*, 1998; Zimbleman *et al.*, 2000). Flank collapses, avalanches, lahars and debris flows represent a continuous and significant threat to both local and more distant communities. Such hazards may occur during times of dormancy, due to weakening of the mountain's structure through extensive hydrothermal alteration. These areas of destabilized rock and pressurised hydrothermal fluids may also provide source areas for non-magmatic phreatic explosions (Frank, 1995).

Hydrothermal alteration is the chemical change in rocks and minerals caused by the circulation of heated, mineral rich fluids. At volcanoes this results from the presence of magmatic-hydrothermal systems, which are characterised by long-lived vents above a central conduit system associated with buried, degassing magmas. During degassing, acidic fluids circulate through the volcano above the magma, leading to the alteration and weakening of rocks towards the summit (Zimbleman *et al.*, 2003). At Mount Rainier, this alteration is caused by the neutralisation of acidic magmatic gases condensing in a hydrothermal system fed by melt waters from the summit mantle of glacial ice (Zimbleman *et al.*, 2000). The exterior rocks of the volcano generally comprise unaltered deposits, whilst the interior may be composed of a buried, weakened core of clay-rich hydrothermally altered rocks (Frank, 1995; Moran *et al.*, 2000; Zimbleman *et al.*, 2003), although other studies dispute the extent of this (Finn *et al.*, 2001). It is the geologic structure and changes in rock strength that affect slope stability, and these structurally weakened zones have been identified as the areas from which future edifice collapse may originate, either as a result of gravity or seismic forces, as well as magmatic intrusion (Zimbleman *et al.*, 2000; Reid *et al.*, 2001; Zimbleman *et al.*, 2003).

The potential distribution of massive avalanches around Mount Rainier's edifice is non-uniform and can vary from sector to sector. This is because controls on the volcano's stability are influenced by the geological and mineralogical properties of the rock, as well as local relief (Reid *et al.*, 2001; Zimbleman *et al.*, 2003). At most stratovolcanoes, the middle and lower flanks are characterised by unaltered and unfractured units, whilst the upper flanks and summit region contain extensive areas of alteration, faulting and fracturing (Zimbleman *et al.*, 2003). At Mount Rainier, these areas are concentrated within the summit and west flank (Reid *et al.*, 2001). This is due to the location of an east-west trending structural zone (EWSZ) that bisects the volcano through its summit, and has probably existed for most of the volcano's history. Its position is marked by the location of the overlapping summit craters, fumaroles, dikes and fractures (Zimbleman *et al.*, 2003). This fracture system serves as a conduit for magma and the ingress for meteoric water, melted from the glaciated summit, as well as a focus for acidic gases from degassing magma (Rye *et al.*, 2003).

A number of studies (Frank, 1995; Crowley & Zimbleman, 1997; Moran *et al.*, 2000; Finn *et al.*, 2001; Reid *et al.*, 2001; John *et al.*, 2008) have conducted field, remote sensing, geological mapping and subsurface geophysical imaging to evaluate the collapse hazard at Mount Rainier. They identified the upper west flank, in the basin of the Sunset Amphitheatre (Figure 5.5) as the least stable sector of the volcano. Located below the summit crater and above the head of the Puyallup glacier, this area has been the source of the majority of historic debris avalanches (Zimbleman *et al.*, 2003), and the Round Pass and Electron Mudflows originated from the failure of hydrothermally altered rocks in this region (Reid *et al.*, 2001; Zimbleman *et al.*, 2003). As well as extensive zones of highly altered rock, Sunset Amphitheatre has numerous radial dikes, faults and open fractures (Zimbleman *et al.*, 2003), and hydrothermal alteration is most intense adjacent to these (Reid *et al.*, 2001; Rye *et al.*, 2003).

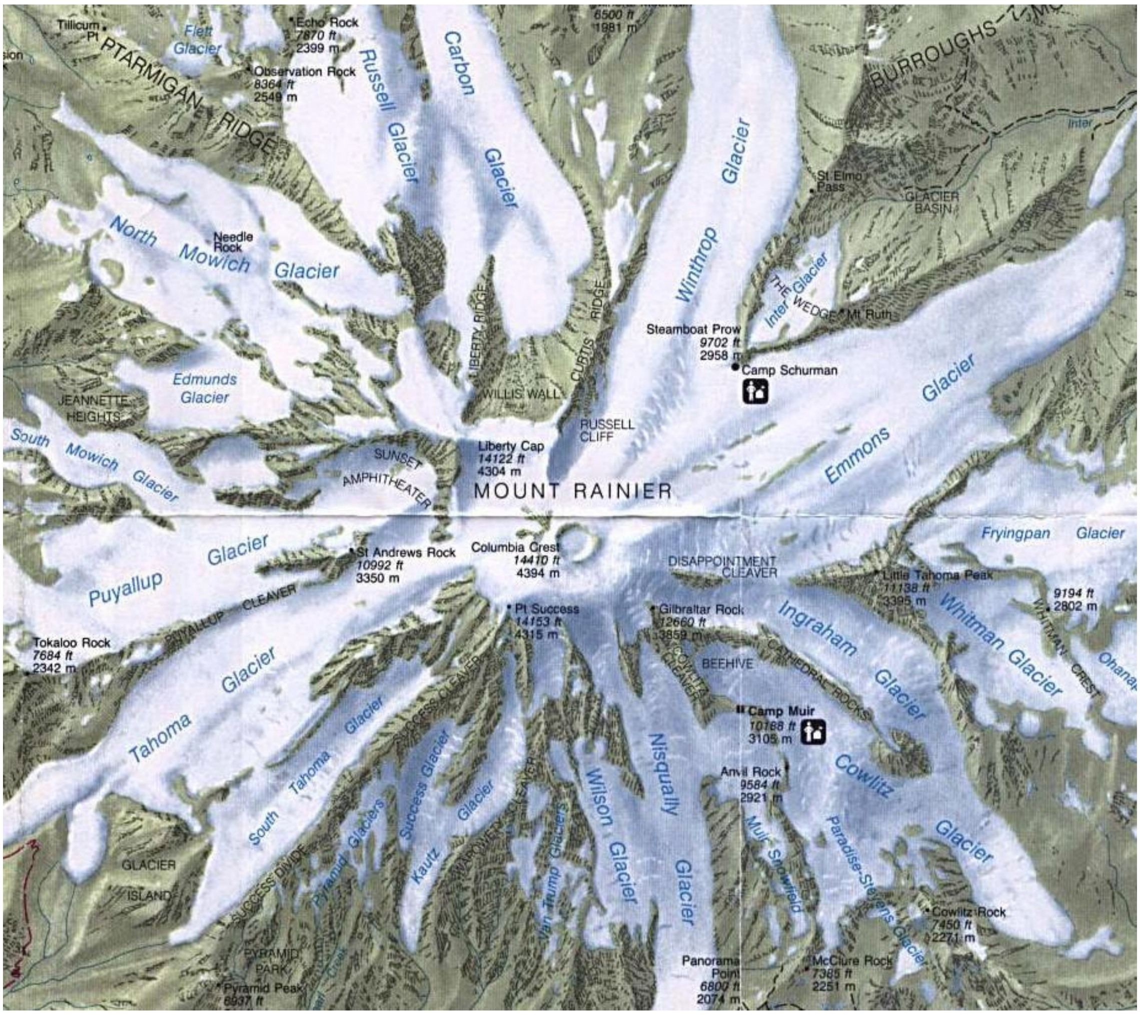


Figure 5.5 Map showing the summit, flanks and glaciers of Mount Rainier. Features referred to in the text include the Sunset Amphitheatre and Puyallup Glacier (west of the summit), Steamboat Prow (northeast of the summit) and the Willis Wall and Carbon Glacier (north of the summit). Scale: 1cm to 1km (National Park Service, 2003).

No significant bodies of hydrothermally altered rock have been detected on the upper east flank, suggesting the Osceola collapse removed much of the altered core and upper eastern portion of the old dyke system from this area (Finn *et al.*, 2001; Reid *et al.*, 2001). Although this has reduced the risk of future collapse in this area, some alteration occurs at both the east and west craters on the volcano's summit (Frank, 1995), as well as Little Tahoma Peak (east of the summit), Steamboat Prow (northeast of the summit) (Finn *et al.*, 2001), and a largely concealed area in the subsurface on the volcano's upper south flank (Reid *et al.*, 2001). Areas such as these are important for accessing not only the collapse hazard but also the debris flow hazard at Mount Rainier. The relatively high level of clay minerals within the altered rock is an important component in the rapid transformation of debris avalanches into far-travelled lahars. Not only is altered rock weaker, and therefore more prone to collapse but the presence of minerals like clay increase porosity, and therefore water content, and the more water contained within an avalanche, the more readily it will transform into a debris flow (Vallance & Scott, 1997).

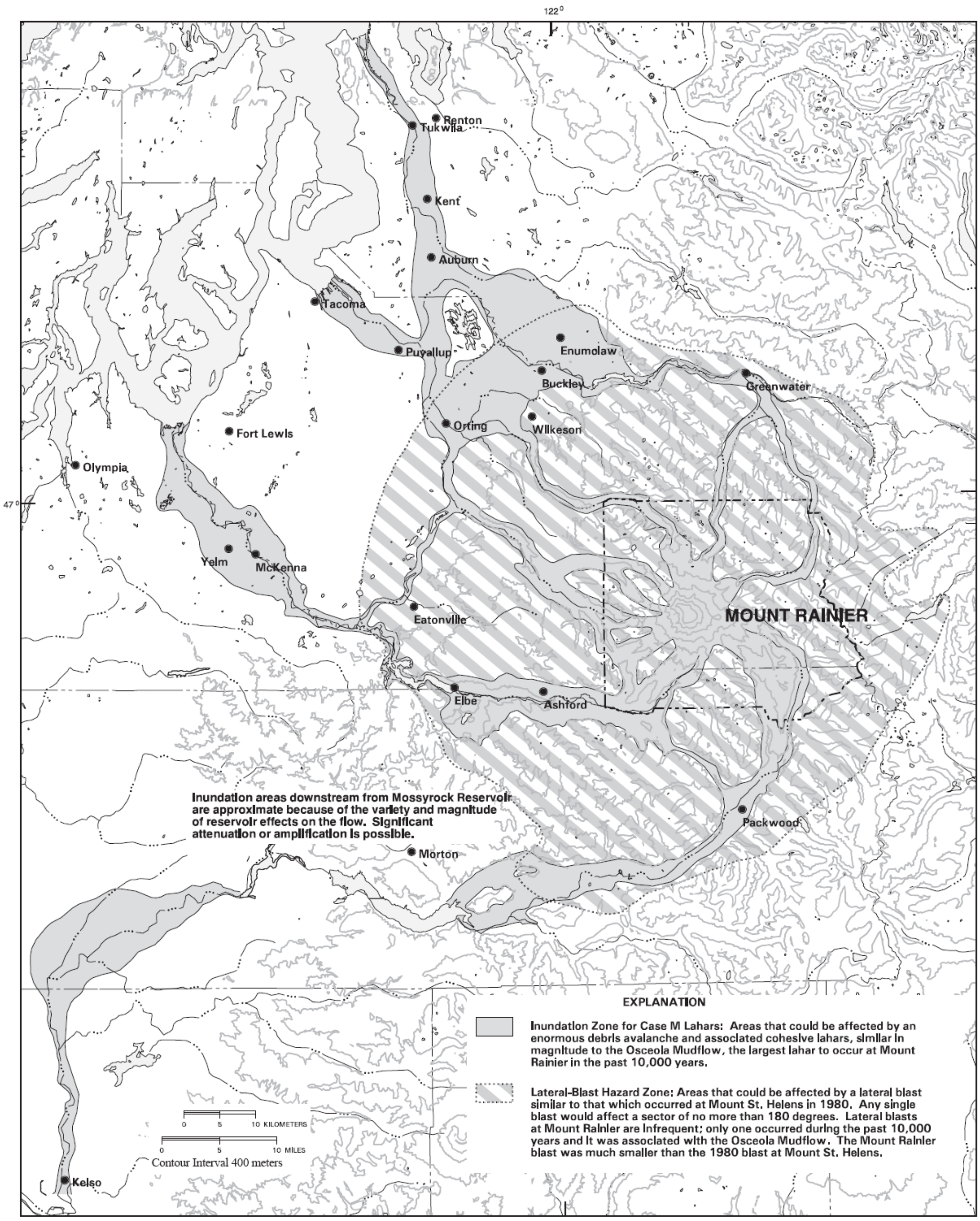
Geological evidence of past debris flows are found in all five major river drainage systems at Mount Rainier (White River, Cowlitz River, Nisqually River, Puyallup River and the Carbon River) (Scott *et al.*, 1995), and the deposits of at least 60 lahars from the last 10,000 years have been recognised (Hoblitt *et al.*, 1998). Large lahars have reached the Puget Sound lowland area as often as once every 500 to 1000 years and the chance of a lahar reaching the heavily populated Puget Sound lowland within an average human lifespan has been calculated as 1 in 10 (Driedger & Scott, 2008). Many more frequent but smaller debris flows have occurred, but often do not extend much beyond the boundaries of the national park (Vallance *et al.*, 2003; Driedger & Scott, 2008).

Table 5.1 Holocene period edifice-collapse-induced clay-rich ‘cohesive’ lahars (modified from John *et al.*, 2008).

Name	Age	Direction	Eruptive Period
Van Trump Debris Flow	9,500-10,000 yrs BP	South	Sunrise Eruptive Period
Reflection Lakes Lahar	6,800-7,200 yrs BP	South	Cowlitz Eruptive Period
Paradise Lahar	5,600-6,000 yrs BP	South	Osceola Eruptive Period
Osceola Mudflow	5,600 yrs BP	Northeast	Osceola Eruptive Period
Round Pass Mudflow	2,600-2,700 yrs BP	West	Summerland Eruptive Period
Unnamed	1,000-1,100 yrs BP	West	Fryingpan Creek Period
Electron Mudflow	500 yrs BP	West	No known eruption

Two types of lahar with different origins and behaviour have been recognised at Mount Rainier, and are categorised as ‘cohesive’ and ‘non-cohesive’ in the current USGS hazard assessment (Hoblitt *et al.*, 1998). Cohesive flows have a relatively high clay content, derived from chemically altered rocks, and are far-travelled, commonly reaching the Puget Sound lowland. They can remain largely untransformed for more than 100km from the volcano. Originating from failures of the deeply fractured, hydrothermally altered flanks of the volcano's edifice, they are generally associated with volcanic activity but can also occur without an eruptive trigger, e.g. through changes in the hydrothermal system or through non-magmatic earthquakes (Hoblitt *et al.*, 1998). Seven flank-collapse-induced cohesive debris flows occurred during the Holocene, six during eruptive periods, and one during a time for which no eruption has been documented (Table 5.1). These types of flows are generally high magnitude but low frequency events, the extreme example being the Osceola Mudflow (Hoblitt *et al.*, 1998; Sisson & Vallance, 2009). At least ten times larger than any other lahar from Mount Rainier during the last 10,000 years, this type of event is classed as a Case M flow, and is too infrequent to calculate an annual probability (Hoblitt *et al.*, 1998). The areas that could potentially be affected by a similar worst-case scenario, low probability, high consequence event are shown in Figure 5.6. Also shown on this map is the boundary of the hazard zone for laterally directed blasts. This was determined assuming a mobility equal to that of the 1980 Mount St Helens eruption, and extends farthest to the northwest due to a lack of topographic barriers. A blast would not effect the entire zone but a sector of no more than 180^{o} (Hoblitt *et al.*, 1998). Lateral blasts are rare at Mount Rainier, with only one occurring in the last 10,000 years associated with the Osceola Mudflow, which was much smaller than the Mt St Helens blast (*ibid*).

In contrast, non-cohesive lahars have a lower clay content, are generally less far-travelled than cohesive flows and readily transform downstream becoming more dilute. They commonly occur as a result of bulking of sediment in water surges caused by volcanically induced melting of glacial ice and snow, intense rainfall, or the abrupt release of water stored within glaciers (glacial outburst floods) following prolonged periods of hot weather. They may also occur following shallow slope failures and generally have a shorter recurrence interval than cohesive flows. Examples include the



Inundation areas downstream from Mossyrock Reservoir are approximate because of the variety and magnitude of reservoir effects on the flow. Significant attenuation or amplification is possible.

Inundation Zone for Case M Lahars: Areas that could be affected by an enormous debris avalanche and associated cohesive lahars, similar in magnitude to the Osceola Mudflow, the largest lahar to occur at Mount Rainier in the past 10,000 years.

Lateral-Blast Hazard Zone: Areas that could be affected by a lateral blast similar to that which occurred at Mount St. Helens in 1980. Any single blast would affect a sector of no more than 180 degrees. Lateral blasts at Mount Rainier are infrequent; only one occurred during the past 10,000 years and it was associated with the Osceola Mudflow. The Mount Rainier blast was much smaller than the 1980 blast at Mount St. Helens.

Figure 5.6 Map showing areas that could be affected in the future by low-probability, high-consequence hazards; (i) debris avalanche and associated cohesive lahar, similar in magnitude to the Osceola Mudflow, and (ii) a lateral blast, similar to the 1980 Mt St Helens event (Hoblitt *et al.*, 1998).

White River lahar of 1,200 years ago and the > 2,200 year old National Lahar, with more than a dozen other non-cohesive lahars extending into the Puget Sound lowland occurring within the last 6,000 years (Scott *et al.*, 1995; Hoblitt *et al.*, 1998; Vallance *et al.*, 2003).

Debris flows resulting from meteorological or hydrological processes have not typically extend beyond the boundaries of the national park. Such flows are commonly confined to drainages with large glaciers and because of their origins usually occur in the summer or early autumn. More than 30 events with volumes of between 1 to 3 million m^3, have occurred in historical times, most frequently within Tahoma Creek, although they have also descended Kautz Creek, the Nisqually River and the West Fork of the White River. At least 35 larger debris flows, with volumes ~10 million m^3, have occurred since 1924 and a significantly more voluminous flow in Kautz Creek during 1947, had an estimated total volume of 38 million m^3 (Vallance *et al.*, 2003). Although the history of Mount Rainier suggests that lahars may occur without an eruptive trigger, it is more likely they will result from renewed activity, which would generally be preceded by weeks or even months of increased seismicity beneath the volcano (Sisson, 1995). However, the small but not insignificant threat of a large, far-reaching debris flow originating on Mount Rainier without warning, represents the greatest volcanic hazard in the Cascade Range (Hoblitt *et al.*, 1998; Zimbleman *et al.*, 2000).

A number of authors have calculated the probability, or recurrence intervals for different magnitude lahar events originating somewhere on the volcano. The hazard zone boundaries for these different magnitude lahars are shown in Figure 5.7, and are based on the behaviour of flows that occurred in the past several thousand years. Events similar in size to the Electron Mudflow, termed Case 1 flows, are large enough to reach some parts of the Puget Sound, and have occurred approximately once every 500 to 1000 years and therefore have an annual probability of between 0.1 and 0.2 percent (Hoblitt *et al.*, 1998; USGS CVO, 2004-). National Lahar type events, termed Case 2 flows, have inundated flood plains well beyond the volcano, with a few reaching the

Puget Sound Lowlands. These have a calculated annual probability of between 0.5 and 1 percent, recurring approximately once every 100 to 500 years (Hoblitt *et al.*, 1998). The 1947 Kautz Creek debris flow provides a more recent, historic example of this type of flow, having an approximate recurrence interval of once every 100 to 200 years (Vallance *et al.*, 2003). The more frequent but smaller events, termed Case 3 flows, are largely restricted within the national park, and have recurrence intervals of one every 1 to 100 years for the volcano as a whole (Hoblitt *et al.*, 1998), and an annual probability of 1 in 2 (Vallance *et al.*, 2003). Cases 1 and 2 can be either eruption triggered or non-eruptive in origin. Case 3 flows are not triggered by eruptions (Hoblitt *et al.*, 1998).

Figure 5.7 also shows the hazard zonation for pyroclastic flows, which were calculated based on several assumption. Firstly, the location of the eruptive event was at the summit. Secondly, a mobility similar to pyroclastic flows and surges which have occurred at Mount Rainier in the past 10,000 years was assumed. Flow mobility was defined by an L/H value of 4.2 (Hoblitt *et al.*, 1998)[6], where L is the horizontal distance between the eruptive vent and the furthest point reached by the flow and H is the elevation distance between the same two points. This produced a boundary which extended approximately 3km beyond all of Mount Rainier's known pyroclastic flow deposits, providing a margin of safety (*ibid*).

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[6] The mobility of landslides, debris avalanches or pyroclastic flows etc, are more usually given as H/L ratios, rather than the L/H figure quoted in the USGS hazard assessment (Hoblitt, 1998). Generally, the ratio of the height dropped (H) over distance travelled (L) is as small as 0.2 for large scale pyroclastic flows and higher than 0.39 for small block and ash flows (Nakada, 2000). The author has calculated a H/L ratio of 0.24 for the pyroclastic flow mobility at Mount Rainier.

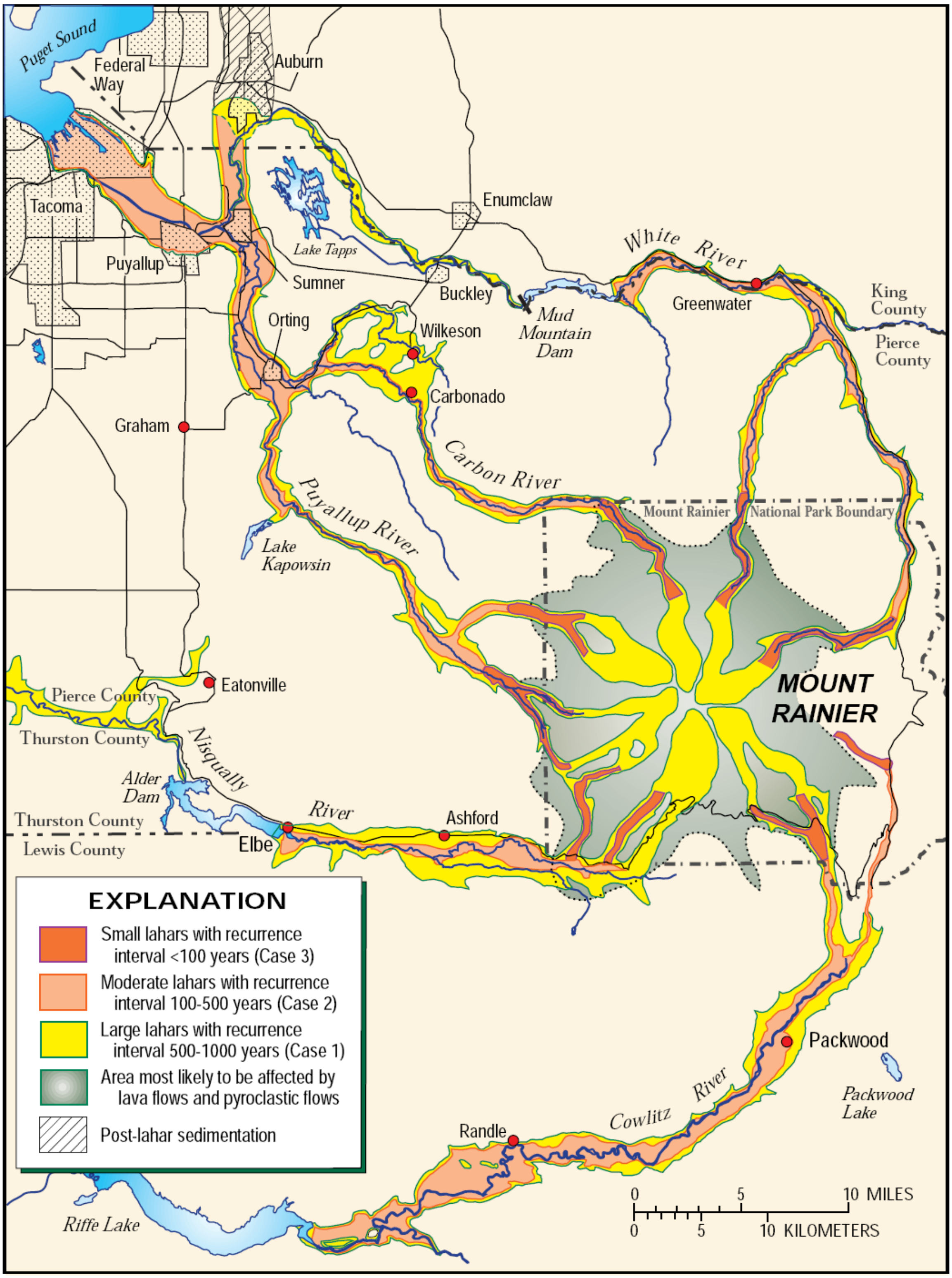


Figure 5.7 Map showing the hazard zones for Case 1, Case 2 and Case 3 type lahars from Mount Rainier, and the areas most likely to be affected by pyroclastic flows and lava flows (Hoblitt *et al.*, 1998).

The overall risk to people and property from lahars and debris flows is increasing. This is due to rapid population growth within the Puget Sound region, and the expansion of communities near Mount Rainier (Sisson, 1995). Economically important businesses, hydroelectric dams, major seaports and highways, as well as utility pipelines, and approximately 80,000 residents are all located within the Mount Rainier lahar hazard zones (Driedger & Scott, 2008). The smaller debris flows that are largely confined to the national park represent a threat to a number of campgrounds, roads and park infrastructure (Vallance *et al.*, 2003). Representing the most likely volcanic hazard from Mount Rainier, lahars are a potential threat to two of the three case study communities selected for this research. The selection of the three sites was based upon their proximity to the volcano, and their potential risk from one or more different volcanic hazards. A novel aspect of this research was the selection of a community located to the east of the volcano, at risk from tephra fall. All previously published research on hazard exposure at Mount Rainier has concentrated on lahar risk in communities located to the north and west of the volcano. An assessment of each of the case study communities and their hazards is detailed in the following three sections.

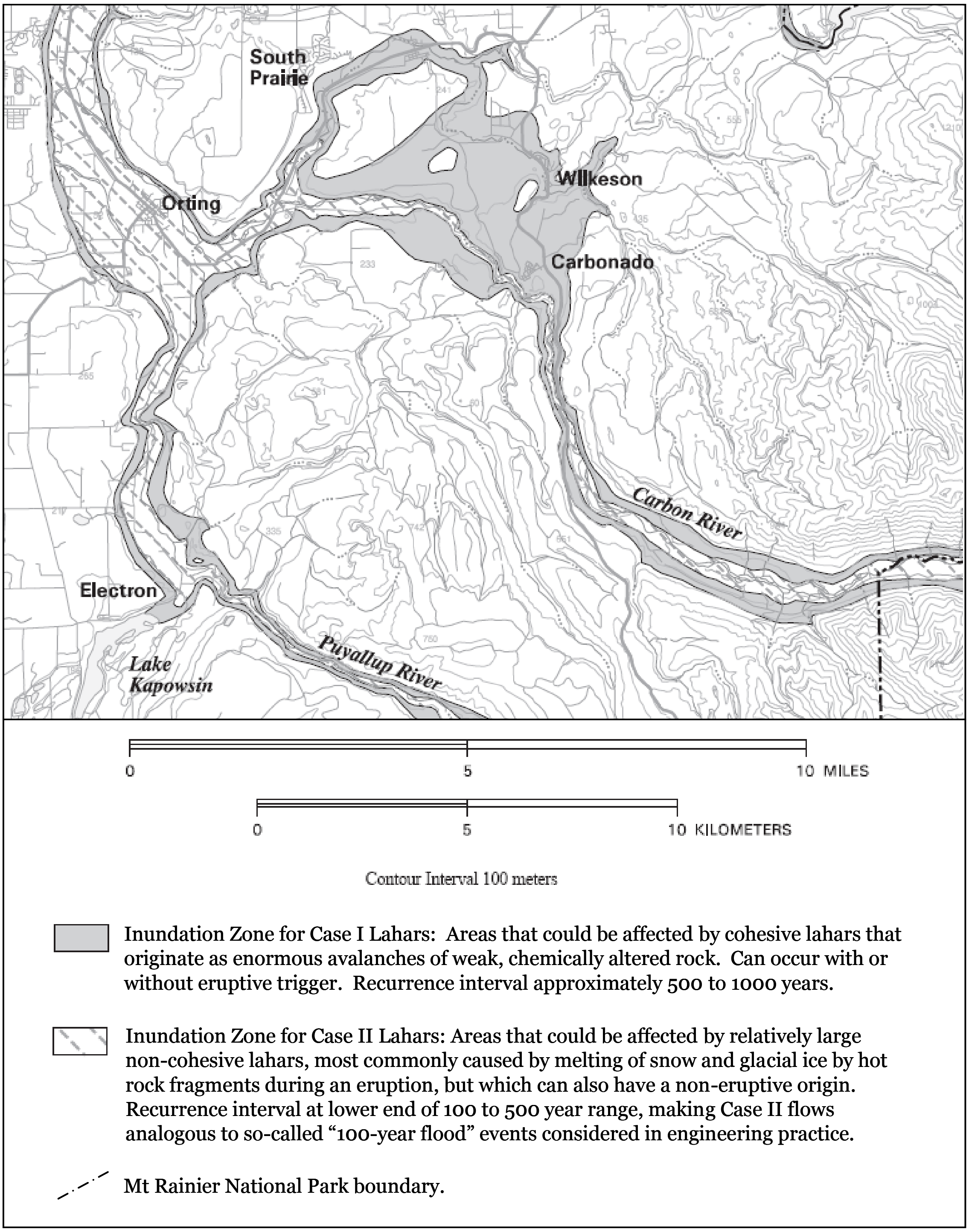
5.2.2. Population, Infrastructure and Possible Hazards in Carbonado

Carbonado is situated 60km south of Seattle, on State Route 165, which continues for approximately 20km to both the Mowich Lake area and Carbon River entrance of Mount Rainier National Park. This small isolated town sits beside a steep sided gorge through which the Carbon River flows approximately 90m below. Around 40 river km upstream, to the south east is Mount Rainier. The direct distance between Carbonado and Mount Rainier's summit is less than 35km. Previously a booming coal mining town, Carbonado's population has been declining since the end of the coal mining era in the 1920s, and at the last census in 2000 there were 621 inhabitants in just over 200 households (US Census Bureau, 2000). Previously serviced by a railroad, it has also lost its hospital, hotel and stores. A small community, the only infrastructure/facilities are a post office, church, town hall, volunteer fire department and school teaching children from kindergarten age through to 8th grade (5 to 13/14 years old). Known as a "bedroom community", the majority of inhabitants are employed out of town and work in the Enumclaw or Puyallup/Sumner districts.

Upstream from Carbonado, the Carbon River drains the Carbon Glacier which extends almost 10km from the northern flank of Mount Rainier (see Figure 5.5). This record breaking glacier is the thickest (200m), most voluminous (0.8km^3) and has the lowest terminus (1100m) of any glacier in the contiguous United States, and is the longest on Mount Rainier (Driedger, 1993). The Carbon River drains this glacier and flows northeast, joining the Puyallup River downstream of the town of Orting. For much of its course it flows through a deeply incised gorge, from which any volcaniclastic flow deposits have been eroded (Scott *et al.*, 1995). Crandell (1971) observed a single lahar deposit, up to 3m thick, at Chenius Falls <5km downstream from the foot of the glacier. Deposited on bedrock, the lahar is overlain by a tephra deposit attributed to an eruption of Mount St Helens around 3,400 years ago (tephra layer Y). Two valley-wide, non-cohesive lahar deposits, neither of which travelled further than 10km from the terminus of the Carbon Glacier were noted by Scott *et al.* (1995). One has been dated as older than 530 years and the other younger than 530 years, based on the relative position of tephra deposits erupted from Mount St Helens during the 1480s. From the preservation of layer Y tephra at the surface low on valley slopes, Scott *et al.* (1995) concluded that in the last 3,400 years (e.g. since layer Y was erupted), no large debris flows have originated in this river system.

Crandell (1971) speculated that the reason so few lahars have originated in this valley is due to the formation of the edifice above the head of the Carbon Glacier. Above the rear wall of the glacier's cirque extends the sheer face of the 1,200m Willis Wall. A ridge extending along the cliff's upper edge is the largest remnant of the old crater rim that remained following the sector collapse that spawned the Osceola Mudflow. The result of this ridge is to divert any flood originating in the summit area away from the head of the Carbon Glacier, directing it to the west, down the Puyallup River valley, or the east, down the West Fork of the White River.

The scarcity of previous debris flow deposits in the Carbon River valley system, and the existence of the diversionary ridge above the Carbon Glacier, does not preclude the occurrence of future cohesive lahars originating from a sector collapse in this area (Frank, 1995; Scott *et al.*, 1995). However, studies by Reid *et al.* (2001) recognised that although the steep topography of the Willis Wall could influence the stability of this sector, they concluded the area was not subject to extensive hydrothermal alteration but was composed of relatively strong and therefore stable rocks, reducing the collapse hazard significantly. Nevertheless, the risk from a non-cohesive lahar originating in this valley is significant due to the large volume of glacial ice which could be subject to melting (Scott *et al.*, 1995). Whatever the formation mechanism for lahars in this drainage, the town of Carbonado is protected from all but the very largest lahars by the gorge through which the river runs at this point. This is reflected in the current volcanic hazard assessment and lahar hazard zonation map, prepared for the USGS by Hoblitt *et al.* (1998). This restricts inundation of Carbonado to a Case I type debris flow (Figure 5.8); a large cohesive flow originating as a massive avalanche of weak, chemically altered rock. The Electron Mudflow is considered to be a characteristic Case I flow, and previous flows of this type have occurred on average about once every 500 to 1000 years, somewhere on Mount Rainier. The travel time for a lahar to reach Carbonado once detected by the current acoustic flow monitoring system installed in the Carbon River valley is less than 15 minutes (Pierce-County-DEM, 2006). It is unlikely that the steps necessary to disseminate this information to the town could be achieved in time to allow any kind of evacuation. However, as discussed, the structure of the mountain above the Carbon Glacier reduces the likelihood of the necessary collapse originating from the northern flank. Furthermore, the more likely non-



▨ Inundation Zone for Case I Lahars: Areas that could be affected by cohesive lahars that originate as enormous avalanches of weak, chemically altered rock. Can occur with or without eruptive trigger. Recurrence interval approximately 500 to 1000 years.

▧ Inundation Zone for Case II Lahars: Areas that could be affected by relatively large non-cohesive lahars, most commonly caused by melting of snow and glacial ice by hot rock fragments during an eruption, but which can also have a non-eruptive origin. Recurrence interval at lower end of 100 to 500 year range, making Case II flows analogous to so-called "100-year flood" events considered in engineering practice.

-·- Mt Rainier National Park boundary.

Figure 5.8 Detail of the USGS hazard map showing the lahar hazard zone boundaries for Case I and Case II lahars for the town of Carbonado and the surrounding area. The lateral blast hazard zone covers the whole of the area shown and extends in an ark approximately 3km beyond the town of Orting (modified from Hoblitt *et al.*, 1998).

cohesive type debris flows, which originate from melting of the Carbon Glacier for example, would be unlikely to be either sufficiently far-travelled to reach Carbonado, or be sufficiently voluminous to overtop the Carbon River gorge (Hoblitt *et al.*, 1998).

The proximity of Carbonado to the volcano increases its risk from a number of other volcanic phenomena. Lava flows and pyroclastic flows have largely been confined within the boundaries of the national park. However, data in Newhall & Hoblitt (2002) show that for VEI 4-5 eruptions (for Mount Rainier a worst case scenario), a pyroclastic flow has a small but significant (approximately 5%) chance of exceeding 30km distance from the vent. This would represent the largest eruption of Mount Rainier in Holocene times, and no geological evidence has yet been found for such far-reaching pyroclastic flows. The risk to the town is therefore thought to be minimal for this type of hazard.

The risk from a massive sector collapse, either as a result of magmatic intrusion into the volcano, seismic activity or erosional forces, is not limited to their transformation into lahars. At Mount St Helens, during the 1980 eruption, the debris avalanche following the collapse of the north flank travelled a distance of 24km down the North Fork of the Toutle River (Tilling *et al.*, 1990) (see Appendix 4 for details of this eruption). Appreciably higher than Mount St Helens, and subject to significantly more hydrothermal weakening, the run-out distance from a sector collapse could be further at Mount Rainier. The various distances from, (i) the snout of the Carbon Glacier (33km) and, (ii) the foot of the Willis Wall (42km) to Carbonado, do not preclude the possibility that a massive flank collapse could reach the town, although this would be unlikely.

Lateral blasts, although rare in the eruptive history of Mount Rainier, have occurred (e.g. during the Osceola Mudflow eruptive event), and could pose a threat to Carbonado residents. Hoblitt *et al.* (1998) base their lateral blast hazard zone on an event of similar size to that of the 1980 Mount St Helens eruption, which extended over 25km from the volcano. Because of the greater altitude of Mount Rainier the blast-hazard zone is larger than the 1980 Mount St Helens blast zone. This greater altitude and the lack of topographic barriers to the northwest of the volcano, could result in a blast zone extending over 15km beyond the town of Carbonado, potentially exposing the town to effects similar to those suffered in the intermediate zone following the Mount St Helens blast (e.g. the complete flattening of old growth forest and searing temperatures). Precursory signals associated with the intrusion of magma, which is usually responsible for creating the conditions necessary for the occurrence of a lateral blast, include seismic activity and bulging of the volcano's flanks. Monitoring of the volcano would detect these signs, allowing the risk of a lateral blast to be anticipated, and the necessary mitigation strategies to be put into place.

Mount Rainier is considered a moderate tephra producer relative to other Cascade volcanoes (Mullineaux, 1974; Hoblitt *et al.*, 1998), and although mapping of tephra deposits within the national park indicate that volcanic ash would generally be carried to the north, east or south (Mullineaux, 1974), the proximity of Carbonado to the volcano means ash hazard in this area cannot be excluded, although the risk compared to communities downwind is small. Newhall & Hoblitt (2002) estimate the probability of tephra accumulation exceeding 10cm at 30km downwind are about 10% for a VEI 3 eruption and about 80% for a VEI ≥4. The accumulation of several cm of tephra would have an adverse effect on transportation, power distribution and surface water supplies. A 10cm accumulation of volcanic ash, particularly if wet, is the threshold beyond which structural damage to buildings begins (Ewert *et al.*, 2005). Current hazard estimates place Carbonado in a zone with an annual probability of less than 0.01% for tephra deposition of 1cm or more (Hoblitt *et al.*, 1998) (see Figure 5.10).

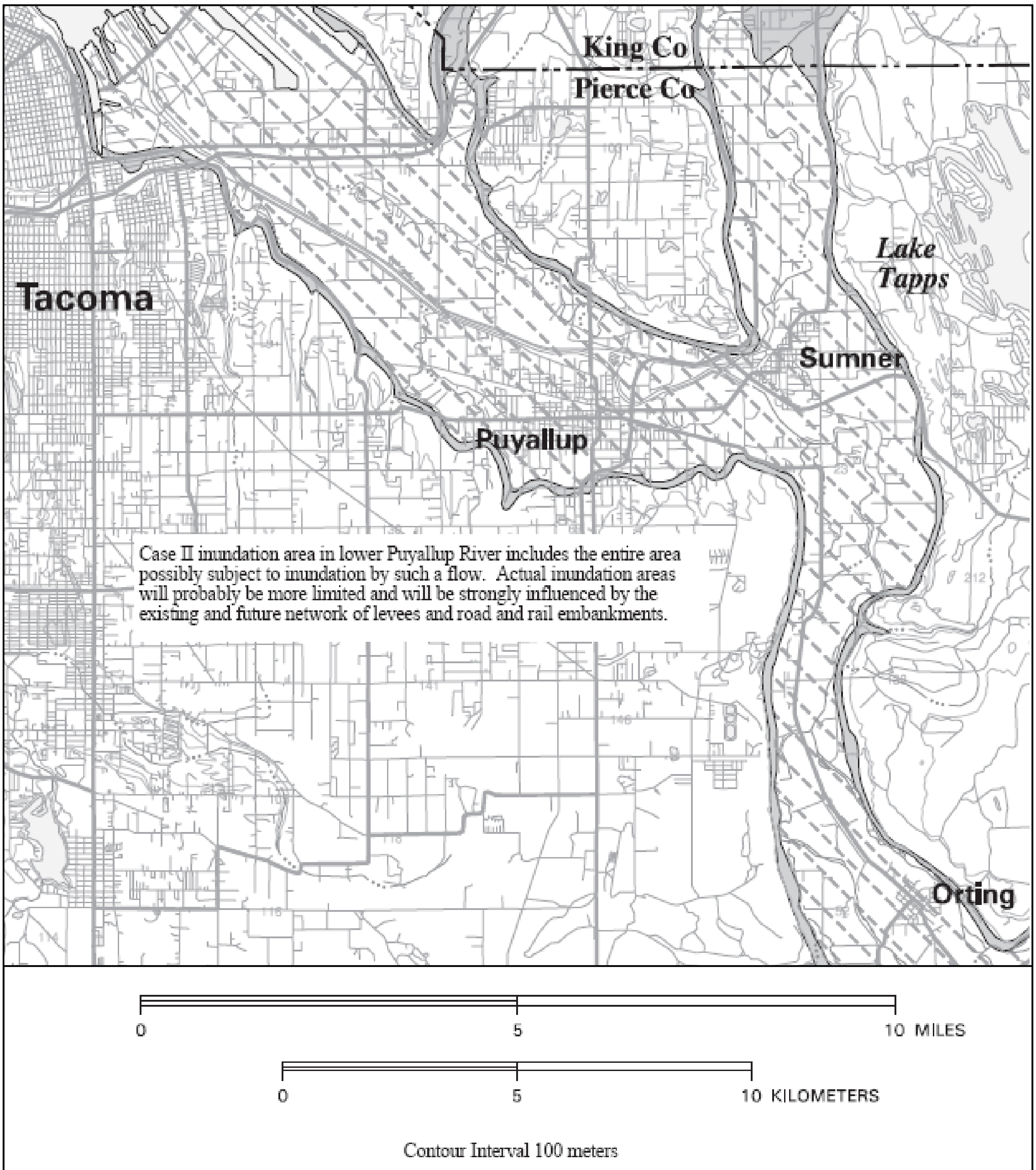
5.2.3. Population, Infrastructure and Possible Hazards in Sumner

Less than 50km to the south of Seattle is the city of Sumner. Together with Puyallup, Auburn and Tacoma, these cities cover the area known as the Puget Sound lowland. Sumner lies on the confluence of the White and Puyallup rivers, both of which head on

Mount Rainier; the White River draining the east flank and the Puyallup River the west (see Figure 5.2). The distance downriver from the volcano to Sumner via the Puyallup River is approximately 65km. The 2000 census recorded a total of 8,504 residents in just over 3,500 households (US Census Bureau, 2000). Growing from a predominantly farming town, the city now has a rapidly expanding industrial area to the north. However, less than 20% of residents are employed in the city, the majority travelling to nearby Puyallup, Tacoma or Seattle for work. Construction, educational services and healthcare are the main employers within the city. There is one high school, three middle schools and six elementary schools, as well as a library, shopping centre, museum, hotel, other stores, restaurants and six banks. The White River Power Plant is situated less than 5km to the north. State Highway 167, or the 'Valley Freeway' connects Sumner, via Interstate 5 with Seattle. Other major routes include State Route 410 and the four lane State Route 512 linking through Puyallup to Tacoma. The town is also linked to Seattle and Tacoma via a passenger rail service.

Sumner's location on the flood plains of the Puget Sound lowland, and at the confluence of two rivers which head on Mount Rainier, contribute to its significant risk from both cohesive and non-cohesive lahars (Figure 5.9). A sector collapse originating from any of the west (via the Puyallup River), north (via the Carbon River into the Puyallup River) or east flank's (via the West Fork or main fork of the White River) could mobilise into a lahar that would threaten the town. The risks associated with the lahar hazard in the Carbon River valley has been discussed in relation to Carbonado, and as this river flows into the Puyallup River above Sumner, a sufficiently far-travelled lahar could reach the town, less than 30 river km beyond Carbonado.

The risk of cohesive lahars moving down the two forks of the White River is dependent on the collapse potential of the east flank of the volcano. Although the existence of small areas of hydrothermally altered rock at the east summit crater, and at several areas on the east and north-eastern flanks (Frank, 1995; Finn *et al.*, 2001; Reid *et al.*, 2001) does indicate areas of reduce stability, much of the weaken, unstable sections of



Case II inundation area in lower Puyallup River includes the entire area possibly subject to inundation by such a flow. Actual inundation areas will probably be more limited and will be strongly influenced by the existing and future network of levees and road and rail embankments.

■ Inundation Zone for Case I Lahars: Areas that could be affected by cohesive lahars that originate as enormous avalanches of weak, chemically altered rock. Can occur with or without eruptive trigger. Recurrence interval approximately 500 to 1000 years.

▨ Inundation Zone for Case II Lahars: Areas that could be affected by relatively large non-cohesive lahars, most commonly caused by melting of snow and glacial ice by hot rock fragments during an eruption, but which can also have a non-eruptive origin. Recurrence interval at lower end of 100 to 500 year range, making Case II flows analogous to so-called “100-year flood” events considered in engineering practice.

Figure 5.9 Detail of the USGS hazard map showing the lahar hazard zone boundaries for Case I and Case II lahars for Sumner and the surrounding area (modified from Hoblitt *et al.*, 1998).

the upper eastern edifice were removed during the Osceola collapse. This means that the summit and upper east side of the volcano are relatively free of weak, highly altered rock, and therefore have a relatively low risk of failure (Finn *et al.*, 2001; Reid *et al.*, 2001). However, several large post-Osceola lahars have occurred in the White River valley, most as a result of the volcanism responsible for constructing the present summit cone (~ 2,000 years ago). Predominantly non-cohesive, these flows probably originated as meltwater surges caused by lava flows, pyroclastic flows, phreatic eruptions or geothermal heating (Scott *et al.*, 1995). Concurrent flows in the White, Nisqually and Puyallup River system are ascribed to this summit-cone volcanism. Approximately 1,500 years ago, the Dead Man Flat lahar assemblage, believed to consist of several synchronous flows, occurred down both the West Fork and main fork of the White River. Deposits from these flows are found outside the park boundaries, at which point they overtop Osceola Mudflow deposits as much as 60m above the river bottom. Further down stream at the Mud Mountain Dam, 56km down-valley from the summit of Mount Rainier (see Figure 5.2), deposits occur at least 30m above the current river bottom. These deposits suggest that the flows were sufficiently voluminous to reach the Puget Sound (Scott *et al.*, 1995). The last large debris flow recognised in the White River valley, is dated to 1550 and is thought to have been non-volcanic in origin, extending at least as far as the Mud Mountain Reservoir (Crandell, 1971; Scott *et al.*, 1995).

Although past evidence for large lahars exists in the White River valley, the greatest threat to Sumner from future debris flows is as a result of the instability of the west flank of the volcano. The largest volume of altered rock, as well as an abundant dyke system, lies beneath Sunset Amphitheatre on the upper west side of the edifice (Finn *et al.*, 2001; Reid *et al.*, 2001; John *et al.*, 2008). Work by John *et al.* (2008) indicates that successively younger debris flows originating in this area have increasingly contained more strongly altered rocks. The last significant collapse, the 1910 to 1927 Tahoma Glacier avalanches are composed of rock and mineral assemblages similar to those of the Osceola Mudflow. This suggests that exposures at Sunset Amphitheatre are approaching a core of alteration formed by an extinct hydrothermal system (John *et al.*, 2008), and explains the abundance of altered rock in a area devoid of hydrothermal activity and fumaroles (Frank, 1995). This area represents the most likely origin for future edifice collapse and could feed cohesive debris flows into the Puyallup River valley, which, if of sufficiently large volume, could reach Sumner less than 65 river km downstream.

Crandell (1971), recognises nine postglacial lahars in the Tahoma Creek valley and the two branches of the Puyallup River. One of the oldest large, cohesive debris flows recognised in the Puyallup River system is the Round Pass Mudflow, dated to approximately 2,800 years ago (*ibid*). Most likely originating as a debris avalanche from the Sunset Amphitheatre, this flow extended into the Puget Sound lowland and had sufficient depth near the park boundary to knock down trees 240m above the valley bottom. A peak flow velocity of at least 40 m/s has been estimated from runup on lateral ridges, and was sufficient to send a major flow across Round Pass and into the Tahoma Creek valley (Crandell, 1971; Scott *et al.*, 1995). A further large lahar occurred around 1,000 years ago and has been recognised in deposits found beyond the confluence with the Mowich River, but may have extended much further (Scott *et al.*, 1995). The last large, clay rich lahar to occur in the Puyallup River valley system is the Electron Mudflow, named after the town of Electron were deposits underlie the valley floor and extend northwards to the suburbs of Sumner. Boulders within this mudflow measuring at least 10m in diameter are found just south of the town of Orting. Here the valley widens and would have caused the lahar to spread out laterally, thin and decelerate, allowing the larger boulders to settle (Crandell, 1971). Dated around 500 years ago, no volcanic activity has been recorded at this time, suggesting a non-eruptive cause for the lahar-triggering debris avalanche. Building on the work of Crandell (1971), Scott *et al.* (1995) documented six postglacial cohesive debris flows that inundated the Puget Sound lowland, and a further seven cohesive flows which may have been large enough to reach the lowland area via the Puyallup River. Deposits of non-cohesive lahars have generally been covered by the larger cohesive flows, but several have been recognised, including the most far-reached non- cohesive flow from Mount Rainier, which extended 6km beyond the lowland boundary (Crandell, 1971; Scott *et al.*, 1995).

Evidence for past cohesive debris flows that were sufficiently voluminous to extended down river to the city of Sumner and beyond, and the existence of large areas of weakened hydrothermally altered rock high on the west flank of the volcano, make the towns and cities which lie along the river valley systems to the west of the volcano some of the most vulnerable to volcanic hazard in the United States (Ewert, 2007). However, the risk from lahars entering the White River valley has been reduced, not only as a result of the lack of altered rock necessary to precipitate a large debris avalanche, but also due to the location of the Mud Mountain Reservoir. Situated on the boundary between the Cascade Range and the Puget Sound lowland, this rock and earth-filled structure is used to control flooding in the lowlands by retaining flood water following heavy rainfall. During normal operation the water level behind the dam is kept to a minimum. Scott *et al.* (1995) estimates the dam would be capable of retaining all but the largest flows, and would still significantly attenuate the maximum lahar, retaining more than 57% of an Electron Mudflow type volume. Any uncontained flow would be held within the White River unless the flow was deep enough to overtop the valley wall near Buckley, sending part of the flow into the Carbon River drainage (Crandell, 1971).

The situation for the Puyallup River valley is very different. The most unstable portion of the volcanic edifice, the Sunset Amphitheatre, is situated above the head of the Puyallup River valley and no dams exist on this drainage to attenuate debris flow hazard. In addition, the last major flank collapse and resulting lahar to occur in this area does not appear to have been precipitated by an eruption. Without concomitant volcanic activity no prior warning would be given until a lahar had been generated. The acoustic flow monitoring systems in the Puyallup and Carbon River valleys were installed in recognition of this threat and provide a real-time lahar warning system for towns along these rivers. The travel time for a lahar detected at the monitoring station within the Puyallup River valley to reach Sumner is estimated at just over one hour (Pierce-County-DEM, 2006). Dissemination of lahar warnings to residents in Sumner is via an auditory warning siren, although opinions expressed by a number of residents interviewed for this research indicated that coverage of the siren does not extend across the entire town, rendering it inaudible in some areas. Depending on the time of day, the ability to evacuate all residents within this time frame via the designated evacuation routes may prove problematic.

A less significant hazard for residents of Sumner would be ashfall. The risk is similar to that faced by Carbonado residents and would therefore be minimal. Prevailing wind directions across western Washington are from the south-west and tephra from Mount Rainier would be carried away from Sumner and Carbonado. Less frequent winds blow from east to west, and during these times ash could be scattered across much of the Puget Sound Lowland (U.S. Geodynamics Committee,1994). The current tephra fall hazard map (Figure 5.10), estimates the annual probability of ashfall of 1cm or more occurring in Sumner as < 0.01% (Hoblitt *et al.*, 1998).

5.2.4. Population, Infrastructure and Possible Hazards in Ellensburg

Home of the Central Washington University (CWU) and the county seat of Kittitas County, Ellensburg is located to the east of the Cascade Mountain Range (see Figure 1.4). It can be accessed from Seattle via Interstate 90, approximately 160km away. The direct distance to the summit of Mount Rainier to the west is just over 90km. The city's resident population was measured at 15,414 in the last US census (US Census Bureau, 2000), but this includes approximately 9,000 CWU students. As well as the university, additional education facilities include two high schools and eight elementary/middle schools. The surrounding Kittitas valley is significant for it hay production, but only a minority work within agriculture. With over 25% of workers, the most common employment is in educational services. Three quarters of residents work within the city. Other facilities include the Kittitas Community Hospital, a library, post office, two museums, numerous hotels and banks, restaurants and stores. Road routes serving the city include I-82 southeast to Yakima and the major interstate highway I-90, the northern coast-to-coast route across the United States. Formally served by the Northern Pacific railroad, the train service through Ellensburg is now only used for freight transportation. Located 3km north of the city is Bowers Field airport, which services mail, passenger and freight flights to various cities within the Pacific Northwest region.

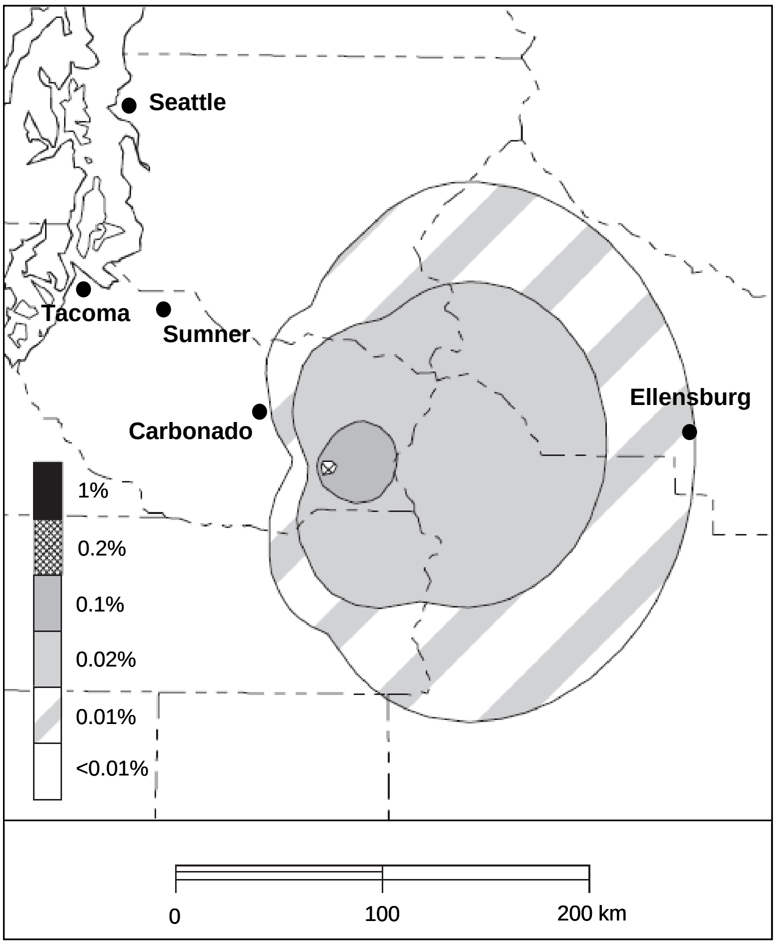


Figure 5.10 Map showing the annual probability of the deposition of 1cm or more of tephra from Mount Rainier.

Due to its distance from the volcano, and because all rivers that head on the mountain drain to the west into the Pacific Ocean, Ellensburg is at risk from only a single hazard originating from an eruption of Mount Rainier. The prevailing wind direction across this region of Washington is from the west (National Park Service, 2003), so tephra from the volcano would be carried towards the Ellensburg area. However, Mount Rainier has produced only minimal tephra during past eruptions (Mullineaux, 1974; Hoblitt *et al.*, 1998), and Hoblitt *et al.* (1998) estimates the annual probability of ash fall of 1 cm or more occurring in the area to be just 0.01% (Figure 5.10). A number of residents questioned during this research reported having direct experience of ashfall within the town during the 1980 Mount St Helens eruption, although ashfall within the town was minimal. The possible implications for the town during an eruption of Mount Rainier, should prevailing winds blow ash towards the community, may be similar to those experienced by the town of Yakima (situated approximately 45km south of Ellensburg) during the Mount St Helens eruption. The city was covered in a blanket of ash measuring up to 8 cm in depth, and the cost of the clean-up operation ran to $5.4 million (Zais, 2001).

5.2.5. Threat Assessment Results and Discussion

Using the systematic review detailed in the previous sections, which provides a discursive assessment of volcanism at Mount Rainier, the eruptive history of the volcano, the potential hazards, and a consideration of the population and infrastructure at risk in three communities, the threat assessment procedure developed using the methodology modified from Ewert was completed for the cities of Carbonado, Sumner and Ellensburg. Using this system, three separate scores can be calculated for; (i) hazards, (ii) exposure and (iii) overall threat. These scores are calculated according to the metric detailed in Chapter 3. The maximum score possible for hazard factors is 14, whilst the maximum score for exposure factors is 4, plus the $\log_{10}$ of the population of the community under assessment. The overall threat assessment score is derived by multiplying the hazard and exposure factors. The completed assessment metrics for each community are discussed below.

5.2.5.1. Threat Assessment of Carbonado

Due to the towns relative proximity to Mount Rainier, its location next to the Carbon River, and its potential exposure to several different volcanic phenomena, Carbonado scored 7 out of a possible 14 on the hazard factor element of the threat assessment metric (Table 5.2). Lahars, debris avalanches and lateral blasts each contributed 2 to the overall score, whilst ashfall scored 1. The town is considered to be sufficiently distant from the volcano to avoid any threat from lava flows, and all but a very small, and unlikely risk from pyroclastic flows, and therefore scored zero for each of these hazard types. Due to local topographic features, e.g. the deep, steep sided gorge through which the Carbon River runs at this point, the town is protected from all but the very largest lahars originating on the volcano. These could be either eruptive or non-eruptive in origin, but most likely cohesive in nature. The most recent example of a lahar sufficiently large to overtop the Carbon River gorge was the Electron Mudflow. This was caused by a flank collapse that was not associated with volcanism. The threat from a massive debris avalanche, although significant compared to other hazards, is mitigated by the location of the Willis Wall, situated at the head of the Carbon Glacier. This region of the volcano has not been subject to significant hydrothermal alteration and is therefore considered stable. In addition, it is thought the position of the Willis Wall could act to redirect melted glacial snow and ice from the summit area away from the Carbon valley. Although there is only evidence of a single lateral blast at Mount Rainier in the last 10,000 years, Carbonado would be at risk due to its proximity (35km from the volcano) and its location to the northwest, where few topographical barriers exist. A lesser hazard, tephra deposition represents a threat because of the towns proximity to the volcano, but its location to the northwest would spare it from the worst of any ashfall, because the prevailing wind direction would carry most tephra to the east.

Table 5.2 Completed threat assessment for Carbonado.

Hazard Factors	***Score***
Ash/tephra:	Max score = 2
• If located ≤ 100km from volcano: score = 1	1
• If yes to above; located in prevailing wind direction = 1	0
Pyroclastic flows:	Max score = 2
• If located within boundaries of National Park: score = 1	0
• If yes to above; within main river valleys: score = 1	0
Lava flows:	Max score = 1
• If located within 4km of summit vent: score = 1	0
Lahars/mudflows:	Max score = 4
• If located on or near river which heads on the volcano: score = 1	1
• If yes to above; ≤ 60km downstream from the volcano: score = 1	1
• If located in area associated with particular geological features, e.g. town protected as river runs through steep-sided, deep valley: score = 0, if town located on a flood plain: score = 1	0
• If located at confluence of one or more rivers that head on the volcano: score = 1	0
Debris avalanche:	Max score = 3
• If located ≤ 30km downstream/slope from volcano: score = 1	1
• If yes to above; located to the northwest of the volcano: score = 1	1
• If located in area associated with particular geological features, e.g. mountain ridges upstream provide protection from avalanche hazard: score = 0, if no such features: score = 1	0
Lateral blast:	Max score = 2
• If located ≤ 50km from volcano: score = 1	1
• If yes to above; located to the northwest of the volcano: score = 1	1
Total of Hazard Factors (Max. score 14)	**7**
Exposure Factors	
Log$_{10}$ of city population:	2.79
• Derived from census data (total population of town/city)	
Local aviation exposure:	0
• If jet-service airport within 10km of the city: score = 1, if none: score = 0	
Power infrastructure:	0
• Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	
Transportation infrastructure:	0
• Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	
Major development or sensitive area:	0
• Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	
Total of exposure factors (max. score 4 + log^{10} of population)	***2.79***
Sum of hazard factors x sum of exposure factors	***19.53***

The total exposure score of 2.79 reflects the towns very small population size and its lack of any major transportation or power infrastructure, or the sighting of any important economic developments. Combining Carbonado's hazard factor and exposure factor scores, provides an overall threat assessment score of 19.53.

5.2.5.2. Threat Assessment of Sumner

The completed threat assessment for Sumner (Table 5.3) indicates a hazard factor score of 5 out of a possible 14. A single point is derived from the relatively minor risk of tephra deposition due to the city's location less than 100km from the volcano, but away from the prevailing wind direction. The remaining four points scored on the hazard factors element is as a result of Sumner's significant risk from lahar inundation. This is due to the towns location within the Puget Sound Lowlands, on the flood plain at the confluence of two rivers which head on the volcano (the Puyallup and White rivers), and the existence of geological evidence from past activity which indicates that the area now occupied by the town has previously been inundated. Sumner could be subject to both cohesive and non-cohesive mudflows, these may be associated with volcanic activity but could also occur without an eruptive trigger. Sufficiently voluminous flank collapses originating on the north, east or west flanks of the volcano could reach the town 65km downriver. The risk from the north flank, via the Carbon River has been discussed in relation to the town of Carbonado, and is considered minimal. The collapse potential of the east flank of the volcano is less likely due to a lack of hydrothermal alteration in this area, whilst the risk from both non-cohesive and cohesive lahars originating on this flank and travelling down the White River would be partially mitigated by the location of the Mud Mountain reservoir. This could contain all but the very largest and therefore least likely flows. The Puyallup River represents the most probable route for a sufficiently mobile lahar to affect the town, either following the melting of glacial snow and ice during an eruption, or following a debris avalanche. The extensive areas of hydrothermal alteration in the Sunset Amphitheatre

Table 5.3 Completed threat assessment for Sumner.

Hazard Factors	***Score***
Ash/tephra:	Max score = 2
• If located ≤ 100km from volcano: score = 1	1
• If yes to above; located in prevailing wind direction = 1	0
Pyroclastic flows:	Max score = 2
• If located within boundaries of National Park: score = 1	0
• If yes to above; within main river valleys: score = 1	0
Lava flows:	Max score = 1
• If located within 4km of summit vent: score = 1	0
Lahars/mudflows:	Max score = 4
• If located on or near river which heads on the volcano: score = 1	1
• If yes to above; ≤ 60km downstream from the volcano: score = 1	1
• If located in area associated with particular geological features, e.g. town protected as river runs through steep-sided, deep valley: score = 0, if town located on a flood plain: score = 1	1
• If located at confluence of one or more rivers that head on the volcano: score = 1	1
Debris avalanche:	Max score = 3
• If located ≤ 30km downstream/slope from volcano: score = 1	0
• If yes to above; located to the northwest of the volcano: score = 1	0
• If located in area associated with particular geological features, e.g. mountain ridges upstream provide protection from avalanche hazard: score = 0, if no such features: score = 1	0
Lateral blast:	Max score = 2
• If located ≤ 50km from volcano: score = 1	0
• If yes to above; located to the northwest of the volcano: score = 1	0
Total of Hazard Factors (Max. score 14)	**5**
Exposure Factors	
Log$_{10}$ of city population:	
• Derived from census data (total population of town/city)	3.93
Local aviation exposure:	
• If jet-service airport within 10km of the city: score = 1, if none: score = 0	0
Power infrastructure:	
• Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	0
Transportation infrastructure:	
• Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	1
Major development or sensitive area:	
• Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	1
Total of exposure factors (max. score 4 + log^{10} of population)	***5.93***
Sum of hazard factors x sum of exposure factors	***29.65***

region above the Puyallup Glacier represent the most likely triggering mechanism for a cohesive lahar.

Sumner scored 5.93 on the exposure factors element of the threat assessment metric. This is due to the towns relatively large population, the sighting of an important centre for economic activity, and the location of both transportation infrastructure, in the form of major highways and a passenger train link to the wider region. Multiplying this figure with the hazard factors score gives an overall threat assessment score for Sumner of 29.65.

5.2.5.3. Treat Assessment Ellensburg

The city of Ellensburg's relative distance from the volcano and its location to the east of the Cascade mountains protects it from the most hazardous volcanic products associated with Mount Rainier volcanism. As a result, the city's hazard factors score is just 2 (Table 5.4) and this is derived from a single hazard; tephra/ashfall. The city is located less than 100 km to the east of the volcano, and therefore within the prevailing wind direction. The current USGS hazard map places Ellensburg within the 0.01% annual probability zone for the accumulation of 1cm or more of tephra. Anecdotal evidence (from the second phase of this research) indicates that city residents experienced some ashfall during the 1980 Mt St Helens eruption, which is located over 150 km to the southwest.

Although Ellensburg scores low on the hazard factors element of the threat assessment metric, it scores relatively high on the exposure factors element; 6.19. This is as a result of the city's large population, the sighting of an airport within 10 km of the city, and the routing of a major interstate highway via the city. Multiplying the hazard factor score by the exposure score gives Ellensburg an overall threat score of 12.38. The significance of this score relative to the other case study communities, and its implications with regards risk management and mitigation are discussed in the following sub-section.

Table 5.4 Completed threat assessment for Ellensburg.

Hazard Factors	***Score***
Ash/tephra:	Max score = 2
• If located ≤ 100km from volcano: score = 1	1
• If yes to above; located in prevailing wind direction = 1	1
Pyroclastic flows:	Max score = 2
• If located within boundaries of National Park: score = 1	0
• If yes to above; within main river valleys: score = 1	0
Lava flows:	Max score = 1
• If located within 4km of summit vent: score = 1	0
Lahars/mudflows:	Max score = 4
• If located on or near river which heads on the volcano: score = 1	0
• If yes to above; ≤ 60km downstream from the volcano: score = 1	0
• If located in area associated with particular geological features, e.g. town protected as river runs through steep-sided, deep valley: score = 0, if town located on a flood plain: score = 1	0
• If located at confluence of one or more rivers that head on the volcano: score = 1	0
Debris avalanche:	Max score = 3
• If located ≤ 30km downstream/slope from volcano: score = 1	0
• If yes to above; located to the northwest of the volcano: score = 1	0
• If located in area associated with particular geological features, e.g. mountain ridges upstream provide protection from avalanche hazard: score = 0, if no such features: score = 1	0
Lateral blast:	Max score = 2
• If located ≤ 50km from volcano: score = 1	0
• If yes to above; located to the northwest of the volcano: score = 1	0
Total of Hazard Factors (Max. score 14)	**2**
Exposure Factors	
Log$_{10}$ of city population:	4.19
• Derived from census data (total population of town/city)	
Local aviation exposure:	1
• If jet-service airport within 10km of the city: score = 1, if none: score = 0	
Power infrastructure:	
• Is there power infrastructure (e.g. generation/transmission/distribution for electricity, oil or gas) within 10km of city? If yes, score = 1	0
Transportation infrastructure:	
• Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within 10km of city? If yes, score = 1	1
Major development or sensitive area:	
• Are there major development or sensitive areas (e.g. flood control projects, government facilities, manufacturing or other significant economic activities) with 10km of city? If yes, score = 1	0
Total of exposure factors (max. score 4 + log^{10} of population)	***6.19***
Sum of hazard factors x sum of exposure factors	***12.38***

5.2.5.4. Discussion

Using the overall threat assessment scores, it is possible to rank the three communities surveyed in order of most to least threatened (Table 5.5). The aggregated scores indicate that Sumner is the city most threatened by future volcanic activity at Mount Rainier, followed by Carbonado, then Ellensburg. Although Carbonado is potentially at risk from more hazards due to its proximity to the volcano, and scores higher on the hazard factors element (7 verses 5), Sumner's larger population, major transportation infrastructure and centre for economic activity has contributed to its higher score on the exposure factors element (5.93 compared to 2.79 for Carbonado), and therefore its overall higher score. Sumner's relatively high hazard exposure score of 5 is derived almost completely from its significant risk of lahar inundation. If allocating resources for the management of volcanic threat, for the three communities surveyed here, Sumner should receive particular attention. Education of the community is made somewhat simpler due to the threat being derived largely from a single hazard. Although identified as the most threatened community (scoring 29.65 overall), it is important to address the city's position with regards to the greatest risk associated with Mount Rainier, i.e. non-eruption generated mudflows. That exposure to the lahar hazard could occur without associated volcanic activity, and without warning, should be explicitly addressed in any communications strategy.

Although Carbonado is a very small settlement, its potential exposure to several different hazards associated with Mount Rainier, indicate a high level of risk. Its small population, lack of infrastructure or major economic activity should be no barrier to ensuring suitable hazard management schemes are put in place. In most scenarios, volcanic activity would need to be sufficiently large to generate hazards that would threaten the town. Such an eruption is likely to be associated with precursory activity, and the extensive monitoring systems in place around the volcano should allow any resumption in activity to be detected. This would allowing adequate time for appropriate hazard planning to be set in motion, in order to mitigate any potential threat to Carbonado residents. The hazard associated with non-eruption generated lahars remains a risk, although significantly less than for Sumner (due to the depth of the Carbon River gorge). Communication efforts within the town should not neglect the risks associated with sudden, unpredictable events.

Table 5.5 Hazard, exposure and overall threat assessment score for the three communities at risk from Mount Rainier volcanism, with scores for Baños and Riobamba, Ecuador for comparison.

	Hazard Factors	Exposure Factors	Overall threat score
Sumner	5	5.93	29.65
Carbonado	7	2.79	19.53
Ellensburg	2	6.19	12.38
Baños	9	6.02	54.18
Riobamba	2	8.10	16.20

As would be expected, the city of Ellensburg has been identified as the least threatened community of those studied. This is predominantly as a result of its low hazard factors score due to its potential exposure to a single hazard. However, its large population, major transport routes and airport, mean that of the three communities, its exposure score is the highest (6.19). Although rated as the least threatened community, Ellensburg's overall threat assessment score indicates that communication directed at local residents should not be neglected. Communities such as Ellensburg situated to the east of the Cascade Range, downwind of the volcano, have largely been ignored in previous studies, but the effects of a relatively small accumulation of ashfall could severely affect transport, power distribution and water supplies. The experiences of the city of Yelm during the Mount St Helens eruption, provide an indication of the disruption that Ellensburg might expect should Mount Rainier erupt (e.g. weeks of clean-up operations, and an estimated economic cost of $5.4 million).

For illustrative purposed, the results of the threat assessment of the Ecuadorian cities of Baños and Riobamba have been included in Table 5.5. Comparisons are valid as the maximum possible score for the hazard factor element is the same for both assessment metrics (14). Baños' close proximity, just 8km to the north of the volcano's summit vent, and its potential exposure to numerous hazards associated with activity at Tungurahua mean it scores highly on the hazard factors element (9). Due to the city's population size, transport infrastructure and the sighting of the hydroelectric Agoyan dam, Baños also scores significantly on the exposure factors element (6.02), a very similar score as that for Ellensburg. Overall the threat assessment score of 54.18 is almost double the score for Sumner. If a community such as Ellensburg were situated just 8km from Mount Rainier, the overall threat assessment score may perhaps reflect those obtained for Baños, suggesting some reliability with the design of the threat assessment metrics developed for the two different volcanic settings. This suggests that the methodology employed here, although not based on a traditional quantitative risk assessment methodology, could provide a useful tool in assessing the relative risk between communities threatened by a particular volcano, and that this approach could be applied equally well to any volcano and the communities around it.

Once a review of current literature, hazard assessments and maps is conducted for the volcano being studied, it is a fairly simple process to assess the threat to any community located around the volcano. Readily available information regarding population size, transport infrastructure, and economic centres can be utilised, without the need to conduct extensive fieldwork in each town or city. The methodology tested here may be more appropriate than a more traditional risk assessment that relies heavily on complex probability estimates and extensive datasets, which may not be available at less well studied volcanoes, can be costly and time consuming to complete and are less easily interpreted by lay-stakeholders. By relying on a single overall threat assessment score, not only is the ranking of communities at risk made simpler but hazard managers, without extensive volcanological knowledge, can readily determine those communities to target for mitigation, communication and education strategies. Additionally, the process readily identifies the specific hazards that each community may be at risk from. It also demonstrates the importance of not restricting threat assessments to the analysis of the geophysical hazard, but that consideration of a communities exposure is of equal importance when determining overall threat.

It should be noted that individual scores would be subject to change should new data on past eruptive activity emerge, or exposure factors change. As additional data becomes available these factors may change value and may increase. Clearly this system would represent minimum numbers for a community situated near a volcano for which past behaviour and hazard knowledge is poor. As more data becomes available, ranking factors could change value, and for many places, probably increase. Nevertheless, the methodology used here could provide a coherent regional picture of relative threat, and help prioritise the most threatened communities to target, particularly when mitigation resources are limited.

As noted with the work carried out in Ecuador, the qualitative assessment methodology developed for this research takes no account of existing mitigation measures, which could act to reduce overall threat. Comprehensive hazard management plans are already in place, particularly in Pierce County, e.g. volcano evacuation routes and school education programs. These mitigation measures may act to reduce overall threat through the improvement of institutional response in the event of an eruption, and/or by reducing the vulnerability of local residents through modification of their behaviour. It is difficult to assess the effectiveness of these measures, and therefore what impact they might have on overall threat levels, but one objective of this research was to address this issue by developing an approach to volcanic risk assessments that integrated the evaluation of both geophysical hazards, exposure and human vulnerability. The threat assessment metric provides an initial stage in this process, whilst considering socio-economic and demographic factors that previous research has indicated as important drivers of vulnerability, would develop this further. The integration of an additional element within the threat assessment metric could be used to assess these 'vulnerability factors'. Communities could be scored based on their income, age and/or gender profiles using readily available census data. In order to justify this approach on theoretical and methodological grounds, it was important to explore the significance of these demographic factors in determining vulnerability. This was achieved during the second phase of the research using a survey of residents in the three case study communities, the results of which are presented in the following section.

5.3. MOUNT RAINIER VULNERABILITY ASSESSMENT

5.3.1. Introduction

By incorporating an evaluation of exposure factors into the threat assessment, a measure of the 'macro-scale' vulnerability *between* communities is provided. This chapter explores further the importance of socio-economic variables in determining vulnerability, the aim being that should these variables prove important predictors of vulnerability, readily available information (e.g. census data) can be incorporated within the threat assessment metric to provide an additional level of complexity. Identifying this 'micro-scale' vulnerability *within* a community would allow risk management strategies to be targeted towards those most at risk. Psychological research involving questionnaire surveys does not, and could not, claim to measure every facet of a person's beliefs, attitudes or behaviour due to the complexity of the personal and contextual factors which influence them (Grothmann & Reusswig, 2006), and this includes the concept of vulnerability, considered within the assessment conducted here. Therefore, rather than attempting to build a comprehensive model of vulnerability, the objective of this phase of the research was to examine the relationships amongst selective socio-economic and psychological characteristics, and protective behaviours.

This section details the results of the questionnaire survey carried out in Carbonado, Sumner and Ellensburg. The questionnaire (Appendix 7) asked participants about their attitudes and beliefs regarding Mount Rainier, including their knowledge and understanding of the volcano and its hazards and risks, their level of preparedness and planned response during a volcanic event, the information sources they had accessed and their level of trust in these, the extent of their feelings of connectedness to their community, and various personal demographic details (age, gender, income etc). The resulting data was entered into an SPSS database, and basic descriptive statistical tests (central tendency, distribution and homogeneity of variance) were carried out to explore the data, and to verify that it met the necessary assumptions for the use of parametric statistical analysis. These initial investigations were followed by a series of inferential statistical tests to answer five specific research questions:

i) Do differences in socio-economic characteristics (e.g. location, age, gender, income) affect public perceptions of risk and other key psychological variables?

ii) To what extent do people's perceptions of risk differ from the 'objectively' measured risk?

iii) To what extent do people's planned responses differ from the official recommendations for action in the event of an eruption?

iv) Can we identify specific socio-economic groups who may be more vulnerable because they hold incorrect views regarding planned response?

v) What psychological factors influence planned behaviour, i.e. what psychological beliefs and attitudes would need to be modified in order to improve planned response, thereby reducing vulnerability to future volcanic events?

Three stages formed the basis for the more detailed analysis required to answer these questions. The first stage aimed to explore the differences between the three case study communities in terms of their beliefs and attitudes towards Mount Rainier, by analysing the results of specific survey questions by location. For this first stage, the same statistical test, one-way analysis of variance (ANOVA), was employed in order to determine whether differences between the three communities were statistically significant. Unlike *t*-tests, chi-squared and correlation analysis, which can only test for relationships between two variables, ANOVA allows for testing of statistical differences between two or more variables (Field, 2005; Langdridge & Hagger-Johnson, 2009), e.g. in this case there were three independent variables or factors; the three case study locations - Carbonado, Sumner and Ellensburg. ANOVA functions in a similar way to a *t*-test, comparing the means of the variables and the variation between scores to determine if they are likely to have come from different populations (Langdridge & Hagger-Johnson, 2009). A series of *t*-tests on every pair of data is not recommended due to the familywise error rate; the increase in probability of making a Type 1 error when conducting a group of tests on the same experimental data (Field, 2005). A Type 1 error is where we believe there is a genuine effect in our population but in reality there is not. In order to test for the assumption of homogeneity of variance, or whether there are any significant differences between group variances, SPSS utilises a test called Levene's, and a non-significant test indicates the assumptions of ANOVA have been met (Field, 2005; Langdridge & Hagger-Johnson, 2009). Where violations of the assumptions of homogeneity of variance occur, an alternative *F*-ratio (the Welch *F*-ratio) has been derived which is sufficiently robust when homogeneity of variance has been violated, and this should be quoted (Field, 2005). Although the ANOVA *F*-ratio tells us that the dependent variable varies by the level of the factor (here by location), it does not tell us which means are significantly different. In order to determine which means are different, the main ANOVA is followed by a further statistical test called *post-hoc* comparisons, these consist of pairwise comparisons, design to compare all different combinations of the test groups. Familywise error is controlled for by correcting the level of significance for each test so that the Type 1 error rate across tests remains .05. Where sample sizes are unequal (as with the location samples in this study), *Gabriel's* test is recommended, unless Levene's is significant (homogeneity of variance is violated) then *Games-Howell* should be quoted (*ibid*). For all tests conducted here, the appropriate *F* value is quoted, and a significant *p*-value of .05 is assumed, followed by the results of the appropriate *post-hoc* comparisons.

During this first stage of the analysis, five key psychological variables were considered, which have been indicated by the literature as important in motivating protective response, and thereby reducing vulnerability. These were; (i) risk perception; (ii) self-efficacy; (iii) trust; (iv) access to information; and (v) preparedness. In addition, two further novel issues were considered; (vi) respondents' perceived risk of the six hazards addressed in the threat assessment were compared with the ‘objective’ risk rating from the threat assessment, giving a measure of the accuracy of lay judgements, termed ‘understanding of risk’, and (vii) the planned response to volcanic activity was compared to the ‘appropriate’ response for each community (as recommended in current Mount Rainier hazard management literature), and was termed ‘appropriate action’. Where applicable, several questions were collapsed to create a single measure of the psychological indicator using factor analysis, and this is detailed where first used.

In the second stage of analysis the seven key psychological variables identified in stage one were explored for differences as a result of variations in socio-economic characteristics. Finally, in stage three, the relative importance of these socio-economic factors versus psychological characteristics in predicting protective response were assessed. This series of analytical stages incorporated a reductionist strategy, which aimed to successively reduce the complexity of the analysis of such a large dataset, with only those socio-economic factors and psychological characteristics found to be important included in the final analysis. The results from each of these three stages are detailed below, followed by a discussion of their implications with regards the literature and the integration of additional factors within the threat assessment metric.

5.3.2. Case Study Comparison of Beliefs & Attitudes

It was expected that participants from each of the three case study communities would hold different beliefs and attitudes towards volcanic hazard and risk from Mount Rainier. It was hypothesised that, as a function of their location in relation to the volcano, nearer communities would have higher perceptions of risk, have accessed more information and be better informed about what action to take in the event of an eruption. This would be not only as a result of their physical proximity but also because communities to the west of the volcano (including Sumner and Carbonado) have been specifically targeted by hazard management strategies (and should therefore be better informed), whilst communities to the east of the Cascade Mountains (including Ellensburg) have not.

5.3.2.1. Hazard Salience

Hazard salience, the extent to which the threat of volcanic activity is on residents' minds, was explored through questions relating to time spent thinking about the hazard, level of worry about future volcanic activity and concern relative to other specific natural hazards . On average participants thought about the possibility of volcanic activity occurring at Mount Rainier 'several times a year' (Table 5.6). Of the 12.4% (n = 30) who said they never thought about the threat, 60.0% (n = 18) were residents of Ellensburg, whilst two-thirds of the 7.4% (n = 18) who reported thinking about the threat once a week or more lived in Sumner.

Table 5.6 Results of the survey question; 'How often do you think about the possibility of volcanic activity at Mount Rainier?'.

	Total %	Sumner %	Carbonado %	Ellensburg %
Never^0	12.4	8.5	10.8	16.4
Rarely^1	33.9	24.5	37.8	40.9
A few times a year^2	33.9	31.9	35.1	34.5
Once a month^3	12.4	22.3	5.4	6.4
Once a week or more^4	7.4	12.8	10.8	1.8
Mean (*SD*)	1.69 (1.08)	2.06 (1.15)	1.68 (1.11)	1.36 (0.90)

Superscript figures indicate coding used in analysis.

The results revealed a significant effect of location; $F(2, 238) = 12.43$, $p < .001$. *Post-hoc* analysis (using Gabriel's procedure due to the unequal sample sizes from each location) indicated that Sumner respondents ($M = 2.06$, $SD = 1.15$) spent the most time thinking about the threat of volcanic activity, and significantly more time then Ellensburg ($M = 1.36$, $SD = 0.90$, $p < .001$), who spent the least time thinking about the threat. Carbonado participants didn't differ significantly from either Sumner or Ellensburg, and spent an average amount of time thinking about the threat of volcanic activity ($M = 1.68$, $SD = 1.11$).

To evaluate levels of concern regarding the volcano, participants were asked to rate how worried they were about possible future volcanic activity (Table 5.7). Over half of respondents reported feeling slightly worried (53.3%, *n* = 129). Of the 7 people (2.9%) who said they were very worried, five were from Sumner and two from Ellensburg. Of those who reported not being at all worried (32.2%, *n* = 78), over half resided in Ellensburg. A one-way ANOVA showed the effect of location was significant; *F*(2, 238) = 4.76, *p* = .009. *Post-hoc* comparisons indicate the same trend as the previous question; Sumner respondents (*M* = 1.02, *SD* = 0.76) reported the highest levels of concern, and were significantly more worried than participants from Ellensburg (*M* = 0.71, *SD* = 0.70, *p* = .007), who were least worried. Although Sumner participants reported the highest levels of concern, a large majority were still no more than slightly worried about future volcanic activity.

Table 5.7 Results of the survey question; *'How worried are you about possible future volcanic activity at Mount Rainier?'*, from most to least worried community.

	Total %	Sumner %	Carbonado %	Ellensburg %
Not at all worried^0	32.2	22.3	29.7	41.8
Slightly worried^1	53.3	58.5	56.8	47.3
Quite worried^2	11.6	13.8	13.5	9.1
Very worried^3	2.9	5.3	0.0	1.8
Mean (*SD*)	0.85 (0.73)	1.02 (0.76)	0.84 (0.65)	0.71 (0.70)

Superscript figures indicate coding used in analysis.

To explore level of concern relative to other natural hazards, respondents were asked to rate whether they were less concerned (-1), felt the same level of concern (0), or were more concerned (+1) about six specific hazards compared to a volcanic eruption. The natural hazards selected for comparison occur in the Pacific north-west of America with varying levels of frequency and severity, and are specifically addressed in the current Pierce County hazard management plan (Pierce County, 2002). They are earthquakes, floods, severe storms, landslides, tsunamis and wildfires. For the sample as a whole, respondents were significantly more concerned about earthquakes than the threat of a volcanic eruption, *t*(241) = 5.15, *p* <.001, and significantly less concerned about all other hazards except wildfires, which they were equally as concerned about as volcanic activity, *t*(241) = 0.53, *p* = .563 (Table 5.8).

Table 5.8 Results of a one-sample *t*-test (test value = 0), ordered from most to least concerned, for the questionnaire item; *'Compared to a volcanic eruption, how concerned are you about the following?*.

	M	*SD*	df	*t*	*p*
Earthquakes	.25	.76	241	5.15	<.001
Wildfires	.03	.89	241	0.58	.563
Severe Storms	-.18	.86	240	-3.22	.002
Floods	-.28	.84	239	-5.12	<.001
Landslides	-.56	.69	239	-12.57	<.001
Tsunamis	-.79	.49	239	24.99	<.001

To explore whether levels of relative concern for each hazard type differed by location, a series of one-way ANOVA were conducted. These revealed no significant difference in relative levels of concern for each of the three locations for all hazards except flooding; *F*(2, 114.83) = 8.59, *p* <.001 and wildfires *F*(2, 97.06) = 44.66, *p* <.001. *Post-hoc* comparisons showed that Carbonado respondents (*M* = - 0.70, *SD* = 0.62) were significantly less concerned about flooding (*p* <.001) than either Sumner (*M* = - 0.20, *SD* = 0.81) or Ellensburg (*M* = - 0.22, *SD* = 0.89), although all residents were less concerned about flooding than the threat of volcanic activity. Sumner (*M* = - 0.53, *SD* = 0.68) were significantly less concerned (at *p* <.001) then both Carbonado (*M* = 0.24, *SD* = 0.83) or Ellensburg (*M* = 0.43, *SD* = 0.81) about wildfires. These results are presented graphically in Figure 5.11, and clearly show all three communities were more concerned about earthquakes, whilst respondents from both Carbonado and Ellensburg were more concerned about wildfires but Sumner participants were comparatively more concerned about volcanic activity. These results are not surprising given the location of both Carbonado, within a highly wooded forestry area, and Ellensburg, located in the arid region to the east of the Cascade Mountains. During fieldwork in Ellensburg, evidence of recent fire damage around the town was noted.

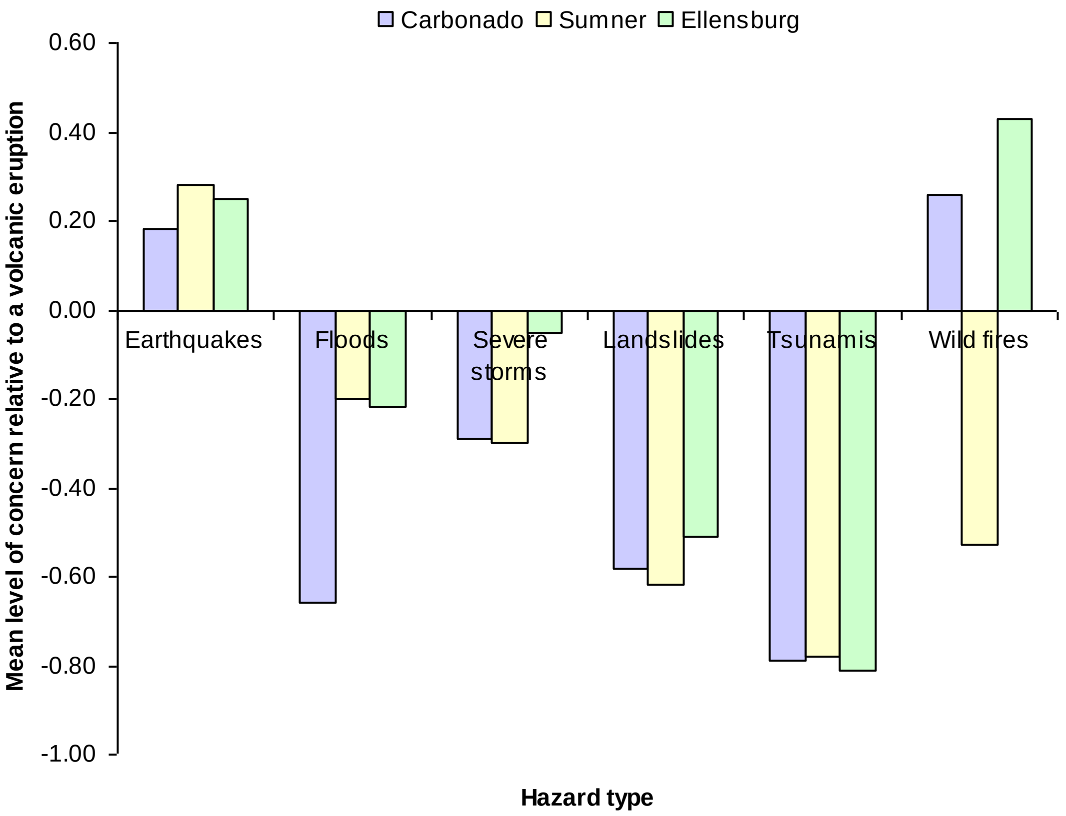


Figure 5.11 Bar chart showing level of concern for various natural hazards relative to the threat of a volcanic eruption, where -1 is less concerned, 0 indicates the same level of concerned and +1 is more concerned.

5.3.2.2. Perceptions of Risk

To evaluate the perception of risk amongst participants, they were asked to rate the likelihood of an eruption affecting their town (Table 5.9), when they thought the next eruption might occur, how serious the effects might be for (i) their community, and (ii) for themselves and their family, and how serious a threat they thought six different volcanic hazard types would be for their town. Overall, respondents felt an eruption would be 'quite likely' to affect their town (*M* = 2.2, *SD* = 0.88). There was some variability in opinion, with almost half of respondents (49.2%, *n* = 119) believing an eruption was 'very likely', whilst a similar number thought an eruption was either 'quite likely' (25.6%, *n* = 62) or 'somewhat likely' to affect their town (22.7%, *n* = 55). Only 6 people (2.5%) believed an eruption was 'not at all likely' to affect their community.

Table 5.9 Responses to the survey question; 'If there is an eruption, how likely do you think it is that this will affect your town?'.

	Total %	Sumner %	Carbonado %	Ellensburg %
Not at all likely^0	2.5	1.1	8.1	1.8
Somewhat likely^1	22.7	11.7	21.6	32.7
Quite likely^2	25.6	17.0	29.7	31.8
Very likely^3	49.2	70.2	40.5	33.6
Mean (*SD*)	2.21 (0.88)	2.56 (0.74)	2.03 (0.99)	1.97 (0.86)

Superscript figures indicate coding used in analysis

A one-way ANOVA showed a significant effect of location, $F(2,238) = 13.68$, $p < .001$, with *post-hoc* tests revealing a significant difference between Sumner ($M = 2.56$, $SD = 0.74$) and both Carbonado ($M = 2.03$, $SD = 0.99$, $p = .002$) and Ellensburg ($M = 1.97$, $SD = 0.86$, $p < .001$), suggesting Sumner participants thought an eruption would be more likely to affect their town than participants from either Carbonado or Ellensburg. This is reflected in the high percentage of Sumner respondents (70.2%) who felt an eruption was very likely to affect their town compared to Carbonado (40.5%) and Ellensburg (33.6%).

On average, respondents thought the next eruption of Mount Rainier might occur within the next 10 to 50 years ($M = 2.97$, $SD = 0.99$). A single participant thought an eruption was imminent ('within the next 12 months'), whilst 5 felt the volcano would never erupt. For those surveys conducted face-to-face it was noted that many respondents found this question particularly difficult to answer, and this may explain the relatively high number of missing values (3.7%, $n = 9$) compared to other items within this section of the questionnaire. There was no significant difference between the three case study locations for this survey item.

When asked to rate the seriousness of an eruption for both their community ($M = 2.02$, $SD = 0.88$), and for themselves and their family ($M = 1.73$, $SD = 1.01$), views were split between 'somewhat', 'quite' and 'very serious' (Table 5.10). Sumner respondents thought the effects would be more serious for themselves and their families, and for their community (answering very serious 46.8% and 59.6% respectively), compared

Table 5.10 Results of the survey question; 'If there is an eruption, how serious do you think the effects would be for…?'

	Total %	Sumner %	Carbonado %	Ellensburg %
…your community?				
Not at all serious^0	2.9	0.0	0.0	6.4
Somewhat serious^1	29.3	9.6	35.1	44.5
Quite serious^2	31.0	30.9	29.7	31.8
Very serious^3	36.8	59.6	35.1	17.3
Mean (*SD*)	2.02 (0.88)	2.50 (0.67)	2.00 (0.85)	1.60 (0.85)
…you and your family?				
Not at all serious^0	10.3	2.1	8.1	18.2
Somewhat serious^1	36.8	26.6	29.7	47.3
Quite serious^2	22.7	24.5	27.0	20.0
Very serious^3	30.2	46.8	35.1	14.5
Mean (*SD*)	1.73 (1.01)	2.16 (0.90)	1.89 (0.99)	1.31 (0.94)

Superscript figures indicate coding used in analysis.

to Carbonado (35.1% for both) and Ellensburg (14.5% and 17.3%). Participants from Ellensburg seemed far less concerned about the potential seriousness of the effects of an eruption. This would be expected given their distance from the volcano and their likely exposure to a single hazard (ash fall). One-way ANOVA results confirmed a significant effect of location for both seriousness questionnaire items: community; $F(2,96.61) = 35.97$, $p < .001$ (Welch *F*-ratio quoted due to violation of assumption of homogeneity of variance; i.e. significant Levene's statistic, $p = .027$) and self and family; $F(2,238) = 21.87$, $p < .001$. Games-Howell *post-hoc* comparisons revealed seriousness ratings for the community were significantly different between all three areas; Ellensburg ($M = 1.60$, $SD = 0.85$) thought the effects would be significantly less serious than either Carbonado ($M = 2.00$, $SD = 0.85$, $p = .042$) or Sumner ($M = 2.50$, $SD = 0.67$, $p < .001$), who also rated the seriousness significantly higher then Carbonado residents ($p = .006$). Whilst seriousness ratings for self and family were not significantly different between Sumner ($M = 2.16$, $SD = 0.90$) and Carbonado ($M = 1.89$, $SD = 0.99$), Ellensburg ($M = 1.31$, $SD = 0.94$) rated the seriousness for themselves significant less than either Carbonado ($p = .008$) or Sumner ($p < .001$).

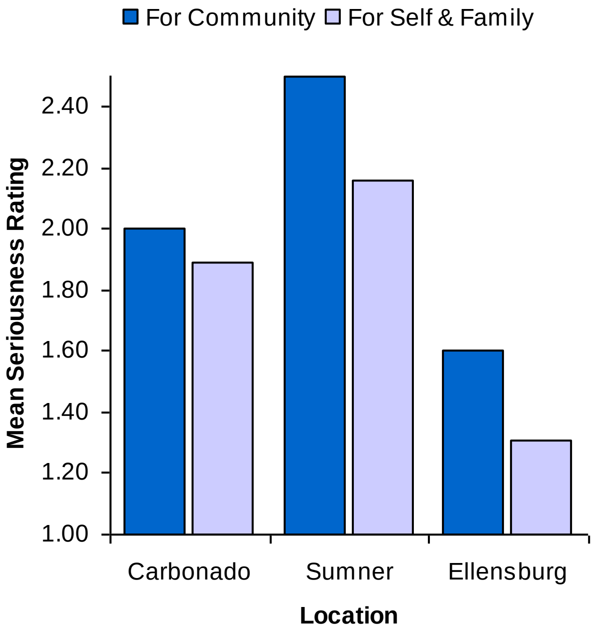


Figure 5.12 Bar chart showing mean seriousness rating, on a four point scale (from 'not at all serious' to 'very serious') of the effects of an eruption for (i) their community and (ii) themselves and their family.

It is interesting to note that for the sample as a whole, *t*-test results indicate that seriousness ratings for self/family and for community differed significantly; *t*(241) = 6.38, *p* <.001. This may demonstrate an example of 'optimistic bias' (Weinstein, 1980), whereby respondents rate the risk to themselves as less than for their community as a whole (Figure 5.12). If we consider the data by location, this trend exists for Sumner (*t* (93) = 4.85, *p* <.001) and Ellensburg (*t* (109) = 4.23, *p* <.001). However, Carbonado residents did not exhibit optimistic bias, believing the effects of an eruption would be equally serious for both themselves and for their community; *t* (36) = 1.00, *p* = .324. One possible explanation for this may be the greater sense of community felt by Carbonado residents, possibly due to it being a very small rural town where many of its residents are close relatives descended from five main families who originally settled the area. Support for this greater closeness within the town is exhibited in their scores on the Sense of Community Index (item 27 on the questionnaire). Carbonado residents (*M* = 10.70, *SD* = 1.67) scored significantly higher on the 12 point scale than either

Sumner (*M* = 9.60, *SD* = 2.12, *t*(90) = -4.92, *p* <.001) or Ellensburg (*M* = 9.55, *SD* = 2.24, *t*(107) = -5.35, *p* <.001).

A further questionnaire item asked respondents to rate how serious a threat they thought six specific volcanic hazards would be to their town/community on a four point scale (Table 5.11). The six hazards used were those identified in the threat assessment. Volcanic ash (*M* = 1.88, *SD* = 0.93) and lahars (*M* = 1.28, *SD* = 1.24) were rated as the most serious hazards by residents (between 1: 'somewhat serious' and 2: 'quite serious'), whilst lava flows (*M* = 0.73, *SD* = 1.01) were rated as least serious. Pyroclastic flows (*M* = 0.90, *SD* = 1.03), debris avalanches (*M* = 0.96, *SD* = 1.12) and lateral blasts (*M* = 0.91, *SD* = 0.95) were rated as similarly threatening (on average rated 'somewhat serious').

Table 5.11 Rating the seriousness of the threat to their town/community from six specific volcanic hazards, ranked from most to least serious.

Hazard type	Total M (SD)	Carbonado M (SD)	Sumner M (SD)	Ellensburg M (SD)
Volcanic ash	1.88 (0.93)	1.97 (0.93)	1.98 (0.97)	1.75 (0.87)
Lahars/mudflows	1.28 (1.24)	1.54 (1.17)	2.28 (0.85)	0.31 (0.68)
Debris avalanches	0.96 (1.12)	1.42 (1.20)	1.46 (1.11)	0.36 (0.74)
Explosions/lateral blasts	0.91 (0.95)	1.57 (1.02)	1.04 (0.89)	0.56 (0.81)
Pyroclastic flows	0.90 (1.03)	1.08 (1.14)	1.51 (0.99)	0.31 (0.59)
Lava flows	0.73 (1.01)	0.81 (0.97)	1.29 (1.10)	0.20 (0.56)

Standard deviations indicated high variability within the sample as a whole, some of which may be explained by locational differences. However, values by area also show high variability for all hazard types, particularly within Carbonado and Sumner. Whilst residents from all three locations felt volcanic ash would be a relatively serious hazard, Ellensburg identified this as their only serious threat, on average rating it 'quite serious' compared to all other hazards, which they perceived as 'not serious'. Sumner participants identified lahars/mud flows as their most serious threat, although they also rated the threat from volcanic ash as 'quite serious'. They also rated all other hazards more seriously than either of the other communities, except explosions/lateral blasts which were rated as a more serious threat by Carbonado respondents.

In order to determine whether respondents perceived the risk from their most seriously rated hazard significantly more than other hazards, a series of one-sample *t*-tests were conducted by area using a test value equal to the mean of the highest rated hazard (Table 5.12). Carbonado and Ellensburg both perceived volcanic ash as their most serious hazard, rating it a significantly more serious threat than any other hazard. Respondents from Sumner rated lahars/mudflows as the most serious threat to their community, also rating it significantly more serious than all other hazards types.

Table 5.12 Results of *t*-test analyses comparing each hazard type with the most seriously rated hazard, for each location and for the sample as a whole.

Hazard type	Total (1.88)	Carbonado (1.97)	Sumner (2.28)	Ellensburg (1.75)
Volcanic ash	---	---	*t* (93) = 3.00**	---
Lahars	*t* (240) = 7.46*	*t* (36) = 2.24***	---	*t* (108) = 22.20*
Avalanches	*t* (240) = 12.80*	*t* (35) = 2.76**	*t* (93) = 7.16*	*t* (109) = 19.69*
Lateral blasts	*t* (240) = 15.78*	*t* (36) = 2.41***	*t* (93) = 13.47*	*t* (108) = 15.34*
Pyroclastic flows	*t* (239) = 14.70*	*t* (36) = 4.75*	*t* (92) = 7.50*	*t* (108) = 25.52*
Lava flows	*t* (240) = 17.65*	*t* (36) = 7.29*	*t* (93) = 8.72*	*t* (108) = 28.99*

* p <.001, ** p <.01, *** p <.05

To explore the accuracy of participants' understanding of the risk to their community from the different volcanic products, the results from this questionnaire item were compared with the results of the threat assessment. The discrepancy between the threat assessment scores and a participant's scores were calculated and this provided a measure of the accuracy of an individual's assessment of the risk posed by each hazard type to their town. The results of this additional analysis are detailed in section 5.3.2.7.

In order to explore the relationships between perceived risk and other psychological variables, as well as to determine variations amongst different demographic groups, it was necessary to collapse the related questionnaire items discussed above into a single measure of risk perception. In psychology and the social sciences, questionnaires are often used to measure psychological constructs. It is frequently not possible to measure this construct directly because it has several different facets, e.g. several different variables are driven by a single underlying factor (Langdridge & Hagger-Johnson, 2009). In order to identify such associated groups of variables, a technique called exploratory factor analysis (EFA) is used. As well as identifying clusters of variables, the technique provides a method of reducing a large dataset to a more manageable size, whilst retaining as much of the original information as possibility (Field, 2005; Langdridge & Hagger-Johnson, 2009). Methodologically, the researcher should consider five key issues; (i) what variables to include in the analysis, (ii) whether EPA is appropriate to address the aims of the research, (iii) what specific procedure to use to fit the model to the data, (iv) how many factors should be included in the model, and (v) what method of rotation should be applied to the output to assist with final interpretation (Fabrigar *et al.*, 1999). The selection of variables to include within the analysis should be guided by theory, which should indicate which variables are measuring the underlying construct of interest. To test whether these variables are measuring aspects of the same underlying dimension, a correlation matrix of all variables should be considered, and any clusters of significant correlation coefficients identified. Inputting the interrelated variables into a factor analysis extracts factors that describe the largest dimension of variance within the data, the next largest dimension and so on until most of the variance has been described, termed eigenvalues (Field, 2005). Data reduction is achieved by retaining those factors with an eigenvalue above one, as per Kaiser's criterion (Kaiser, 1960). In order to determine whether there is sufficient reliability to treat the extracted factor(s) as a single scale, Cronbach's alpha is used. This provides a measure of the inter-item correlation of the variables on the scale, with an alpha value greater than 0.7 indicating a reliable scale (Pallant, 2001). However, it has been noted that values below 0.7 can be expected when dealing with psychological constructs because of the diversity of the constructs being measured (Kline, 1999).

Theoretically, hazard salience (level of concern/worry) and perceptions regarding the seriousness/likelihood of a hazard form facets of risk perception (Davis *et al.*, 2006; Johnston *et al.*, 2006; Barberi *et al.*, 2008). Therefore, the five survey items relating to both hazard salience (Q1 and Q3) and perceptions of risk (Q4, Q5 and Q6) were analysed using a one-tailed Pearson's correlation coefficient[7]. The resulting matrix indicated significant positive correlations between all five items (all at *p* <.001) (Table 5.13). These five items were subjected to principal component analysis (PCA). PCA was selected as unlike common factor analysis, PCA does not ignore the portion of variance which is unique (uncorrelated with other variables) and therefore, initially the output retains the same number of components as original variables (Johnston *et al.*, 2000). In addition, PCA assumes a closed model where the variables themselves account for all the variation (Crosweller, 2009). Orthogonal (Varimax) rotation was applied to aid data interpretation, allowing components to be rotated whilst remaining independent of each other (Field, 2005).

Table 5.13 Correlation matrix for salience and perception items and the results of a principal component analysis of risk perception, with factor loadings >.4 in bold.

	Correlations					Component	
	Q1	Q3	Q4	Q5	Q6	1	2
Q1. Time thinking about	-					.185	**.877**
Q3. Level of worry	.594	-				.220	**.862**
Q4. Likelihood effect town	.290	.340	-			**.877**	.197
Q5. Likelihood effect self	.358	.338	.614	-		**.851**	.242
Q6. Seriousness for self	.357	.390	.586	.729	-	**.822**	.161
Eigenvalues						2.86	1.03
Variance explained (combined total = 77.69%)						57.16%	20.53%
Cronbach's alpha (combined total = .811)						.842	.711

all correlations significant at *p* <.001.

---

[7] Pearson's correlation coefficient *r*, is a standardised measure of the strength of relationship between two variables, and can take any value from -1 (as one variable changes, the other changes in the opposite direction by the same amount), through 0 (as one variable changes, the other stays the same), to +1 (as one variable changes, the other changes in the same direction by the same amount). Pearson's is suitable for parametric data (as here) and is considered more powerful than the non-parametric Spearman's correlation coefficient (Field, 2005; Langdridge & Hagger-Johnson, 2009).

Two factors with eigenvalues greater than one emerged with Q4, Q5 and Q6 having factor loadings of >.4 on component 1, and Q1 and Q3 having factor loadings of >.4 on component 2 (Table 5.13). As discussed, on a theoretical level both factors form facets of risk perception, it was therefore felt appropriate (and in order to simplify further analysis) to combined these five questions to form a single scale measuring levels of concern/salience and likelihood/seriousness of risk, collectively termed 'risk perception'. The combined Cronbach's alpha of .811 for this scale indicated high scale reliability. To form this single variable, question one was converted from a five point scale to a four point scale by multiplying an individual's score by 0.8. An individual's 'risk perception' score was then determined by calculating an overall mean from all five questionnaire items (Q1, Q3, Q4, Q5 and Q6). Scores ranged from a minimum of zero (one respondent) to a possible maximum of 4 (although the highest score recorded was 3.04 by four participants). This combined scale of risk perception was used in all subsequent analysis.

5.3.2.3. Self-efficacy

In order to assess feelings of control regarding one's ability to protect oneself and family from the effects of an eruption, respondents were asked to rate how well they thought they would cope in protecting themselves and their family in the event of a volcanic eruption, and how well prepared they thought they were to deal with the effects of an eruption. Although people rated both their ability to cope (M = 2.58, SD = 0.86) and their level of preparedness (M = 2.12, SD = 0.81) between 'somewhat well'/'somewhat prepared' and 'quite well'/'quite prepared', they rated their ability to cope significantly higher than their level of preparedness; $t(241) = 9.96$, $p < .001$. This difference existed for all three locations (Table 5.14).

Table 5.14 Self-efficacy and preparedness means (and standard deviations) and paired-sample *t*-test results.

	Total *M* (*SD*)	Carbonado *M* (*SD*)	Sumner *M* (*SD*)	Ellensburg *M* (*SD*)
Ability to cope	2.58 (0.86)	3.19 (0.85)	2.45 (0.83)	2.50 (0.81)
Level of preparedness	2.12 (0.81)	2.46 (0.87)	2.12 (0.83)	2.00 (0.76)
Comparison	t(240) = 9.96*	t(36) = 5.52*	t(93) = 4.51*	t(108) = 7.51*

* Significance level: *p* <.001 (2-tailed).

One-way ANOVA results indicate ratings for both questions differed significantly by location; ability to cope, *F*(2, 237) = 11.97, *p* <.001; and level of preparedness, *F*(2, 237) = 4.52, *p* = .012. *Post-hoc* tests revealed that for both ability to cope and level of preparedness there was no significant difference between Sumner's and Ellensburg's ratings (*p* = .965). Carbonado rated their ability to cope significantly higher than either Sumner or Ellensburg (both *p* <.001), and also felt they were significantly more prepared than respondents from Ellensburg (*p* =.009). Although Sumner participants rated their preparedness level lower than those from Carbonado, the difference was not significant (*p* = .658).

For further analysis, the two questionnaire items (Q21 and Q22) were collapsed to created a single measure of self-efficacy by calculating the mean score. The two questions were significantly correlated (*r* = .625, *p* <.001), and a single factor emerged from a principal component analysis explaining 81.72% of variance. Cronbach's alpha coefficient for this factor indicated a scale reliability of .769.

5.3.2.4. Trust in Information Sources

A single survey item asked individuals to rate the amount of trust they had in government agencies, scientists, the media and various unofficial sources to provide them with accurate information about future volcanic eruptions. Results indicate there was 'some' trust in all sources of information, with a general tendency to rate official sources as more trustworthy than unofficial sources. The most trusted source of information were scientists (*M* = 1.64, *SD* = 0.85), with over 60% of respondents stating they had 'a lot' or 'complete' trust in their ability to provide accurate information. The internet (*M* = 0.97, *SD* = 0.77) and church/community groups (*M* = 0.93, *SD* = 0.84) were deemed least trustworthy, with around a third of people saying they had no trust. The Federal, State and County Departments of Emergency Management (DEM) were the least trusted official sources of information, with the Federal Emergency Management Agency (FEMA) perceived as less trustworthy than the media or family and friends (Figure 5.13/Table 5.15). It is worth noting that standard deviations are high relative to the mean for all sources of information suggesting high levels of variability in trust ratings amongst respondents.

Table 5.15 Results of the questionnaire item; 'How much trust do you have in each of the following to provide you with accurate information about future eruptions?'. Results ranked from most trusted to least.

Source of information	None %	Some %	A lot %	Complete %	M (*SD*)
Scientists (CVO/USGS)	11.0	27.6	47.8	13.6	1.64 (0.85)
Emergency Services	9.2	42.5	36.8	11.4	1.50 (0.82)
National Park Service	14.5	33.5	40.7	11.3	1.49 (0.88)
State DEM	12.7	49.5	32.3	5.5	1.30 (0.76)
County DEM	15.8	48.9	29.4	5.9	1.25 (0.79)
Media	15.3	52.3	28.5	3.8	1.21 (0.74)
Family/friends	21.4	53.3	18.8	6.6	1.10 (0.81)
FEMA	29.1	47.6	18.9	5.3	1.00 (0.83)
Internet	29.3	45.9	23.0	1.8	0.97 (0.77)
Church/community group	33.0	47.1	14.0	5.9	0.93 (0.84)

One-way ANOVA results indicate similar levels of trust across the different study areas, except for church/community groups; *F* (2, 86.02) = 4.67, *p* =.012), which Carbonado (*M* = 1.14, *SD* = 1.03) rated as significantly more trust-worthy than Ellensburg (*M* = 0.74, *SD* = 0.70, *p* = .024). Carbonado also rated trust in church/community groups higher than Sumner (*M* = 1.04, *SD* = 0.86), but the difference was not significant (*p* = .872). Although not significantly different, there was some variation in reported levels of trust in respondents' family and friends; *F*(2, 90.97) = 3.04, *p* = .054, with Carbonado (*M* = 1.39, *SD* = 0.90) reporting higher levels of trust than either Sumner (*M* = 1.12, *SD* = 0.88, *p* = .284) or Ellensburg (*M* = 0.99, *SD* = 0.69, *p* = .052).

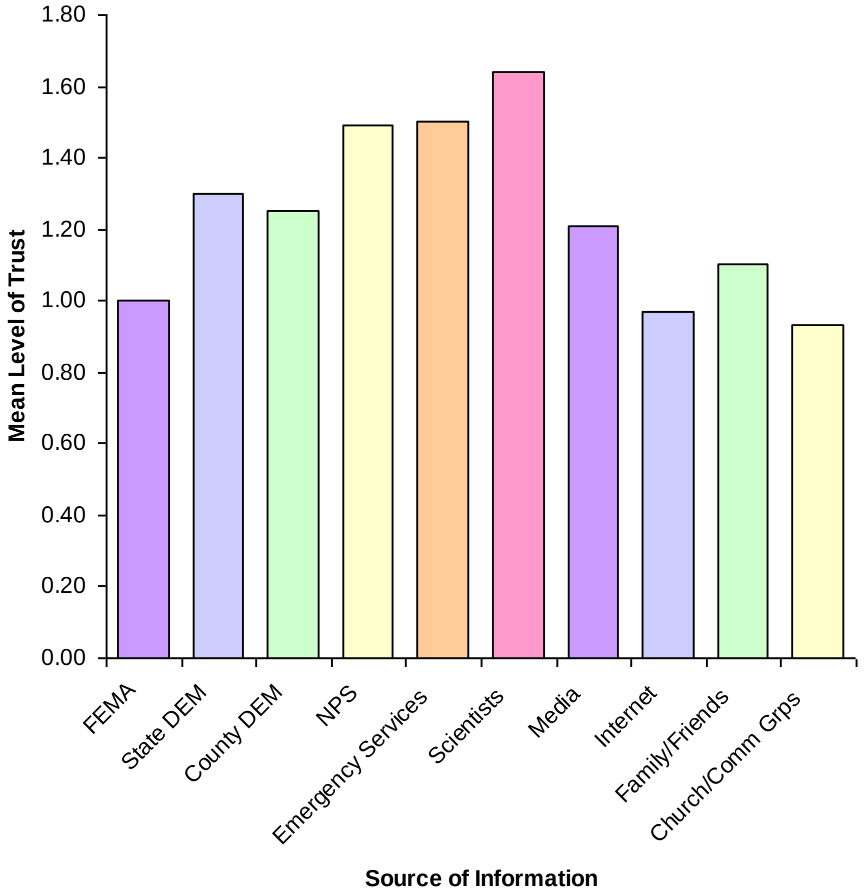


Figure 5.13 Bar chart showing mean levels of trust in different information sources.

Although the trust scores for the ten different sources of information are all significantly correlated (except FEMA and family/friends, see Table 5.16), the results above appear to indicate that respondents made a distinction between the ability of official agencies (government and scientific) and unofficial or informal sources to provide them with accurate information. To test this, PCA was applied and the results identified two factors that correspond to the two types of information sources (official and unofficial/informal). FEMA, State and County DEMs, the National Park Service, Emergency Services and Scientists loaded onto the first factor (explaining 35.67% of variance). As these dimensions largely represent organisational authorities, this factor was labelled 'official trust'. The remaining four variables loaded onto a second factor (explaining an additional 24.67% of variance), which has been termed 'unofficial trust'. Scale reliability for these two factors were tested using Cronbach's alpha coefficient, both alpha's were above the recommended reliability threshold of .7 (Table 5.17). For all further analysis two variables were created to represent these different trust components by calculating the mean level of trust from the sum of the relevant questions relating to each factor.

Table 5.16 Results of a one-tailed Pearson's correlation coefficient matrix for levels of trust in different information sources.

	1	2	3	4	5	6	7	8	9	10
1. FEMA	-									
2. State DEM	.596*	-								
3. County DEM	.481*	.753*	-							
4. NPS	.449*	.639*	.522*	-						
5.Emer. Services	.469*	.625*	.629*	.570*	-					
6. Scientists	.314*	.518*	.455*	.540*	.539*	-				
7. Media	.280*	.341*	.386*	.264*	.476*	.377*	-			
8. Internet	.179**	.247*	.294*	.220**	.297*	.253*	.426*	-		
9. Family/friends	.102	.115***	.179**	.233*	.342*	.211**	.379*	.367*	-	
10. Church/comm.	.256*	.253*	.307*	.300*	.408*	.256*	.382*	.245*	.564*	-

* p < .001; ** p < .01; *** p = > .05.

Table 5.17 Results of a principal component analysis on levels of trust in the ability of difference sources to provide accurate information about future volcanic eruptions. Factor loadings >.4 (in bold) on two components; (1) official sources, (2) unofficial sources, with scale reliability alphas.

Information Source	Components	
	1	2
State DEM	**.893**	.104
County DEM	**.786**	.223
National Park Service	**.771**	.167
Emergency Services	**.712**	.430
FEMA	**.701**	.085
Scientists (CVO/USGS)	**.642**	.284
Family/friends	.047	**.835**
Church/community group	.207	**.723**
Media	.257	**.704**
Internet	.185	**.624**
Eigenvalues	4.55	1.48
Variance explained (total = 60.33%)	35.66%	24.67%
Cronbach's alpha	.871	.718

5.3.2.5. Access to Information

A number of survey items asked respondents to consider the information they had seen about the volcano in general, and that regarding the development of personal hazard mitigation plans. Firstly, they were asked what types of information they had accessed concerning what action to take in the event of an eruption. A number of choices were provided along with an additional open-ended option, which they were asked to state. Of the 242 people surveyed 57.4% had accessed at least one source of information. The percentages for each case study location were; Carbonado: 73.0%, Sumner: 68.1%, and Ellensburg: 42.7%. These figures support the work of hazard managers who have been involved in communicating volcanic hazard and mitigation advice within those communities to the west of the volcano, whilst no such communication strategy has been undertaken in communities to the east of the volcano.

Of those people who indicated they had accessed some form of information, the most popular was radio/television programmes, accessed by around half of respondents (Figure 5.14). Two-thirds of these had also accessed other information souorces. An interesting additional source of information mentioned by 12.9% of respondents was an employer. There were three main sources for this, firstly, a number of residents surveyed in Sumner were employed by, or had a family member employed by, a local concrete manufacturer (COMCO), who have conducted employee training sessions and provided leaflets with hazard and mitigation information. Secondly, a number of respondents were school teachers, and particularly those from Sumner and Carbonado stated that they were responsible for teaching both hazard information and emergency response activities to their pupils. Finally, in Carbonado, the local Fire Chief (directly responsible during an emergency situation within the town) and a number of members from the City Council, who are involved in emergency planning, completed the questionnaire. Additionally, a number of other participants from Carbonado were either closely related to or friends of these officials and had discussed the issues with them, hence the relatively high number of people who sited community meetings/

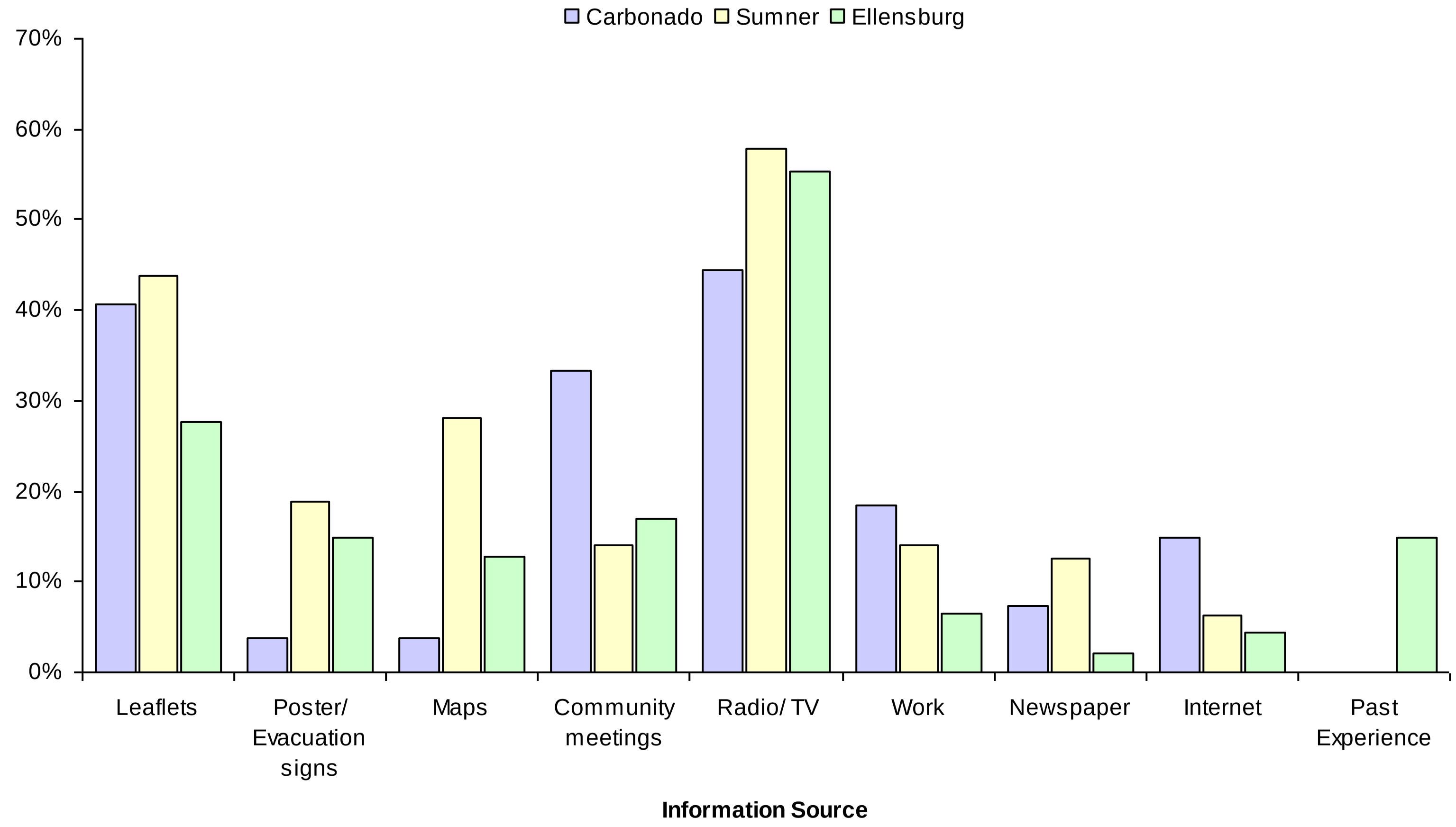


Figure 5.14 Bar chart showing the percentage of respondents from each location who had accessed each information source. Data based on the 139 participants who had accessed information; 28 from Carbonado, 64 from Sumner and 47 from Ellensburg

discussions in Carbonado; 33.3%. Seven of the people questioned in Ellensburg had experienced ash fall during the 1980 eruption of Mount St Helens and felt this had provided them with the necessary information about how they should respond if Mount Rainier erupted. Respondents were then asked to rate how useful they had found this information (Table 5.18). The median rating for the sample was 'quite useful' (*M*= 1.79, *SD* = 0.88). Very few people thought the information was 'not at all useful' (5.0%), whilst over two-thirds felt the information was either 'quite useful' or 'very useful'. ANOVA results indicated no significant difference between locations.

Table 5.18 Rating how useful respondents found the information they had accessed.

	Total %	Carbonado %	Sumner %	Ellensburg %
Not at all useful^0	5.0	0.0	7.7	4.2
Slightly useful^1	36.2	37.0	33.8	39.6
Quite useful^2	34.0	33.3	36.9	31.2
Very useful^3	24.8	39.6	21.5	25.0
Mean (*SD*)	1.79 (0.88)	1.93 (0.83)	1.72 (0.89)	1.77 (0.88)

Superscript figures indicate coding used in analysis.

When asked what respondents felt about the amount of information they had access to regarding what to do in the event of an eruption, almost two-thirds of the sample (63.5%) felt they hadn't had enough, whilst 33.6% said they'd received 'enough'. Just 2.9% thought they'd had 'too much'. Ratings did not differ significantly between the three case study communities.

A further questionnaire item asked respondents to think about what they knew about the volcano in general (unlike the former which related specifically to mitigation advice), and to say where this information had come from. Several potential sources where cited, along with an additional open-ended option, which they were asked to state. From the responses given, nine sources of information were identified. These were; (i) the authorities (including State and County DEMs and FEMA), (ii) the National Park Service, (iii) scientists (including USGS and CVO), (iv) newspapers/ magazines, (v) TV/radio, (vi) the internet, (vii) family/friends, (viii) school/employer,

(ix) other. All but twelve participants reported having seen at least one piece of information about the volcano, whilst two-thirds had seen two or more. The most popular source was the media, split between newspapers/magazines (47.1%), and television/radio (52.9%). The next most frequently mentioned sources were friends and family (29.6%) and official sources (26.3%), which included FEMA and the State/County DEMs. Although previously cited as the most trusted source of information, scientists (USGS and CVO) were the least frequently mentioned provider of information (13.2%). However, it may be that much of the information provided by the authorities, and to some extent the media and via the internet, could have originally been sourced from these scientific groups. Other sources cited included personal experience from exploring the area/climbing the mountain, and again those who said they'd experienced the 1980 Mount St Helens eruption.

In order to create a variable for further analysis that provided a single measure of how well informed participants were about what action they should take in the event of an eruption, the types of information sources accessed were summed. Values ranged from none to five, with a mean score of 1.01 (*SD* = 1.16). It is not possible to determine how accurate or otherwise the information contained within the different sources were. For example, of the 139 people who had accessed information about personal mitigation strategies, 76 said this had come from television/radio, and although this may be considered an unofficial resource, the program makers may have compiled their information from scientific sources. For this reason, the 'information' variable may more accurately be said to provide a proxy of how informed an individual perceives themselves to be, rather than a measure of how informed they actually are.

5.3.2.6. Preparedness and Hazard Adjustment

In order to assess levels of preparedness, a survey item asked participants if they knew what action they should take to help protect themselves and their families in the event of a volcanic eruption affecting their town. For those who answered yes, an open ended option asked them to detail what protective measures they would take. The results were examined to uncover similarities between responses and these were grouped and coded for quantitative analysis. Six clear categories, which accounted for the majority of responses, emerged. Nineteen participants mentioned items which did not code into a convenient group, either because the item was not mentioned by anyone else or only by one or two other people. These items were coded 'other' and are discussed below. Results are displayed in Table 5.19, and show for the sample as a whole, almost two-thirds of people surveyed (172) said they knew what action to take in the event of an eruption affecting their town. This differed by location with only 3 (8.1%) participants from Carbonado saying they didn't know what to do, compared to Ellensburg, where 41.8% (46 respondents) felt they didn't know what action to take. The most frequently mentioned response for the sample as a whole was the storage of emergency supplies (38.7%). However, many of those who mentioned this action said these were kept for any emergency situation and not specifically for a volcanic eruption. This may be in response to a nationwide push to increase personal emergency preparedness by Federal and State emergency management following 9/11 and natural disasters such as Hurricane Katrina.

Table 5.19 Results for the survey item; 'In the event of a volcanic eruption affecting your town, do you know what action you should take to help protect yourself and your family?'.

	Total %	Carbonado %	Sumner %	Ellensburg %
No	28.9	8.1	21.3	41.8
Yes	71.1	91.9	78.7	58.2
Store emergency supplies	38.7 (27.7)	37.8 (34.2)	27.0 (21.3)	51.6 (30.0)
Move to higher ground	25.4 (18.2)	32.4 (28.9)	43.2 (34.0)	1.6 (0.9)
Evacuate	25.4 (18.2)	32.4 (28.9)	31.1 (24.5)	14.1 (8.2)
Stay indoors	24.3 (17.4)	14.7 (13.2)	5.4 (4.3)	51.6 (30.0)
Avoid ash	22.5 (16.1)	11.8 (10.5)	6.8 (5.3)	46.9 (27.3)
Emergency contact	10.4 (7.4)	8.8 (7.9)	14.9 (11.7)	6.3 (3.6)
Other	11.6 (8.3)	5.9 (5.3)	9.5 (7.5)	17.2 (10.0)

Percentages for each action are for those people who said yes, and total more than 100% as selection of more than one item was possible (figures in parenthesis are percentages of the sample as a whole).

The most frequently mentioned protective measures for Carbonado participants were 'evacuate' (32.4%) or 'move to higher ground' (32.4%) and the 'storage of emergency supplies' (37.8%). In the case of 'evacuate' and 'move to higher ground', these were mentioned by different participants, with just 2 people citing both actions. The distinction between 'evacuate' and 'move to higher ground' is particularly interesting for residents of Carbonado. Given the towns relatively close proximity to the volcano and the possibility that there may not be time, or only a short time in which to issue a lahar warning, current mitigation advice suggests not attempting to leave town, but to move off the valley floor. This is because the single road out of town is within the Case I lahar hazard zone from Carbonado for a distance of approximately 18 kilometres, e.g. should a lahar warning be issued or residents hear the sounds of an approaching lahar, it would be too late to evacuate away from the town, therefore moving to higher ground would be the most appropriate action. However, if there were precursory volcanic activity prior to an eruption, evacuation may be the most appropriate response. Appropriateness of response is explored further in section 5.3.2.8.

Of those participants from Ellensburg who said they knew what action to take, the three most popular responses were; (i) 'store emergency supplies' – 51.6% (including food, water and equipment, e.g. torches, radios, fuel and batteries), (ii) 'stay indoors' – 51.6%, and (iii) 'avoid ash' – 46.9% (this included the use of breathing masks, sealing windows and doors in the home, and avoiding the use of vehicles). Items (ii) and (iii) were cited by 33 and 20 people respectively, 19 of whom mentioned both items. The most frequently mentioned protective measure quoted by Sumner residents was to move to higher ground (43.2%), followed by 'evacuate' (31.1%). Evacuation routes within the city (which are clearly signposted) all lead to higher ground, so the distinction between these 2 measures is less clear than for Carbonado, and in this instance are taken to mean the same thing. Each was mentioned 32 and 23 times respectively but never both by the same person. A number of respondents (10.4%, n = 18) also said they would arrange an emergency contact; an out-of-state family member or friend who would provide a single point of contact for the family should they be unable to communicate or became separated. Of the 11.6% (n = 20) 'other' responses, these included monitoring television or radio for information, checking on neighbours and/or assisting elderly/children in the community, pray, or simply stated they had an emergency plan but did not provide details.

To explore whether hazard adjustments had already been adopted, a further question asked respondents whether they had already made plans to protect themselves and their families in the event of an eruption. This item provided options ('purchased insurance', 'planned an evacuation route', and 'stored emergency supplies of food and water') and an open ended element for additional responses (Table 5.20). Of the 57.9% of people who said they had already made plans to help protect themselves and their families in the event of an eruption, the storage of emergency supplies (80.9%), followed by 'planned an evacuation route' (55.7%) were the most popular. 'Stored emergency supplies' was selected by a high percentage of residents from all three locations, but as mentioned previously, many stated this was for any emergency situation and not specifically for the volcanic hazard. A high percentage of respondents from Carbonado and Sumner said they had 'planned an evacuation route' (73.1% and 75.8% respectively), with an equal percentage having stockpiled food, water and emergency equipment. Although purchasing insurance was mentioned by 14.3% of people, a number of other respondents said they had been unable to find insurance cover against the risk of volcanic activity.

Table 5.20 Types of hazard adaption already undertaken.

	Total %	Carbonado %	Sumner %	Ellensburg %
No	42.1	29.7	29.8	57.3
Yes	57.9	70.3	70.2	42.7
Emergency supplies	80.7 (46.7)	73.1 (52.6)	75.8 (53.2)	93.6 (40.0)
Planned evacuation route	55.7 (32.2)	73.1 (52.6)	75.8 (53.2)	17.0 (7.3)
Purchased insurance	14.3 (8.3)	15.4 (10.5)	19.7 (13.8)	6.4 (2.7)
Arranged emergency contact	6.4 (3.7)	7.7 (5.3)	9.1 (6.4)	2.1 (0.9)
Purchased dust masks	4.3 (2.5)	0.0 (0.0)	1.5 (1.1)	10.6 (4.5)
Purchased house on higher ground	3.6 (2.1)	0.0 (0.0)	7.6 (5.3)	0.0 (0.0)

Percentages for each action plan are for those people who said yes, and total more than 100% as selection of more than one item was permitted (figures in parenthesis are percentages of the sample as a whole).

Using the results of this questionnaire item, a single measure representing the level of preparedness or 'hazard adjustment', was calculated by summing the number of protective measures already adopted. The number of measures reported ranged from 0 to 4 items, with a mean for the whole sample of 0.96 (*SD* = 0.99). Preparedness measures were both hazard specific, e.g. planning an evacuation route and purchasing protective breathing equipment, or more general, e.g. storing emergency supplies and arranging a family contact, applicable to any emergency situation.

5.3.2.7. Risk Understanding – Threat Assessment vs. Lay Beliefs

In order to assess how well respondents understood the risks from the six main hazards associated with eruptions at Mount Rainier, the questionnaire item concerned with rating the seriousness of each hazard type (Q9) were compared with the results from the threat assessment detailed in Section 5.2. The threat assessment rating for each hazard was measured on a three point scale, so the questionnaire scale was collapsed into a similar scale; 'low seriousness or risk' (0), 'medium risk' (1), and 'high risk' (2). Ratings 'somewhat serious' and 'quite serious' from the questionnaire were collapsed to form the new value 'medium risk'.

To determine whether each hazard type was assigned a significantly different risk rating by respondents within each area, a series of one-way repeated measures ANOVA were conducted for each case study location. Results indicate that respondents made clear distinctions between the different hazard types, assigning significantly different ratings to each: Carbonado; $F(5, 175) = 11.15$, $p < .001$, Sumner; $F(5, 460) = 23.34$, $p < .001$; Ellensburg, $F(5, 535) = 110.42$, $p < .001$ (see Table 5.21, 5.22 and 5.23 for *post-hoc* comparisons). Included in each table are the assessment ratings for each hazard type derived from the threat assessment. By ordering the hazards from those rated as most serious by respondents to least serious, we can see that each area correctly identified their most threatening hazard type(s).

Table 5.21 Carbonado: Threat assessment and respondent risk ratings for six volcanic phenomena, from most seriously rated hazard to least serious, and results of a one-way repeated measures ANOVA, including *post-hoc* test results.

Hazard type	Threat assess. Rating	Mean	*SD*	*F*(5,175) = 11.15, p <.001
Volcanic ash	1	1.35	0.54	Significantly different to all other hazard ratings @ p <.05, except lateral blast & lahars
Lateral blast	1	1.05	0.62	Significantly different to lava; p <.001 and pyroclastic flows; p = .048
Lahars	1	1.00	0.75	Significantly different only to lava; p = .007
Debris avalanche	1	0.92	0.77	Significantly different only to ash; p = .024
Pyroclastic flows	0	0.73	0.73	Significantly different to ash; p <.001 and lateral blasts; p = .048
Lava flows	0	0.59	0.64	Significantly different to all other hazards at p <.01, except avalanches and pyroclastic flows

Table 5.22 Sumner: Threat assessment and respondent risk ratings for six volcanic hazards, from most to least seriously rated, and results of a one-way repeated measures ANOVA, including *post-hoc* tests.

Hazard type	Threat assess. Rating	Mean	SD	*F*(5,460) = 23.34, p <.001
Lahars	2	1.47	0.56	Significantly different to all other hazards at p <.001, except ash
Volcanic ash	1	1.29	0.62	Significantly different to all other hazards at p <.05, except lahars
Pyroclastic flows	0	1.02	0.61	Significantly different to all hazards at p <.05 except debris avalanche and lava
Debris avalanche	0	0.96	0.70	Significantly different only to lahar, p <.001 and ash p = .006
Lava flows	0	0.86	0.69	Significantly different only to lahar, p <.001 and ash p <.001
Lateral blast	0	0.78	0.57	Significantly different to all other hazards at p <.01, except lava and avalanches

Table 5.23 Ellensburg: Threat assessment and respondent risk ratings for six volcanic hazards from most to least seriously rated, and results of a one-way repeated measures ANOVA, including *post-hoc* tests.

Hazard type	Threat assess. Rating	Mean	SD	$F(5{,}535) = 110.42, p < .001$
Volcanic ash	2	1.15	0.51	Significantly different to all other hazards at $p < .001$
Lateral blast	0	0.45	0.59	Significantly different to all other hazards at $p < .05$
Pyroclastic flows	0	0.28	0.49	Significantly different to all hazards at $p < .05$ except debris avalanche and lahars
Debris avalanche	0	0.26	0.50	Significantly different only to ash $p < .001$ and lateral blast $p = .007$
Lahars	0	0.25	0.49	Significantly different only to ash $p < .001$ and lateral blast $p < .001$
Lava flows	0	0.17	0.42	Significantly different to all other hazards except lahars and debris avalanches

In order to explore whether an individual's judgement of the risk concurred with the threat assessment rating, a variable measuring the discrepancy between a participant's risk rating and the threat assessment risk rating for each hazard type was calculated. The threat assessment derived score was subtracting from an individual's rating of each hazard, allowing for where they lived (i.e. the threat scores for a given hazard is different for each location, so an individuals location was considered to ensure the correct threat score for their location was used, e.g. if two participants rate the threat from lahars as 2, but one is from Sumner and one Ellensburg, the respondent from Sumner would be said to have an accurate understanding of the risk, whilst the person from Ellensburg would have overestimated the risk). This resulted in scores ranging from 0, were there was no discrepancy, to -1 or -2 where risk was increasingly underestimated, to +1 or +2 where risk was increasingly overestimated (Figure 5.15). From the three repeated measures ANOVA conducted previously, we can see these discrepancy scores are not simply a function of respondents assigning similar risk ratings to each hazard type, but reflect a genuine difference in the accuracy of their understanding of risk associated with each hazard type, for their location.

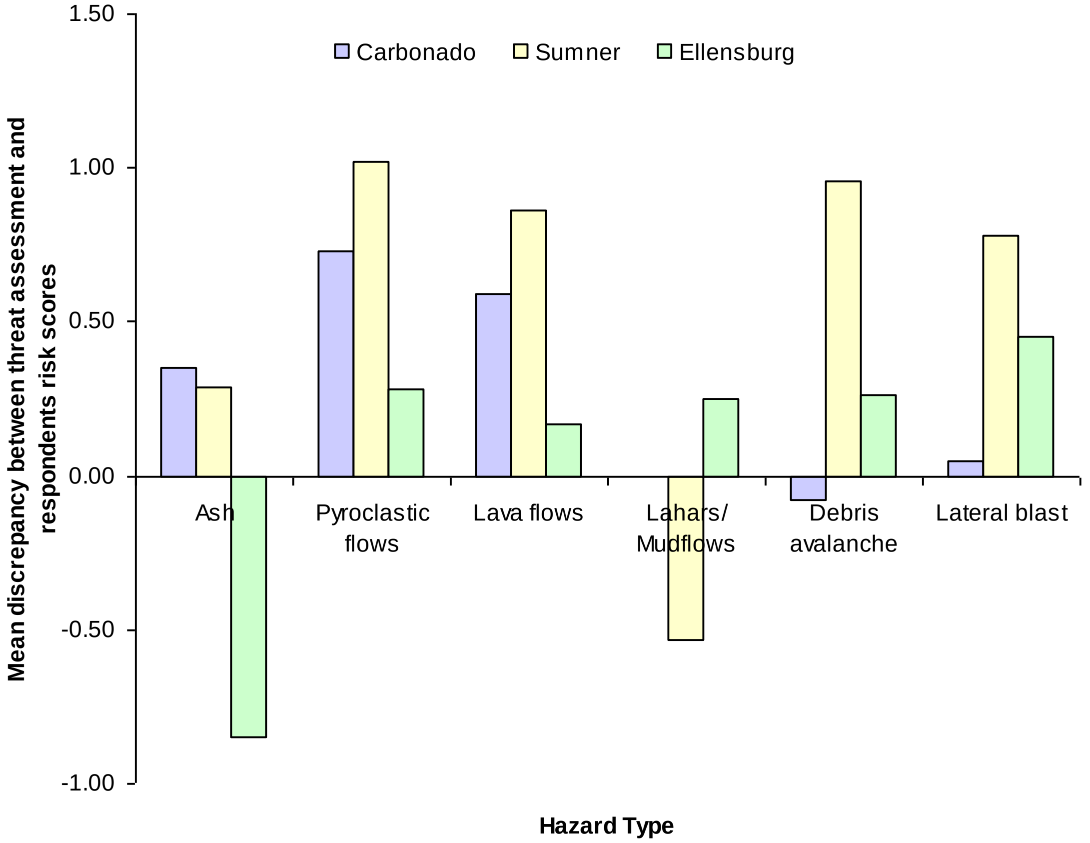


Figure 5.15 Bar chart showing the mean discrepancy between the threat assessment and respondents' risk ratings for different hazard types by location, where 0 equals no discrepancy.

The threat from most hazards appears to have been overestimated. This is particularly the case for those posing little or no threat to any of the three communities due to the hazards likely confinement within the boundaries of the national park (pyroclastic flows and lava flows), and for those only posing a threat to the most proximal community (debris avalanches and lateral blasts). The hazards most likely to threaten residents, e.g. volcanic ash in the case of Ellensburg and lahars for Sumner, appear to have been underestimated by each of the specific communities most at risk. Carbonado's average risk rating for lahars corresponds with the threat assessment score and only small discrepancies exist between their rating's for avalanches and lateral blasts compared to the threat assessment, indicating a relatively accurate understand of the risk to their town posed by these hazards (Table 5.24).

Table 5.24 Mean risk discrepancy scores for different volcanic phenomena by area, where zero indicates an accurate understanding of the risk.

Hazard	Carbonado *N* = 36 Mean (*SD*)	Sumner *N* = 93 Mean (*SD*)	Ellensburg *N* = 108 Mean (*SD*)
Ash	0.35 (0.54)*	0.29 (0.62)*	- 0.85 (0.51)*
Pyroclastic flows	0.73 (0.73)*	1.02 (0.61)*	0.28 (0.49)*
Lava flows	0.59 (0.64)*	0.86 (0.70)*	0.17 (0.42)*
Lahars/mudflows	0.00 (0.75)	- 0.53 (0.56)*	0.25 (0.49)*
Debris avalanche	- 0.08 (0.77)	0.96 (0.70)*	0.26 (0.50)*
Lateral blast	0.05 (0.62)	0.78 (0.57)*	0.45 (0.59)*
Total	0.28 (0.53)	0.56 (0.40)	0.10 (0.38)

zero = no discrepancy, positive value = overestimate, negative value = underestimate.
* significantly over or underestimate the risk @ *p* <.001.

To explore whether each location significantly under or overestimated the risk associated with each hazard, a series of one-sample *t*-tests for each location were carried out on the risk discrepancy variable. A test value of 0 was used, corresponding to an assessment of the risk equal to that of the threat assessment. All significant results detailed below are reported at *p* <.001. Carbonado significantly overestimates the risk from pyroclastic flows (*t*(36) = 3.97), lava flows (*t*(36) = 6.06) and ash fall (*t*(36) = 3.97), whilst accurately rating the risk from lahars (*t*(36) = 0.00, *p* = 1.00). There was no significant difference between their ratings for both debris avalanches (*t*(36) = 0.65, *p* = .520) and lateral blasts (*t*(36) = 0.53, *p* = .600) and the threat assessment, indicating an accurate understanding of the risk for these hazards.

Sumner significantly overestimates the risk to their town from all hazards except lahars, which they significantly underestimate (*t*(93) = -9.17). Ellensburg also significantly overestimates the risk from most hazards but significantly underestimates the risk from ashfall (*t*(109) = - 17.39). Both these communities overestimate the risk from hazards they are not assessed to be at risk from, whilst significantly underestimating the hazard they would be most threatened by during an eruption. However, it should be remembered that although they underestimate the risk compared to the threat assessment, both communities correctly identified the hazard from which they would be most at risk during an eruption.

In order to explore how risk understanding differed by case study location, a three (location: Carbonado, Sumner, Ellensburg) by six (discrepancy between risk ratings: ash, pyroclastic flows, lava flows, lahars/mudflows, debris avalanches, lateral blasts) mixed factorial ANOVA with repeated measures on the second factor (discrepancy) was conducted. Mixed ANOVA allow means to be compared when there are two or more independent variables (location) *and* two or more dependent variables (discrepancy), and also allow any interactions between these variables to be explored (Field, 2005). Results indicate there was a significant main effect of location $F(2, 234) = 30.85$, $p < .001$, indicating (ignoring hazard type) that ratings were different for each of the three case study areas. *Post-hoc* comparisons revealed that Sumner ($M = 0.56$, $SD = 0.40$) had a significantly larger discrepancy between their ratings and that of the threat assessment when compared to both Carbonado ($M = 0.28$, $SD = 0.53$) and Ellensburg ($M = 0.10$, $SD = 0.38$). There was no significant difference between Carbonado and Ellensburg. This suggests that although all three areas on average overestimated the risk, Carbonado and Ellensburg respondents had a similar, and more accurate, perception of the risk to their town from the hazards associated with an eruption of Mount Rainier than respondents from Sumner.

The results of the analysis also indicated a significant effect of hazard type, $F(5, 1170) = 96.51$, $p < .001$, suggesting that for the sample as a whole (ignoring location), ratings were significantly different for each of the six hazard types. Details and *post-hoc* comparisons are given in Table 5.25. These show there was a significantly larger discrepancy between pyroclastic flow risk ratings and the threat assessment than for any other hazard type ($p < .01$). The levels of understanding concerning the risk posed by lahars and volcanic ash are both significantly different to other hazards ($p < .001$), but not significantly different from each other; both are equally underestimated. There is no significant difference between the discrepancy scores for lava flows, lateral blasts and debris avalanches.

Table 5.25 Results of mixed factorial ANOVA; understanding of risk.

Hazard type	Mean	*SD*	*F*(5, 1170) = 96.51, *p* <.001
Pyroclastic flows	0.68	0.67	Significantly different to all other hazards @ *p* <.001, except lava; *p* <.01
Lava flows	0.55	0.63	Significantly different to all hazards @ *p* <.01, except lateral blasts (not significant)
Lateral blast	0.43	0.66	Significantly different to pyroclastic flows, ash and lahars; *p* <.001, no significant difference to lava and avalanches
Debris avalanche	0.38	0.74	Significantly different to all hazards; *p* <.01, except lateral blasts (not significant)
Volcanic ash	- 0.08	0.67	Significantly different to all hazards @ *p* <.001, except lahars (not significant)
Lahars	- 0.10	0.80	Significantly different to all hazards @ *p* <.001, except ash (not significant)

Zero indicates an accurate understanding, a positive score indicates an overestimate and a negative score equals an underestimate of the risk.

There was also a significant interaction effect between risk understanding and location; *F*(10, 1170) = 72.14, *p* <.001. The graph in Figure 5.15 shows how discrepancies between questionnaire risk ratings and the threat assessment scores for each hazard type varied by location. This indicates that each study site has a different understanding of the risk associated with each hazard type, which is what we would expect to see given that each area is likely to be subject to different hazards and different levels of risk associated with those hazards during an eruption.

In order to include a measure of an individual's understanding of the risk associated with different hazards from an eruption of Mount Rainier in further analysis, a single variable measuring 'risk understanding' was derived from these risk discrepancy scores. The risk discrepancy scores for each hazard type were folded to create a scale from a maximum of 0; 'accurate', to a minimum of -2; 'inaccurate'. The mean of these scores was then calculated for each participant, and provided a measure of the variance between their overall risk rating for all volcanic phenomena compared to the threat assessment.

5.3.2.8. Appropriate Responses to Volcanic Activity

Previously considered in section 5.3.2.6., a single questionnaire item asked respondents whether they knew what action to take in the event of an eruption affecting their town, and allowed an open-ended response for those who answered yes to detail what actions they would take. In order to evaluate how appropriate these actions would be in the event of an eruption, the results were compared to the advice for planned response detailed in published information campaigns designed to inform residents what action to take in the event of an eruption (Pierce County, 2006; Sumner School District, 2007; Washington Military Department: Emergency Management Division & Washington State Department of Health, 2007; Driedger & Scott, 2008). Given their exposure to different hazard types, different emergency actions are recommended for Ellensburg compared to Carbonado and Sumner. For all three areas it would be appropriate for residents to ensure they; (i) had emergency supplies, and (ii) had an out-of-state emergency contact. For each of these variables those who mentioned the action were coded 1 (correct) and those who didn't know what action to take, or didn't mention the action were scored 0 (didn't know/didn't mention).

Location specific actions for residents from Carbonado and Sumner would be to evacuate or move to higher ground, whilst those from Ellensburg should stay indoors and avoid ashfall. Although residents from Carbonado and Sumner may also be at risk from ashfall, their risk is lower than for lahars, and their main hazard-specific response should be to evacuate. Ellensburg is at risk from a single hazard and their key response should be to avoid ashfall by remaining at home or staying indoors and using breathing equipment. They are not advised to evacuate and therefore cannot score on this variable. It was therefore decided that only two location-specific responses should be including, e.g. (i) 'evacuate' for respondents from Carbonado and Sumner, and (ii) 'avoid ashfall' for Ellensburg. Therefore, all respondents regardless of location could score a maximum of 3 on this variable; 2 for the non location-specific action and 1 for the location-specific response.

It should be noted that the ‘don’t knows’ included the 30.2% of respondents who didn’t know what action to take in the event of an eruption affecting their town. It should also be noted that 8.7% (n = 21) of people incorrectly mentioned either evacuate or stay at home. These were split between the three locations, with 11 people from Carbonado (13.5%, n = 5) and Sumner (6.4%, n = 6) saying they would remain in their homes, and 10 people from Ellensburg (9.1%) stating they would evacuate. In almost any type of eruption scenario it would be unnecessary for people from Ellensburg to evacuate, and should ashfall threaten, they are advised to remain in their homes. Those from Sumner should be prepared to leave their homes for all but the smallest eruption, given their vulnerability to lahars. The situation is a little more complex for residents of Carbonado who are, to some extent, protected from all but the largest lahars due to the surrounding geological features. However, they should also be prepared to leave their homes, either by moving to higher ground or evacuating the town, if directed. Although only a small number of the people questioned mentioned what could be considered an inappropriate mitigation response, this may have implications should they be given advice during an eruption which conflicts with their own previously held beliefs. However, for the purposes of this analysis they were coded as for those who didn’t know/didn’t mention the action.

Table 5.26 shows that around 60% of people from both Carbonado and Sumner correctly mentioned evacuation, whilst only 40% of Ellensburg respondents mentioned the need to avoid ashfall. This result is not surprising given that over two-thirds of respondents from Carbonado and Sumner reported accessing information about what action to take in the event of an eruption, compared to less than half of those from Ellensburg. For the two non-hazard, non-location specific actions, 27.7% of people said they would store emergency supplies, and 7.5% mentioned the need for an emergency contact.

Using the results of this analysis, a single measure representing ‘appropriate action’ was calculated by summing the number of correctly identified mitigation responses mentioned by each participant. The mean number of measures reported was 0.95 (*SD* = 0.82), and ranged from 0 to 3 items. This variable attempts to quantify whether an individual would respond in a manner that would reduce the impact of an eruption upon themselves, and therefore provides a proxy for measuring post-event, but pre-recovery vulnerability.

Table 5.26 Appropriate response in the event of an eruption affecting town, percentages for total sample and by area.

	Total %	Carbonado %	Sumner %	Ellensburg %
Evacuate				
Didn't know/mention/incorrect	38.6	40.5	37.2	-
Correct	61.4	59.5	62.8	-
Avoid ash/stay indoors				
Didn't know/mention/incorrect	60.0	-	-	60.0
Correct	40.0	-	-	40.0
Emergency supplies				
Didn't know/mention	72.3	62.2	78.7	70.0
Correct	27.7	37.8	21.3	30.0
Emergency contact				
Didn't know/mention	92.5	91.9	93.6	96.4
Correct	7.5	8.1	6.4	3.6
Mean no. actions (*SD*)	0.95 (0.82)	1.08 (0.64)	1.02 (0.73)	0.84 (0.93)

5.3.3. Socio-economic Comparison of Beliefs & Attitudes

The previous sections explored the results from the survey conducted in the three case study locations around Mount Rainier, and looked specifically at differences between the three communities on measures of seven key psychological variables, suggested in the literature as important indicators of vulnerability. These were; (i) risk perception, (ii) self-efficacy, (iii) trust (in official sources of information), (iv) access to information, (v) preparedness, (vi) understanding of risk, and (vii) appropriate action. Where appropriate, PCA was used to collapse items to form a single measure for each of these vulnerability indicators, and scale reliability was tested using Cronbach's alpha. Details of the questionnaire items used to form these scales and their scale reliability scores are given in Appendix 8. These variables were then used for further analysis to explore the relationships between the vulnerability indicators and selected socio-economic characteristics. The socio-economic characteristics selected were those indicated in the literature as important in determining vulnerability. These were gender, age, income, education (number of years of schooling completed), household composition, e.g. household size, number of children (16 years or less) and number of older household members (65 and over), property ownership (renter or home owner), and location (Carbonado, Sumner and Ellensburg). If socio-economic variables are important in determining vulnerability, we would expect to see significant differences in the psychological vulnerability indicators between groups with different socio-economic characteristics. To explore this, categorical variables were analysed using either *t*-tests or one-way ANOVA (depending on the number of independent variables), whilst other relationships were explored using Spearman's correlation coefficient. Spearman's correlations are reported due to asymmetric distribution on some variables (information accessed, preparedness, risk understanding and appropriate action) violating a key assumption (normal distribution) for the use of Pearson's correlation coefficient. Pearson's was applied previously on normally distributed data as it is statistically more powerful.

Firstly, gender differences were considered using a series of *t*-tests to explore whether the psychological vulnerability indicators differed between men and women (Figure 5.16). There was no significant difference between men and women for risk perception, levels of preparedness, understanding of risk and appropriate action. Levels of self-efficacy were significantly higher for men (*M* = 2.53, *SE* = 0.17) compared to women (*M* = 2.28, *SE* = 0.12); *t*(236) = 2.39, *p* <.05, whilst men (*M* = 3.78, *SE* = 0.27) reported accessing significantly more sources of information than woman (*M* = 3.11, *SE* = 0.16); *t*(237) = 2.21, *p* <.05. Conversely, levels of trust in official sources of information were significantly lower for men (*M* = 1.43, *SE* = 0.05) compared to women (*M* = 1.20, *SE* = 0.07); *t*(234) = -2.54, *p* <.05 (Table 5.27).

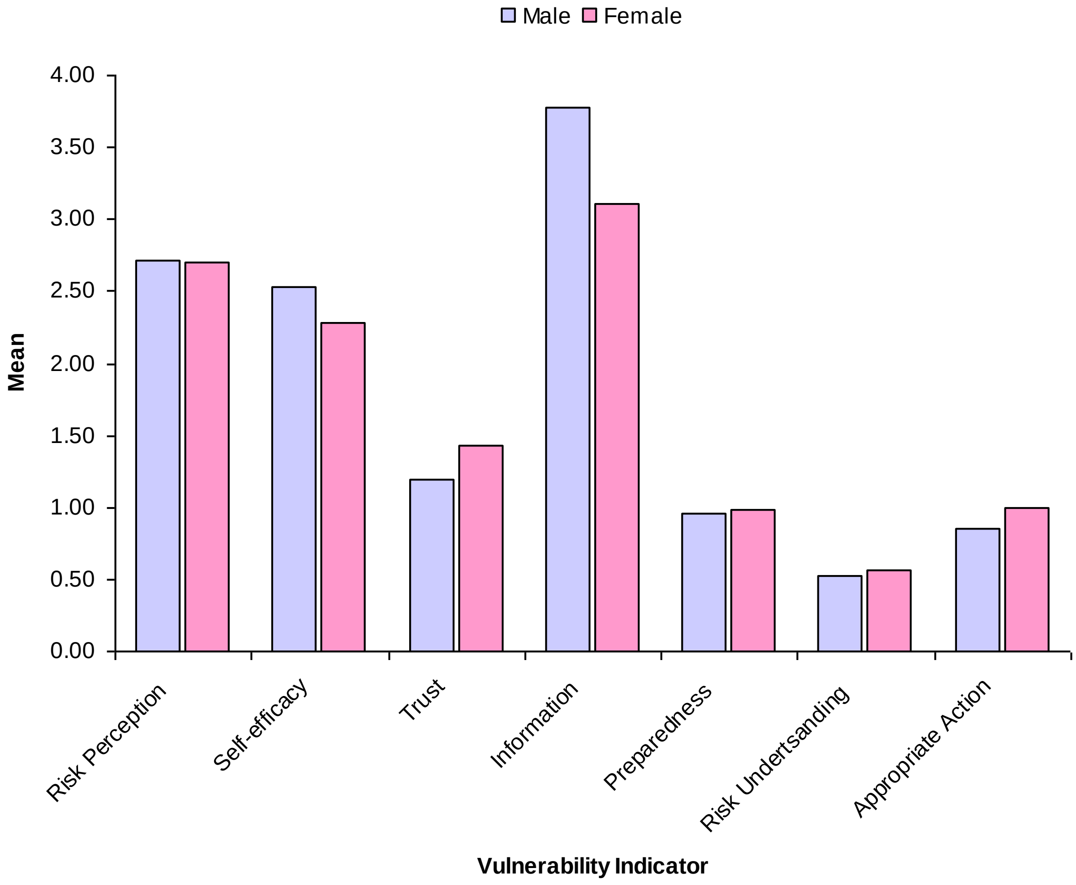


Figure 5.16 Bar chart showing mean scores for men and women for the seven vulnerability indicators.

Table 5.27 Results of independent samples *t*-tests by gender on the seven key psychological vulnerability indicators.

	Male *M* (*SE*)	Female *M* (*SE*)	df	*t*	*p*
Risk Perception	2.71 (0.08)	2.70 (0.05)	237	0.13	.896
Self-efficacy	2.53 (0.17)	2.28 (0.12)	236	2.39*	.018
Trust	1.20 (0.07)	1.43 (0.05)	234	-2.54*	.012
Information	3.78 (0.27)	3.11 (0.16)	237	2.21*	.028
Preparedness	0.96 (0.12)	0.98 (0.08)	237	-0.08	.937
Risk Understanding	-0.53 (0.41)	-0.57 (0.03)	237	0.71	.476
Appropriate Action	0.85 (0.08)	1.00 (0.07)	237	-1.31	.192

* significant at *p* <.05

A further series of independent sample *t*-tests on property ownership indicated that those who owned their own homes (*M* = 2.41, *SE* = 0.12) reported significantly higher levels of self-efficacy (*M* = 2.15, *SE* = 0.05) than those who rented; *t*(236) = 2.16, *p* .032. In addition, home owners (*M* = 1.08, *SE* = 0.07) appeared more prepared than renters (*M* = 0.57, *SE* = 0.13), having adopted significantly more hazard adjustment measures; *t*(237) = 3.41, *p* .001. However, levels of trust were significantly lower amongst home owners (*M* = 1.31, *SE* = 0.05) compared to tenants (*M* = 1.54, *SE* = 0.10); *t*(234) = 2.24, *p* .026. There was no significant difference between property ownership and the remaining four psychological variables.

Although the individual items which form the components of each psychological variable have been analysed by location in the preceding section, to explore whether the collapsed measurers of each psychological indicator differed by case study location (Figure 5.17), a series of one-way ANOVA were conducted. These revealed a significant difference for all indicators except levels of trust and appropriate action (Table 5.28). *Post-hoc* tests showed that risk perception differed significantly (*p* <.01) between all three locations, with Sumner reporting the highest levels. Respondents from Carbonado reported significantly higher levels of self-efficacy (*p* <.001) than either Sumner or Ellensburg, who felt similarly able to cope. The number of sources of information accessed by Carbonado and Sumner respondents were similar, and both significantly higher than participants from Ellensburg (*p* <.05). Risk understanding differed significantly between all three locations (*p* <.05), with Ellensburg rating the overall risk most accurately whilst Sumner respondents showed the largest discrepancy from the threat assessment. The number of protective hazard adjustment measures adopted by respondents in preparation for a potential volcanic eruption was significantly lower amongst Ellensburg residents than either Carbonado or Sumner (*p* <.001), who reported similar levels of preparedness.

Table 5.28 Results of a series of one-way ANOVA exploring case study location by the seven psychological vulnerability indicators.

	Carbonado M (*SD*)	Sumner M (*SD*)	Ellensburg M (*SD*)	*F*(df)
Risk Perception	2.69 (0.67)	3.06 (0.61)	2.39 (0.62)	*F*(2, 238) 29.43, *p* <.001
Self-efficacy	2.82 (0.76)	2.28 (0.71)	2.25 (0.75)	*F*(2, 237) 9.30, *p* <.001
Trust	1.33 (0.66)	1.38 (0.66)	1.37 (0.64)	*F*(2, 235) 0.08, *p* = .921
Information	3.89 (2.21)	3.74 (2.26)	2.71 (1.96)	*F*(2, 238) 7.81, *p* <.001
Preparedness	1.22 (0.98)	1.33 (1.11)	0.55 (0.71)	*F*(2, 92.29) 20.64, *p* <.001
Risk Understanding	-0.54 (0.32)	-0.77 (0.32)	-0.38 (0.32)	*F*(2, 238) 38.51, *p* <.001
Action	1.08 (0.64)	1.02 (0.73)	0.84 (0.93)	*F*(2, 111.37) 1.90, *p* = .155

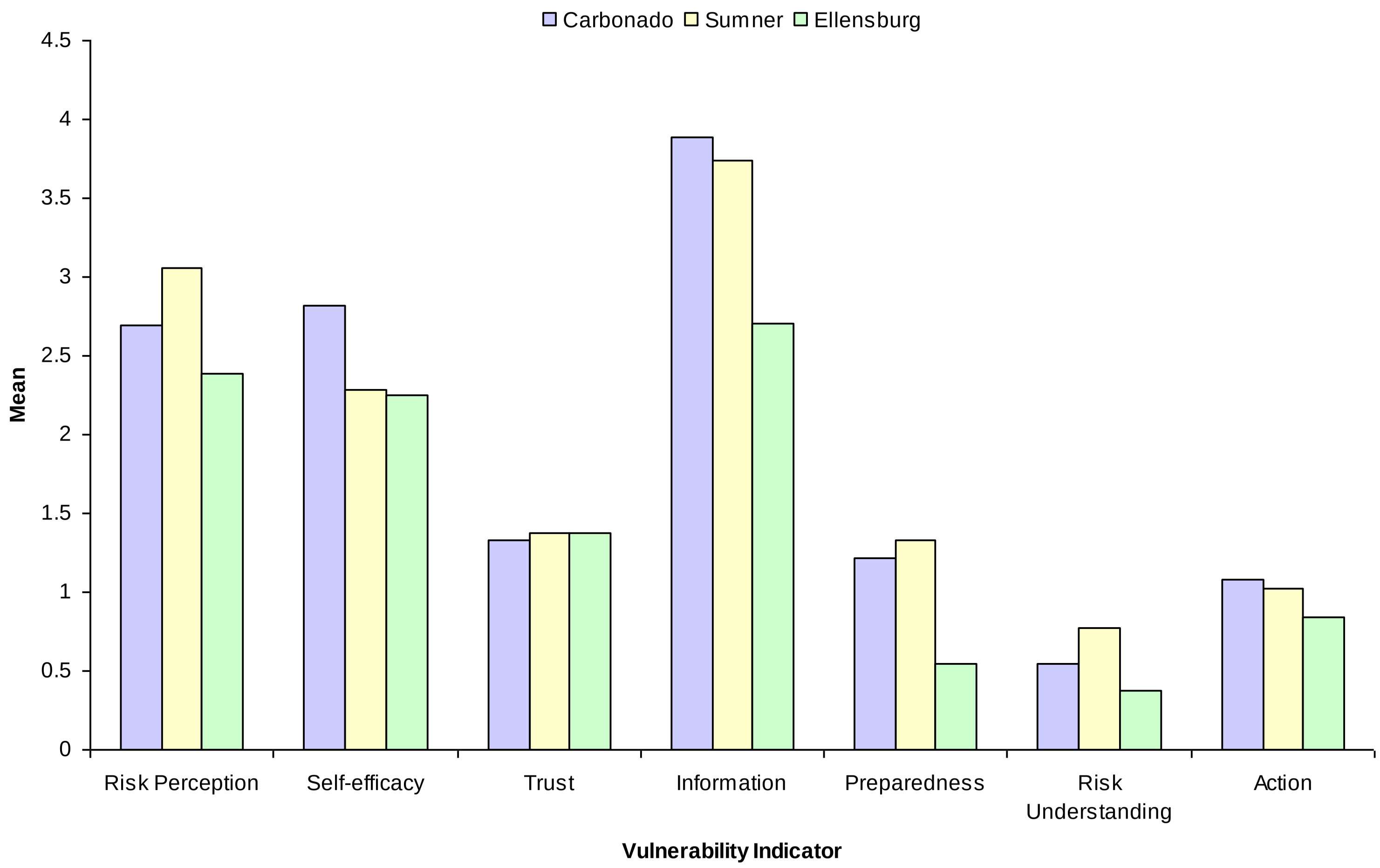


Figure 5.17 Bar chart showing the mean ratings for each of the seven key vulnerability indicators by case study location.

Relationships between the remaining six demographic variables and the psychological vulnerability indicators are detailed in the correlation matrix in Table 5.29, with location, gender and property ownership included for comparison. All relationships between psychological variables and socio-economic variables showed in the expected direction. Age and elderly in the home, were negatively correlated with risk perception and trust, whilst elderly in the home was also negatively correlated with preparedness and appropriate action. Both were positively correlated with understanding of risk. So although older respondents appear to assess the risk from volcanic hazards more accurately, they perceive the risks as lower and are therefore less likely to make hazard adjustments to prepare for an eruption, or to know the appropriate action to take should an eruption occur. Larger households and those with children were positively correlated with preparedness, appropriate action, risk perception and trust, as well as information seeking for the former, and self-efficacy for the latter. Homes with children not only appear more prepared and more likely to respond appropriately, they also feel more able to do so. As would be expected, level of education was positively correlated with risk understanding. There was no significant relationships between income level and any of the psychological variables.

Table 5.29 Correlations matrix of socio-economic characteristics and psychological vulnerability indicators.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Location[a]	-															
2. Gender[b]	0.07	-														
3. Age	0.10	-0.08	-													
4. Income	-0.09	-0.04	-0.10	-												
5. Education	0.24***	-0.04	0.03	0.40***	-											
6. Children in home	-0.19**	0.17**	-0.41***	0.20**	-0.03	-										
7. Elderly in home	0.05	-0.12*	0.77***	-0.23***	-0.09	-0.30***	-									
8. Household size	-0.15*	0.15*	-0.41***	0.27***	0.01	0.73***	-0.27***	-								
9. Property[c]	-0.04	0.04	0.12*	0.42***	0.15**	0.07	0.03	0.18**	-							
10. Perception	-0.32***	-0.01	-0.14*	0.05	-0.07	0.07	-0.15*	0.13*	0.03	-						
11. Self-Efficacy	-0.20**	-0.17**	-0.03	0.11	-0.06	0.12*	-0.02	0.11	0.13*	-0.08	-					
12. Trust	0.02	0.19**	-0.19**	0.05	0.01	0.04	-0.22***	0.12*	-0.12*	0.14*	0.04	-				
13. Information	-0.29***	-0.11*	-0.09	0.09	0.02	0.06	-0.10	0.15*	0.09	0.30***	0.18**	0.01	-			
14. Understanding	0.41***	-0.05	0.13*	0.03	0.18**	-0.05	0.12*	0.01	0.07	-0.43***	0.04	-0.15*	-0.20**	-		
15. Preparedness	-0.34***	0.01	-0.10	0.05	-0.06	0.15*	-0.16**	0.18**	0.24***	0.28***	0.40***	0.09	0.35***	-0.22***	-	
16. Action	-0.17**	0.07	-0.06	0.09	0.01	0.13*	-0.15*	0.18**	0.10	0.22***	0.33***	0.10	0.33***	-0.05	0.55***	-

* p <.05; ** p <.01; *** p <.001.

[a] 1 = Carbonado, 2 = Sumner, 3 = Ellensburg. [b] 0 = male, 1 = female. [c] 0 = tenant, 1 = owner.

5.3.4. Predictors of Vulnerability

The aim of the questionnaire survey was to determine the importance of socio-economic variables in predicting vulnerability in order to justify the inclusion of census data within the threat assessment metric on empirical grounds. The previous analysis explored the relationships between psychological indicators and socio-economic characteristics. In order to assess their relative importance in determining vulnerability, a series of multiple regression analyses were conducted. Whereas correlations describe the strength of a relationship between two variables, regression analysis is a statistical method which aims to predict the value of a dependent or 'outcome' variable from the value of an independent or 'predictor' variable. Multiple regression is simply an extension of this, whereby the outcome is predicted from several predictor variables (Field, 2005). Multiple regression is the statistical test most frequently employed in psychological research when examining relationships between attitudes, intentions and behaviour (Langdridge & Hagger-Johnson, 2009). Its use is appropriate here as it enabled the predictive power of the independent variables (e.g. socio-economic characteristics and psychological indicators) on the dependent variable (e.g. vulnerability, represented by specific psychological variables and a proxy for behaviour) to be determined. Regression provides a measure of how much of the variance in the dependent variable is explained by the independent variables, and also the strength of the relationships between them (*ibid*). The order in which each variable was entered into the multiple regression analyses detailed in the following section was guided by theory, in particular PMT (Rogers, 1983; Grothmann & Reusswig, 2006; Martin *et al.*, 2007).

5.3.4.1. Socio-Economic Model of Vulnerability

To investigate the importance of the socio-economic characteristics as predictors of vulnerability, a series of multiple regression analyses were conducted on two psychological variables. These were; (i) risk perception, and (ii) risk understanding. These variables were selected as they encompass the attitudes and beliefs people hold with regard to the risks associated with living near Mount Rainier. If distinct groups of people can be identified by demographic traits as holding views which may amplify their vulnerability, they can be targeted for education and risk communication strategies.

To avoid problems associated with multicollinearity; i.e., correlation coefficients in excess of .70 (Bryman & Cramer, 1994), the correlation matrix was examined for all predictor variables (Table 5.29). Two correlations higher than .70 occurred between; (i) age and elderly in the household, and (ii) household size and children in the home. Accounting for the least variance, elderly in the home and household size were excluded from all regression analyses.

Table 5.30 presents the results of the two multiple linear regression analyses used to assess the explanatory power of the socio-economic model of residents' beliefs and attitudes regarding risk perception and risk understanding of volcanic activity at Mount Rainier. A separate regression analysis corresponds to each of the two risk beliefs with the same demographic predictors used in each (gender, age, income, education, children in the home, property ownership and location). Hierarchical linear regression was applied to test the unique and combined effects of the demographic characteristics and location, which form the socio-economic model. For each predictor variable, the table reports the unstandardised regression coefficient (*B*), the standard error (*SE*), the value of *t*, and the significance value (*p*), as well as a measure of the variance explained (R^2), and the change in R^2 as an indicator of the extra variance explained with the addition of further variables ($R^2\Delta$). Blocks 1 and 1i represent the inclusion of demographic variables (age, gender etc) into the regression model, whilst Blocks 2 and 2i indicate the addition of location with the model. A minimum significant level of .05 is assumed for all statistics.

Table 5.30 Prediction of risk perception and risk understanding by socio-economic factors.

	Risk Perception								Understanding of Risk							
Predictor variables	Block 1				Block 2				Block 1i				Block 2i			
	B	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*
Demographics																
Gender	.01	.09	0.11	.92	.06	.09	0.72	.47	-.04	.05	-0.82	.41	-.08	.05	-1.73	.09
Age	-.01	.01	-1.77	.08	-.01	.01	-2.46	.02*	.01	.01	0.54	.59	.01	.01	1.33	.19
Income	.04	.03	1.28	.20	.02	.03	0.69	.49	-.02	.02	-1.02	.31	-.01	.02	-0.28	.78
Education	-.08	.04	-2.35	.02*	-.06	.03	-1.69	.09	.05	.02	2.54	.01*	.03	.02	1.82	.07
Children in house	-.05	.05	1.08	.28	-.08	.04	-1.81	.07	-.01	.03	-0.11	.91	.02	.02	0.70	.48
Property ownership	.04	.12	0.31	.76	.12	.11	1.13	.26	.09	.06	1.37	.17	.03	.06	0.53	.60
Location[a]																
Carbonado	-	-	-	-	.17	.12	1.40	.16	-	-	-	-	-.12	.07	-1.80	.07
Sumner	-	-	-	-	.58	.09	6.71	.00**	-	-	-	-	-.40	.05	-8.68	.00**
N				218				218				218				218
$R^2\Delta$				-				.17				-				.26
R^2				.05				.22***				.05				.31***

* p <.05, ** p <.01, *** p <.001.
[a] Reference location: Ellensburg

The socio-economic model of vulnerability yielded statistically significant explanations for both risk perception and understanding of risk, explaining 22% and 31% of the variance respectively. This degree of explained variance represents good levels of explanation based on standards in psychological research (Field, 2005; Langdridge & Hagger-Johnson, 2009). These small standards are acceptable due to difficulties in psychology, particularly relating to the limited amount of time people are willing to spend completing questionnaire surveys, which means not all the personal or contextual factors that may influence a persons beliefs or behaviour can be measured (Field, 2005; Grothmann & Reusswig, 2006; Langdridge & Hagger-Johnson, 2009).

Education was the single demographic factor that significantly predicted risk perception (B = -.08, p = .02). The negative B value indicates a negative relationship, therefore as levels of education increased, perception of risk decreased. However, when the effects of location were added to the model (Blocks 2 and 2i), this effect was mediated, whilst age became a significant predictor (B = -.01, p = .02). This suggests that older residents have decreasing levels of risk perception, when controlling for location and all other socio-economic variables. With Ellensburg entered as the reference location, the results showed no significant change in risk perception between residents of Ellensburg and those from Carbonado. However, respondents living in Sumner showed a significantly higher perception of risk (B = .58, p <.001), when controlling for demographic features. This suggests that compared to respondents from Ellensburg, risk perception was over half a point higher on the original 4 point scale for Sumner residents, if all other socio-economic factors in the model are held constant. It should be noted that the R^2 and R^2 change values indicate that the variability in risk perception attributable to demographic factors was just 5% (Block 1/1i), whilst the inclusion of location explained an additional 17% (Block 2/2i). So although the overall variance explained (22%) represents a good level of explanation, location is a significantly more important predictor of a persons risk perception than all other demographic factors.

A similar picture emerged for risk understanding, with level of education the only significant demographic predictor (B = .05, p = .012). As level of education increased, so did the accuracy of an individual's understanding of the risks associated with hazards from Mount Rainier. When we included location (Block 2i), the effects of education were mediated, whilst gender became more important. This suggests that when controlling for all other variables in the model, women had a slightly less accurate understanding of the risk than men, although the difference was not significant. In terms of location, both Carbonado (B = -.12, p = .07) and Sumner (B = -.40, p <.001) had a less accurate understanding of the risk compared to Ellensburg respondents, although the difference between Ellensburg and Carbonado was not significant. Risk understanding was .40 less for participants from Sumner compared to those from Ellensburg (on the original three point scale), representing a 13.3% reduction in the accuracy of their risk rating, if all other variables in the model are held constant. The demographic factors explained just 5% of the variance in risk understanding Block 1i; R^2 = .05), whilst location accounted for an additional 26% (Block 2i; $R^2\Delta$ = .26). Although the overall variance explained (31%) represents a good level of explanation, location is responsible for the majority of this variance, whilst the socio-economic factors appear to be weak predictors of risk understanding.

5.3.4.2. Socio-Psychological Model of Vulnerability

Investigating the two main belief/attitude variables (risk perception and risk understanding), highlighted the limitations of the socio-economic model, but the relative importance of location. To explore the main behavioural factors, the explanatory power of a socio-psychological model of vulnerability was investigated, and compared to a socio-economic model. The two key behavioural variables developed were; (i) preparedness (number of protective hazard adjustment measures adopted), and (ii) appropriate action (number of correctly identified mitigation responses mentioned).

Relationships between all psychological variables were analysed using Spearman's correlation coefficient (Table 5.29, page 262). As would be expected, appropriate action and preparedness were significantly positively correlated, and both were also positively correlated with risk perception, self-efficacy and access to information. The negative correlation between both preparedness and information accessed, and risk understanding appeared inconsistent with expected results, but may be explained by the negative feedback effect of risk perception. As risk perception increases, understanding of risk becomes less accurate. As the direction of inaccurate answers predominantly overestimated the risk, it is not surprising that this would be related to increasing levels of concern (risk perception). The information accessed was not related to volcanic hazards but was explicitly concerned with information relating to mitigation responses. The positive correlation between information accessed and risk perception ($r = 0.30$, $p < .001$), is consistent with theories which suggest that increasing risk perception stimulates information seeking (Perry & Lindell, 2008). Therefore, the negative relationship between information accessed and risk understanding may also be explained by the feedback effect of risk perception.

A multiple linear regression analysis was used to assess the explanatory power of the socio-psychological model of residents' preparedness, and this was compared to a model based solely on socio-economic predictors. Hierarchical multiple regression was applied to test the unique and combined effects of the different factors included in the two models. The same demographic characteristics were retained in the socio-economic model as used in the previous analysis (gender, age, income, education, children in the home, property ownership and location). To simplify the model, psychological indicators that were found not to be significant predictors of preparedness where excluded, these were trust and risk understanding. That risk understanding is not a significant predictor of preparedness, despite a significant negative correlation ($r = -0.22$, $p < .001$), suggests the effects are being mediated by other factors within the model, possibly location.

The context of the analysis were theories of protective response ((Grothmann & Reusswig, 2006; Martin *et al.*, 2007; Perry & Lindell, 2008) that define hazard adjustment as a process wherein the characteristics of the hazard, the individual and the adjustments are examined. Threat appraisal or perceived risk focuses the individuals attention on the threat, which leads to coping appraisal (i.e. self-efficacy), whereby an individual evaluates their ability to cope with the threat. These two perceptual processes stimulate protective responses (e.g. information seeking and preparedness). Using this theoretical model, the psychological variables were entered into the regression analysis in the following order; risk perception and self-efficacy, followed by information accessed, and the results of this analysis are presented in Table 5.31.

The socio-psychological model of protective response yielded a statistically significant explanation for levels of preparedness, explaining 39% of the variance, representing a very good level of explanation. The socio-economic model (Block 1), including gender, age, income, education, children in the household and property ownership accounted for 7% of this variance ($p < .05$). Property ownership was the only statistically significant predictor ($B = .61$, $p < .001$). That home ownership is an important factor in explaining residents' preparedness is unsurprising. Firstly, owners would have much more to lose than tenants in the event of an eruption affecting their town, particularly as a result of damage from the most threatening hazards. To support this theory, we would expect home owners to have significantly higher levels of risk perception than tenants. However, there was no difference in perceived risk between owners and tenants (independent sample t-test; $t = .410$, $p = .682$). Secondly, ownership showed a positive correlation with self-efficacy ($r = 0.13$, $p < .05$), supporting the suggestion that owners are likely to both have and perceive more opportunities to take independent action to protect themselves compared to tenants, who for example may not be able to obtain insurance cover or be in a position to choose to live on higher ground. However, when we included risk perception and self-efficacy, in the socio-psychological model,

Table 5.31 Prediction of preparedness or hazard adjustment by socio-economic and psychological factors.

	Block 1				Block 2				Block 3				Block 4			
	B	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*
Demographics																
Gender	-.05	.14	-0.35	.73	.02	.13	0.18	.86	.14	.13	1.15	.25	.16	.12	1.33	.18
Age	-.01	.01	-1.02	.31	-.01	.01	-1.39	.17	-.01	.01	-1.07	.29	-.01	.01	-1.51	.13
Income	-.06	.05	-1.21	.23	-.09	.05	-1.96	.06	-.12	.04	-2.65	.01**	-.11	.04	-2.54	.01**
Education	-.02	.05	-0.45	.65	.03	.05	0.50	.62	.06	.05	1.27	.21	.04	.05	0.87	.39
Children in house	.11	.07	1.49	.14	.06	.07	0.92	.36	.04	.06	0.64	.52	.05	.06	0.82	.41
Prop. ownership	.61	.18	3.48	.00***	.69	.17	4.13	.00***	.56	.16	3.58	.00***	.51	.15	3.42	.00***
Location[a]																
Carbonado	-	-	-	-	.48	.19	2.47	.01**	.26	.18	1.46	.15	.17	.17	0.95	.34
Sumner	-	-	-	-	.78	.14	5.82	.00*	.61	.14	4.45	.00***	.51	.13	3.79	.00***
Perceptual Process																
Risk Perception	-	-	-	-	-	-	-	-	.31	.10	3.10	.00***	.21	.10	2.15	.03*
Self-Efficacy	-	-	-	-	-	-	-	-	.46	.08	5.81	.00***	.51	.08	5.27	.00***
Protective responses																
Info Accessed	-	-	-	-	-	-	-	-	-	-	-	-	.23	.05	4.45	.00***
N				217				217				217				217
$R^2\Delta$				-				.13				.13				.06
R^2				.07*				.20***				.33***				.39***

* $p < .05$, ** $p < .01$, *** $p < .001$.
[a] Reference location: Ellensburg

the effects of property ownership remained, suggesting other factors relating to home ownership were stimulating hazard adjustment behaviour. One factor could be attachment to place, and comparisons of SCI scores suggested home owners had a significantly higher sense of community than tenants (t = 3.41, p <.001), and therefore may be more inclined to carry out hazard adjustments to maintain their place within the community.

Inclusion of location within the model (Block 2) explained an additional 13% of variance (p <.001), with both Carbonado (B = .48, p <.05) and Sumner (B = .78, p <.001) showing significantly higher levels of preparedness compared to Ellensburg, when controlling for socio-economic factors. Given the relative levels of risk each town is exposed to from volcanic activity, and the variation in perceived risk between towns, we might expect this difference in hazard adjustment. Additional factors must be responsible for the 16% higher levels of preparedness found in Sumner residents compared to Ellensburg, because when we included perceptual processes in the model, the effects of location remained significant (B = .61, p <.001). The difference in levels of preparedness between Carbonado and Ellensburg residents was mediated by the addition of perceptual factors. The significantly higher levels of self-efficacy reported by Carbonado residents (compared to both Ellensburg and Sumner), may be responsible for this mediation.

The psychological model of protective response (Blocks 3 and 4) explained an additional 19% of the variation in levels of preparedness (p <.001), with all three variables significant predictors; risk perception (B = .21, p <.05), self-efficacy (B = .41, p <.001) and information seeking (B = .23, p <.001). This means that, controlling for all other variables, as risk perception increases by one point on the original four point scale, preparedness increases by .21, or 4.2%, as self-efficacy increases by one point, preparedness increases by 8.2%, and as the number of information sources accessed increases by one, preparedness increases by 4.6% (as noted earlier, we make no distinction between the quality of the information, and conceptually this aspect must be left to subsequent research). Controlling for psychological characteristics, the increase in levels of preparedness between Sumner and Ellensburg reduced to 10% but was still significant (p <.001). The effect of risk perception was partially mediated by information accessed. The effects of property ownership remained (p <.001), and income became a significant negative predictor (B = -.11, p <.05). This suggests that controlling for all other demographic and psychological factors within the model, those on lower incomes display higher levels of preparedness. It is difficult to account for this counter intuitive result given previous research into vulnerability and poverty levels, especially given the near zero correlation between income and preparedness. A possible explanation is provided by the concept of a suppressor variable in statistical analysis. This is defined as a variable with a zero or near zero correlation with the dependent variable, but which still contributes to the predictive validity of the test. Although the variable may on its own predict none or almost none of the variance of the dependent variable, it may suppress irrelevant variance in other predictor variable(s), with which it correlates, thereby providing an *indirect* effect (Lancaster, 1999).

Most theories of protective response only consider hazard adjustments carried out as a proactive reaction to perceived risk. This research attempted to take the approach one step further by considering the behavioural responses of an individual, assuming a volcanic eruption is affecting their town. Using the appropriate action variable, we can explore what socio-economic and psychological characteristics directly influence whether an individual will respond in a manner most likely to protect themselves and their family during an eruption. As a persons vulnerability can be amplified or attenuated by whether they respond to a volcanic crisis appropriately, e.g. by evacuating or avoiding ashfall, this variable provides a proxy measure for vulnerability.

A multiple linear regression analysis was used to assess the explanatory power of the socio-psychological model of vulnerability, and this was compared to a model based solely on socio-economic predictors. Hierarchical multiple regression was applied to test the unique and combined effects of the different factors included in the two models. The same socio-economic characteristics (gender, age, income, education, children in the household, property ownership and location), and psychological factors (risk perception, self-efficacy and information accessed) used in the previous analysis were retained. In addition, level of preparedness was included as a predictor variable in the final protective response block.

The socio-psychological model of vulnerability yielded a statistically significant explanation for appropriate action, explaining 36% of the variance, representing a very good level of explanation (Table 5.32). The socio-economic factors (Block 1) accounted for just 2% of the variance, and inclusion of location (Block 2) explained a further 2%. There were no significant predictors amongst these variables, and contributing only slightly to the differences in vulnerability (just 4%), the socio-economic model fails to significantly explain the variance in appropriateness of planned response.

In the second step of the analysis, the two perceptual processes; risk perception and self-efficacy, were included (Block 3). Explaining an additional 15% of variance, both were statistically significant (p <.001). As with the previous regression analysis involving levels of preparedness, both risk perception (B = .38, p <.001) and self-efficacy (B = .37, p <.001) proved significant predictors of appropriate action. This was not unexpected given that appropriate action correlated positively with risk perception (r = 0.22. p <.001) and self-efficacy (r = 0.33, p <.001). The regression analysis suggests that if socio-economic variables are held constant, and risk perception increases by one unit (on the 4 point scale), appropriate action will increase by 9.5%, and as self-efficacy increases by one, appropriate action will increase by 9.3%. All socio-economic factors remained non-significant predictors of appropriate action when controlling for perceptual processes.

Table 5.32 Prediction of appropriate action by socio-economic and psychological factors.

	Block 1				Block 2				Block 3				Block 4			
	B	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*	*B*	*(SE)*	*t*	*p*
Demographics																
Gender	.08	.12	0.65	.51	.10	.30	0.04	.40	.19	.11	1.66	.10	.14	.10	1.40	.16
Age	.01	.01	0.51	.61	.01	.01	0.52	.60	.01	.01	1.17	.24	.01	.01	1.58	.12
Income	.01	.04	0.29	.77	.01	.04	0.06	.96	-.02	.04	-0.48	.64	.03	.04	0.75	.45
Education	.01	.05	0.03	.98	.02	.05	0.47	.64	.06	.04	1.31	.19	.03	.04	0.67	.51
Children in house	.09	.06	1.51	.13	.08	.06	1.25	.21	.07	.06	1.23	.22	.06	.05	1.16	.25
Prop. ownership	.08	.15	0.56	.58	.08	.15	0.53	.60	-.04	.14	-0.29	.77	-.26	.13	-2.03	.04*
Location[a]																
Carbonado	-	-	-	-	.25	.17	1.41	.16	.05	.16	0.32	.75	-.09	.15	0.57	.57
Sumner	-	-	-	-	.19	.12	1.58	.12	-.03	.13	-0.20	.84	-.29	.12	-2.50	.02*
Perceptual Process																
Risk Perception	-	-	-	-	-	-	-	-	.38	.09	4.22	.00***	.23	.08	2.71	.01**
Self-Efficacy	-	-	-	-	-	-	-	-	.37	.07	5.07	.00***	.16	.07	2.51	.02*
Protective responses																
Info Accessed	-	-	-	-	-	-	-	-	-	-	-	-	.10	.05	2.18	.03*
Preparedness	-	-	-	-	-	-	-	-	-	-	-	-	.36	.06	6.15	.00***
N				217				217				217				217
$R^2\Delta$				-				.02				.15***				.17***
R^2				.02				.04				.19				.36

* $p < .05$, ** $p < .01$, *** $p < .001$.
[a] Reference location: Ellensburg

In the final step of the analysis (Block 4), protective responses (information accessed and preparedness) were included and explained an additional 17% of variance in appropriate action ($p < .001$). Both information seeking ($B = .10$, $p < .05$) and levels of preparedness ($B = .36$, $p < .001$) were significant predictors of appropriateness of planned response. This represents an increase in appropriate action of 2.5% for every additional source of information accessed and a 9.0% increase for every additional preparedness measure adopted. Controlling for these protective responses partially mediated the effects of both risk perception ($B = .23$, $p < .01$) and self-efficacy ($B = .18$, $p < .05$). Re-running the analysis with the two protective response factors in separate blocks, showed that preparedness partially mediates the two psychological variables, as well as information accessed. When controlling for socio-economic factors, location, perceptual processes (risk perception and self-efficacy), and information seeking, preparedness (number of emergency measures already adopted) explained 11.8% of the variance in appropriate action.

Controlling for all psychological variables, property ownership becomes a significantly negative predictor of appropriate action ($B = -.26$, $p < .05$). The previous analysis indicated that home owners were significantly more prepared than tenants, yet this result indicates that owners are less likely to respond appropriately in the event of an eruption. Given that owners appear more prepared, this result seems counter-intuitive, but as discussed in relation to what motivates people to adopt protective measures, owners have much more to lose than tenants, and particularly in the case of evacuation, may feel less inclined to leave their homes. The effect of location also became significant when controlling for psychological factors. Sumner respondents ($B = -.29$, $p < .05$) are less likely to respond appropriately compared to Ellensburg participants. Given that relative to Ellensburg, Sumner is significantly more at risk, this result could be particularly worrying for hazard managers. However, the actions Ellensburg residents would need to perform in order to protect themselves during an eruption are relatively benign (e.g. avoid ashfall and stay indoors), whereas Sumner residents may be required to evacuate their homes, a considerably more disruptive activity, possibly suggesting a similar driver as that influencing home owners. As the only two significant socio-economic predictors of vulnerability (home ownership and location, when controlling for all other factors in the model) this analysis demonstrates the limitations of a model based solely on socio-economic factors. Inclusion of psychological beliefs and attitudes as well as protective responses improved the model significantly, and provided a very good level of explanation of the variance in vulnerability, as represented by appropriate protective response.

5.3.5. Discussion

Analysing the results of the questionnaire survey conducted in the three case study communities, which is comprehensively detailed in the previous section, provides an indication of some of the factors which may be most important in shaping an individual's vulnerability. Firstly, the pattern of results suggested that residents from the three case study communities surveyed did, as was expected, differ with regards to how they perceived the risk posed by volcanic activity at Mount Rainier, and how able they felt to cope with this threat. These factors in turn influenced whether they had adopted protective responses to the risk, and ultimately their knowledge of what action to take in the event of an eruption. Although location proved important in predicting perceived behaviour in the event of a volcanic eruption, only a single socio-economic variable, home ownership, was found to be important, when controlling for all other variables. This finding has serious implications with regards the over-riding aim of this research, i.e. the integration of socio-economic factors, in the form of census data, into the threat assessment. The results of this analysis failed to provide empirical evidence that socio-economic factors are important in amplifying or attenuating vulnerability, and therefore their inclusion as an additional layer in the threat assessment metric is not justified. The results which support this finding are discussed below, and begin with a profile of the three case study communities.

In Carbonado, the small remote community situated within sight of the summit of Mount Rainier, hazard salience was relatively low, almost 50% of participants reported thinking about the possibility of an eruption 'rarely' or 'a few times a year'. There are a number of possible explanations for this low salience, given the towns relative proximity to the volcano. Although just over half said they were slightly worried about the volcano, the community as a whole was significantly more concerned about wildfires. That wildfires are a more salient hazard amongst Carbonado residents is unsurprising given the rural location of the town, surrounded as it is by woodland, which has suffered wildfires within the lifetime of many residents. Additionally, over 80% of respondents thought the next eruption of Mount Rainier would occur '10 to 50 years' or 'more than 50 years' from now, suggesting the majority felt an eruption was not an imminent threat and perhaps unlikely to occur within their lifetime. Similarly, there is no living memory of the hazard, which further serves to distance all three communities from the potential threat of an eruption.

Past experience of a hazard has been linked with higher perceptions of risk and motivation to prepared (Johnston *et al.*, 1999; Paton *et al.*, 2001a; Perry & Lindell, 2008). It has also been suggested that biases may develop due to a lack of experience or no living memory of the hazard. This can result in the development of denial regarding the threat, where information about the hazard is deemed unnecessary and self-protective behaviour is not stimulated (Dibben & Chester, 1999; Dominey-Howes & Minos-Minopoulos, 2004). The high levels of preparedness reported here (discussed later) suggest that lack of past experience of volcanic activity has not impacted significantly upon the adoption of protective behaviour in the communities surveyed. However, Johnston *et al.* (1999), also noted that 'normalisation bias', whereby an at-risk population grows accustomed to the hazard and downplays its potential threat can be created by vicarious or benign exposure to a hazard. Ellensburg is the only community with direct experience of a volcanic eruption (albeit 20 years ago), having suffered light ashfall during the Mount St Helens eruption. However, questions regarding past experience were not included within this study, and therefore speculation regarding its importance in stimulating or suppressing hazard preparedness cannot be made.

Perceptions of risk amongst Carbonado participants fell between levels expressed by residents from Sumner and Ellensburg, with 70% of respondents believing if there were an eruption, it would be 'quite likely' or 'very likely' to affect their town. They also felt the risks would be equally serious for both themselves and their community (on average rating the risk as 'quite serious'). Carbonado differed from the other two survey locations by displaying no optimistic bias, possibly as a result of the strong bonds exhibited within the community. This strong community bond, measured on the SCI scale, on which Carbonado scored significantly higher than the other two communities, has variously been found to be positively associated with volcanic risk perception (Davis *et al.*, 2005; Barberi *et al.*, 2008) and the adoption of hazard responses (Bishop *et al.*, 2000), negatively associated with risk perception towards seismic risk (Armaş, 2006), and heeding hurricane evacuation warnings (Riad & Norris, 1998), or unrelated to vulnerability following a volcanic eruption (Paton *et al.*, 2001b). However, it has been suggested that cognitive biases, caused by a lack of community interaction can be a barrier to preparedness (Weinstein, 1980; Paton, 2003), whilst strong community bonds are thought to foster positive behaviour with regards to preparedness (Bandura, 1977; Lindell & Whitney, 2000; Barberi *et al.*, 2008). Results for the survey sample as a whole tend to support this latter theory, with a positive relationship found between SCI and the adoption of appropriate protective behaviour. Although SCI was excluded from the regression analysis it was not found to be an important predictor for any of the key vulnerability indicators.

Carbonado residents identified ash as their most likely threat, but slightly overestimated the risk compared to the 'objective' threat assessment. The discrepancies between the 'objective' threat assessment scores and 'lay judgements' for other hazards indicate they had an accurate understanding of the risk from lahars, debris avalanches and lateral blasts. However, further analysis indicated that the relative importance of understanding the risk of specific hazards was not a significant predictor of risk perception, preparedness or appropriate action, and therefore may not have implications with regards to vulnerability. This suggests that a lack of understanding regarding the risk from specific hazard types would be no barrier to the adoption of self-protective behaviour.

Although Carbonado residents perceived the volcano as a threat, they felt they had strong control over their exposure to an eruption's effects, rating their levels of self-efficacy significantly higher then either Sumner or Ellensburg respondents. For the survey sample as a whole, positive correlations were found between self-efficacy and information accessed, preparedness, and appropriate action, reflecting similar results found by Paton *et al.* (2001a), in relation to volcanic hazards. However, it is not possible from these results to determine the direction of causality, i.e. whether higher self-efficacy leads to self-protective behaviour, or self-protective behaviour leads to increased self-efficacy, although as noted by Flynn *et al.* (1995 p. 73), "*...several experiments have indicated that it is the former and not the latter*." Carbonado participants did demonstrated; (i) high levels of perceived preparedness, with over 90% stating they knew what action to take in the event of an eruption, and over 60% of these correctly stating they would evacuate or move to higher ground; (ii) high numbers who had already adopted protective behaviour, with 70% reporting adjustments such as planning an evacuation route (>50%) and storing emergency supplies (>50%); and (iii) a high number of people accessing several information sources about what action to take (70%).

In Sumner, a slightly different picture emerged. Although situated further from the volcano, the town could experience some of the worst effects of an eruption. Due to its location on low-lying land at the confluence of two rivers that head on the volcano, the town is particularly exposed to the risk of lahars and was identified as the most vulnerable of the three communities in the threat assessment. Despite this, hazard salience, although highest amongst the three communities surveyed, was relatively low on the four point scale used here, with residents only 'slightly worried' about the risk of possible future volcanic activity. Participants did report thinking about the threat 'a few times a year', and significantly more often than those from Ellensburg, but were more concerned about the risk of earthquakes than from an eruption of Mount Rainier. Although they displayed similar levels of hazard salience to residents of Carbonado, they rated the likelihood of their town and themselves being seriously affected significantly higher than residents from their neighbouring community. Over 70% thought an eruption 'very likely' to affect their town, whilst almost 60% thought the effects would be 'very serious'. When asked to consider the risk posed by specific hazards, Sumner were significantly more concerned about all hazards, except explosions/lateral blasts, than the other two communities surveyed. Although they were most concerned about the lahar hazard, when compared to the threat assessment rating they significantly underestimated the risk, whilst overestimating the risk for all other hazards.

Sumner participants demonstrated an inclination to depersonalise the danger by rating the seriousness to themselves significantly lower than for their community as a whole. This suggests the existence of optimistic bias, described as an unrealistic optimism regarding an individual's susceptibility to a hazard, whereby they rate their chances of being exposed to a negative event as lower than average (Weinstein, 1980; Sjoberg, 2000), or they rate themselves as being more prepared than the average, whilst recognising the need for preparedness but believing it does not apply to them (Gregg *et al.*, 2003). This might be due to cognitive errors or as a result of defensive mechanisms designed to distort reality so as to reduce anxiety (Weinstein, 1980). Such unrealistic biases may result in individuals being less likely to adopted preparedness measures (Johnston *et al.*, 1999). Findings here do not seem to support this later theory, as adoption of protective measures are similar to those found in Carbonado who did not display optimistic bias.

Results indicate that Sumner residents rated their ability to protect themselves in the event of an eruption far lower than residents from Carbonado; almost 80% of Carbonado residents said they would cope 'quite well' or 'very well', compared to just 40% of Sumner residents. However, both communities have very similar levels of knowledge about appropriate protective behaviour, numbers of people who have adopted preparedness measures, and levels of information accessed. This seems contrary to work by Paton (2003) who noted that lower levels of hazard adjustment have been associated with high levels of fear concerning a threat, coupled with low levels of perceived control over one's exposure to the hazardous effects. The significant difference in self-efficacy between the two communities must therefore be due to some other mechanism. Several authors have noted the importance of domain-specific measures of self-efficacy (i.e. efficacy relating to volcanic hazards) in relation to risk perception (Bandura, 1977; Davis *et al.*, 2005), and its link to the adoption of hazard adjustments (Paton, 2003). It may be speculated here that domain specific self-efficacy is low, but that self-reported hazard adaptation (which is high), may, as was indicated by several participants, not be explicitly adopted for protection against volcanic hazards. Certainly during the fieldwork period, local city council's were conducting a campaign, via radio programmes and posters, to encourage households to assemble an emergency kit. An explicit hazard was not mentioned, rather this was to be carried out in response to an unspecified threat.

Although, this may in part limit our ability to draw conclusions about motivations for the adoption of self-protective behaviour and the role of self-efficacy, several of the preparedness measures outlined here were domain specific (e.g. evacuate and avoid ash). However, although Sumner's risk perception was the highest of the three communities surveyed, they were significantly more concerned about earthquakes, therefore as suggested by PMT, it may be that the specific threshold of threat appraisal necessary to initiate the process of coping appraisal, with regards volcanic activity, had not been reached (Grothmann & Reusswig, 2006). Alternatively, threat appraisal may be sufficiently high but self-efficacy is low and non-protective responses, e.g. wishful thinking and denial, have been adopted thus reducing the negative emotional consequences of perceived risk. An additional supposition could be that the high levels of self-reported preparedness in Sumner may actually reflect knowledge of where information could be obtained rather than actual preparedness, a phenomenon recognised by Paton *et al.* (2008).

Although the city of Ellensburg, situated to the east of the Cascade Mountains could experience some of the effects of an eruption of Mount Rainier, they are situated furthest from the volcano, and were identified as the least threatened community. This is reflected in their survey responses; they spent the least time thinking about the threat, with 60% saying they 'never' thought about it; and they were the least worried, with almost 60% stating they were 'not at all worried' about possible future volcanic activity. As with Carbonado residents, Ellensburg felt more concerned about the threat from wildfires, having suffered a serious fire on land close to the city in the year prior to the survey taking place. Levels of perceived risk were significantly lower than either of the communities to the west of the volcano. Whilst residents felt an eruption would be 'quite likely' to affect their town, approximately half thought the effects would be 'not at all serious' or only 'somewhat serious'. Evidence of optimistic bias, similar to that reported in Sumner was found. Residents correctly identified ash as their most serious threat, but underestimated the risk, when compared to the threat assessment rating.

Perhaps unsurprisingly given its distance from the volcano, and levels of perceived risk, Ellensburg residents were significantly less well prepared than participants from either of the other two communities surveyed. Over 40% didn't know what action to take in the event of an eruption affecting their town, although one third knew to avoid ash, and a similar number had taken precautionary action, particularly the storage of emergency supplies. Adoption of protective behaviour is influenced by outcome expectancy (a facet of self-efficacy), and the perceived benefit of taking action is weighed against the perceived cost. If, as may be the case for Ellensburg residents, the costs out weigh the perceived benefit due to low levels of perceived risk, non-protective responses may be adopted (Grothmann & Reusswig, 2006).

The amount of information accessed was significantly lower amongst Ellensburg residents than for Carbonado and Sumner. Almost 60% said they hadn't seen any information about what action to take in the event of an eruption. However, the provision of information during periods of quiescence has been found to have little impact on perceived risk and increasing levels of preparedness (Johnston *et al.*, 1999; Davis *et al.*, 2005). A possible reason for this is that information is deemed not relevant due to the low levels of perceived risk (Dominey-Howes & Minos-Minopoulos, 2004; Barberi *et al.*, 2008). However, for the sample as a whole, a positive relationship between perceived risk, preparedness and appropriate action was found. It is not possible to say whether exposure to information results in increased risk perception (leading to the adoption of self-protective behaviour) or that higher perceived risk stimulates information seeking. The results presented here favour the former, given that the most frequently mentioned sources of information were the media, either via radio/television programmes or newspapers, suggesting a passive exposure to information rather than explicit information seeking.

For those people in Ellensburg who had accessed information, over 50% felt it had been 'quite useful' or 'very useful', although almost two-thirds thought they hadn't seen enough. Levels of trust in official institutions responsible for communicating information was low, but similar to that reported by the other communities, with scientists rated as the most trustworthy source. A small but significant positive relationship between trust and perceived risk was found for the sample as a whole.

This has implications for risk communication, particularly when decisions are taken about who should deliver the information and via what medium. However, other research has suggested that trust in the sources of information may in fact be of limited importance in acceptance of the message, as over time recall of the actual source is often forgotten (Sjöberg, 2001). The role of communication should be to balance an increased awareness of the threat, with assurances that the effects can be adapted to, termed the *reassurance-arousal paradox* (Otway & Wynne, 1989). This is to ensure that belief in ones own ability to cope (self-efficacy) is not negatively impacted, resulting in non-protective responses such as denial and wishful thinking, rather than a protective responses.

In addition to this exploration by location of the relationships between variables identified as important in the adoption of protective behaviour and therefore vulnerability, a further objectives of this research was to determine the usefulness of a socio-economic approach in assessing vulnerability to volcanic activity in the communities around Mount Rainier. The aim being that if found to be important predictors of key vulnerability indicators, the inclusion of socio-economic data (in the form of census data) as an additional layer within the threat assessment metric would be supported on empirical grounds. To identify whether socio-economic variables were more important in motivating precautionary hazard adjustments and appropriate behaviour in the event of an eruption compared to psychological characteristics, the researcher conducted a series of regression analyses to compare a socio-psychological model (including measures of people's perceptions of risk, self-efficacy, information seeking etc) with a socio-economic model (gender, age, income, education, children in the household and property ownership). Many of the findings have previously been discussed in the preceding results section, but to summarise here; perceptual factors were found to be a significantly better predictor of the adoption of protective hazard adjustment measurers than socio-demographic factors. The socio-demographic factors explained just 7% of the variance in preparedness. This was significantly improved by the addition of location (explaining an additional 13% of variance), but inclusion of the psychological variables almost double the variance explained (from 20% to 39%). That perceptual processes are significant predictors of preparedness is consistent with theories of planned behaviour (Ajzen, 1985) and PMT (Mulilis & Lippa, 1990; Lindell & Perry, 2000; Grothmann & Reusswig, 2006).

A final regression analysis indicated that the most important predictor of appropriate action was preparedness, which in turn was predicted by information accessed, self-efficacy and perceived risk. Location and property ownership were the only two socio-demographic variables found to be significant predictors of appropriate response. Here home-owners were found to be less likely to adopt the appropriate protective behaviour, despite being more prepared than tenants, and it was suggested that this may be due to the perceived benefits (avoiding a hazard that has been perceived as low risk) outweighing the perceived costs (of leaving their home). Residents of Sumner were less likely to adopt the appropriate response, even when controlling for differences in perceived risk and self-efficacy, and a possible explanation for this are the higher costs associated with evacuation (an appropriate response in Sumner) compared to avoiding ashfall (an appropriate response in Ellensburg). This suggests that hazard managers should continue to direct specific attention towards education and communication programmes within the most vulnerable community. Particularly as access to information and preparedness were found to be key factors in predicting appropriate action, and therefore provide the greatest scope for influencing self-protective behaviour.

Several relationships between socio-economic factors and psychological variables support findings from previous research, particularly the negative correlation between gender and risk perception. A similar link with gender was found by Flynn *et al.* (1994) and Slovic *et al.* (2000). However, when controlling for other perceptual factors e.g. self-efficacy, gender was not found to be a significant predictor of risk perception, preparedness or appropriate response. That readily available socio-economic variables were found to be poor predictors of risk perception, preparedness and the adoption of appropriate behaviour, is disappointing. These results do not support theories of vulnerability from the field of hazard research (e.g. Varley, 1991; Aysan, 1993; Blaikie *et al.*, 1994; Buckle *et al.*, 2000; Cutter *et al.*, 2000; e.g. Cutter *et al.*, 2003; Bolin, 2006) but are unsurprising when considering the psychological research into factors that motivate protective behaviour (Ajzen, 1985; Wurtele & Maddux, 1987; Mulilis & Lippa, 1990; Lindell & Perry, 2000; Rimal & Real, 2003; Grothmann & Reusswig, 2006; Martin *et al.*, 2007; McIvor & Paton, 2007). This has serious implications with regards the overall aim of this study: the integration of readily available socio-economic data into the threat assessment, in order to provide a measure of *within* community vulnerability. These results found no useful socio-economic predictors of protective behaviour, rather the psychological factors were found to be more important in determining protective response, and by implication reducing individual vulnerability.

Although the results of this empirical study do not support the integration of socio-economic data within the threat assessment, they have clearly demonstrated that psychological characteristics are more fundamental in shaping individual vulnerability. Without extensive surveying of at-risk communities, prohibitively expensive and time-consuming, such psychological factors cannot be integrated within a threat assessment. However, they can provide useful insights into how communication and education strategies might be structured to manipulated these constructs in order to reduce vulnerability. The results also provide support for PMT, only previously applied to a limited number of studies relating to natural hazards (e.g. earthquake preparedness in the USA (Mulilis & Lippa, 1990; Lindell & Perry, 2000), flood preparedness in Germany (Grothmann & Reusswig, 2006) and the case of wildfires in the western United States (Martin *et al.*, 2007)) as a useful model for explaining volcanic risk preparedness.

CHAPTER 6: SUMMARY & CONCLUSIONS

This chapter concludes the thesis by firstly providing a summary of the work conducted, focusing on an evaluation of the methodological procedures used, the research findings and the contributions of the two phases of the research; (i) the threat assessment, and (ii) the vulnerability assessment. This is followed by a discussion of the relationship between the work done and the original research questions, and the previous work discussed in the literature review. A summary of the key findings is discussed in relation to their contribution to the case study countries, and the wider field of risk research, as well as their implications for policy and practise. Finally, limitations with the methodological approach are considered, along with recommendations for future work.

6.1. SUMMARY OF THE RESEARCH

The economic, social and cultural traditions that shape communities form a central theme for understanding the complexities involved in assessing risk, but are frequently ignored or marginalised within physical science disciplines. This wider social context should form a fundamental component of risk research, particularly where populations are at risk from natural hazards, e.g. in settlements located within the hazard zones of potentially active volcanoes. In an attempt to address this issue, the research presented here sought to develop an interdisciplinary approach to volcanic risk assessments, which considered the geophysical hazards, as well as the physical and social vulnerability of at-risk communities. Combining theory and practice from the natural and social sciences, as well as psychology and social geography, quantitative and qualitative methods were employed to assess both risk and human vulnerability to volcanic activity at two case study volcanoes; Volcán Tungurahua, Ecuador and Mount Rainier, USA. Utilising a comparative cases methodology, the research explored the physical characteristics, as well as the different social, cultural and demographic features that shape vulnerability in a number of communities at varying levels of risk from volcanic activity.

The first phase of the research sought to develop a simplistic approach to volcanic risk assessments, utilising readily available information in order to quantify and rank the relative threat to each community surveyed. During the development of this methodological process, the term *risk* assessment was substituted with *threat* assessment, as the approach depicted a more *qualitative* measure of the risk posed by the volcanoes studied, compared to traditional quantitative risk assessment methodologies. The second phase of the research sought to explore the social vulnerability and resilience within the case study communities, by investigating the beliefs, attitudes and perceptions that people have according to social, cultural and economic differences. Specifically, questionnaire surveys were conducted to identify key socio-economic characteristics associated with differences in the adoption of precautionary behaviour. The objective being that the identified characteristics could be integrated as an additional layer into the threat assessment metric, using census data, to provide a measure of social vulnerability.

The interdisciplinary nature of this research necessitated the use of terminology, techniques and methodologies employed within disciplines outside the natural sciences, specifically those used in social science research and psychology. Some of the language used and techniques employed, as well as the assumptions underlying them, may be unfamiliar to physical risk researchers, and do not adhere to the same principles which govern more quantitative disciplines, but are considered standard within social science research. Differences in the language used, and in the methodological approaches employed, were recognised as key barriers to the development of a more holistic, multi-disciplinary approach to risk understanding. Attempting to bridge these epistemological differences, the methodologies utilised in this research and the findings from each research phase are discussed in detail below.

6.1.1. Threat Assessment

The first phase of the research project focused on the geophysical exposure and physical vulnerability of communities at risk from volcanic activity at the two case study volcanoes. Based on work conducted by the USGS, which focused on assessing the relative threat from the 169 volcanoes of the United States (Ewert *et al.*, 2005; Ewert, 2007), a semi-quantitative, ranking methodology was devised. This threat assessment metric was applied separately to each community surveyed and consisted of two sections; (i) provided a measure of the physical hazards associated with volcanism, termed *hazard factors*, and (ii) considered the physical vulnerability of the community, termed *exposure factors*. The latter section included an assessment of population size, aviation exposure, power and transport infrastructure, as well as significant economic developments. Field observations, interviews with local emergency managers and desk-based studies provided the information required to quantify these exposure factors. Development and completion of the hazard factors element utilised a systematic review of the geophysical hazards associated with volcanism at each case study volcano. This exploited previously published material including journal articles, emergency management reports, conference proceedings, hazard maps and the applicable volcano reference file from the Smithsonian's GVP database. Information concerning historical activity, eruptive behaviour and hazards were compiled into a comprehensive review, which provided the data necessary to assess each hazard type associated with volcanism at Tungurahua and Mount Rainier, as well as its threat to each community surveyed. This information also provided the necessary documentation to support the reasoning behind, and justification for, each score given, as recommended for more qualitative assessments. The hazard and exposure factor scores were combined to provided an overall threat assessment score, allowing the communities to be ranked from least to most threatened.

The original threat assessment tool developed by Ewert *et al.* (2005), placed the volcano at the centre of the assessment and considered all the communities potential at risk located within the volcanic hazard zones. In this way an overall threat assessment for a volcano was compiled, and could be compared relative to all other US volcanoes. In contrast, the threat assessment metric developed here considered each community around a volcano as the unit of measure. The assessment, compiled for each volcano, was completed for each community surveyed, which were then compared and ranked relative to one another. The five exposure factors used in this research were selected from the ten factors included in Ewert's original assessment tool. The selected factors were those most applicable to a specific community, rather than relating to all communities within the hazard zones around a volcano. Factors excluded included; the $\log_{10}$ of the population downstream of the volcano, and whether the volcano formed a significant portion of an island. Two factors on Ewert's tool related to local and regional aviation exposure, and this was collapsed into a single factor measuring aviation exposure within 10km of the surveyed community.

Two further factors on the Ewert scale related to historical fatalities and historical evacuations. Determining accurate figures for these variables for a volcano as a whole is difficult due to a lack of, or inaccuracies within, the historical documentation (Newhall & Hoblitt, 2002; Witham, 2005). Uncovering such information for a specific town or city at risk from the case study volcanoes was considered even more problematic. There has been no significant volcanic activity at Mount Rainier since the Pacific Northwest was colonised by white settlers (Crandell, 1971; Mullineaux, 1974; Sisson, 1995; Vallance & Donoghue, 2000; Sisson & Vallance, 2009), and only uncorroborated eyewitness accounts exist for a possible small phreatic eruption in 1894 (Driedger *et al.*, 2005; Sisson & Vallance, 2009). Similarly, written accounts relating specifically to historical fatalities and evacuations in the communities around Tungurahua are scarce, and those that do exist do not specify a given town (Hall *et al.*, 1999; Le Pennec *et al.*, 2004; Le Pennec *et al.*, 2006b; Le Pennec *et al.*, 2008). Records for recent events are more numerous (BBC News Online, 2000; Tobin & Whiteford, 2002b; 2002a; Lane *et al.*, 2003; Toulkeridis, 2007). One of the aims of this research was to develop an assessment methodology that could be applied equally well to different volcanoes. Therefore, due to this lack of sufficiently robust historical data, particularly in relation to Mount Rainier, it was decided to excluded the two items relating to historic fatalities and evacuations from the threat assessment metric. However, if this assessment tool were applied to a volcano where this information was available for the surrounding communities, its inclusion in the metric may be recommended to provide a further measure of physical vulnerability.

Although this research aimed to develop an assessment tool applicable to any volcano, differences in the geophysical hazards associated with volcanism at each volcano, specifically hazard types, geological features and past activity, required the assessment metric to be adapted to reflect the specific volcanic features at each volcano. However, the assessment tool was design such that the maximum hazard factors score for each volcano were equal, and by retaining the same exposure factors, comparisons between the results of the two metrics can be drawn. Although this was not an explicit aim of the study, and would not be recommended for 'real-world' assessments, it was carried out here to assess the validity and reliability of the assessment tool. In particular, the results for the city of Ellensburg in the USA were compared to those for Riobamba in Ecuador, as they achieved the same score for hazard factors, and Baños (Ecuador), as they achieved similar scores for the exposure factors (Table 6.1).

Table 6.1 Comparison of the threat assessment scores for Ellensburg, Baños and Riobamba to assess the validity and reliability of the assessment metric.

	Hazard Factors	Exposure Factors	Overall threat score
Ellensburg	2	6.19	12.38
Riobamba	2	8.10	16.20
Baños	9	6.02	54.18

The cities of Ellensburg and Riobamba are both only at significant risk from a single volcanic hazard (ashfall), and both scored 2 on the hazard factors element, despite their construction using different scales created specifically for each volcano. In contrast Ellensburg and Baños scored similarly on the exposure elements (which were the same), and qualitatively it can be speculated that if Ellensburg where located just 8km from Mount Rainier (or even at the current location of Carbonado), we could expect similar overall threat assessment scores, as for Baños. Although the internal validity and reliability of the assessment tool has only been evaluated subjectively, the results suggest consistency of scale across the two volcanoes assessed here. This evaluation also indicates the relative importance of the geophysical hazards and the physical vulnerability of the community being assessed, and suggests that both aspects are of equal importance when assessing volcanic risk.

The decision to conduct a semi-quantitative assessment of volcanic threat, rather than a traditional risk analysis was based on methodological and epistemological considerations. One objective of this study was to develop a methodology that could be applied equally well at less comprehensively studied volcanoes, where sufficient data to conduct a traditional quantitative risk assessment may be lacking. Although the two case study volcanoes considered here have relatively comprehensive resources regarding past activity, geophysical hazards and geological features, it is felt that the developed assessment metric could be applied equally successfully at less well studied volcanoes. By placing the emphasis on individual settlements, and ranking their relative threat rather than the overall risk posed by a volcano, the burden of geophysical evidence is less important, particularly when compared to that required to conduct a traditional risk assessment. Additionally, no claims about the objectivity of the results are made. The nature of volcanic activity, often with recurrence intervals of tens to hundreds of thousands of years, increases the level of uncertainty, and the need for subjective estimates when conducting quantitative risk estimates. As well as insufficient length in the geological record (Crandell *et al.*, 1984), the lack of recognisable deposits for smaller more frequent activity (Crandell *et al.*, 1984; Cronin *et al.*, 1997; Magill & Blong, 2005b), changes in behavioural patterns over time (Crandell *et al.*, 1984; Magill & Blong, 2005b), decreases in edifice stability, which may lead to flank collapse (Crandell *et al.*, 1984), and topographic changes leading to different areas of the volcano being affected by different volcanic phenomena than during past eruptions (*ibid*), our understanding of the complexities of most volcanic systems are simply too rudimentary to make claims regarding the reliability and validity of any quantitative risk evaluation (Crandell *et al.*, 1984; Connor *et al.*, 2001; Newhall & Hoblitt, 2002; Sparks & Aspinall, 2004). Although the designed assessment metric may be applied to less well studied volcanoes, any overall threat score obtained would likely represent minimum values for at-risk settlements. However, as further fieldwork, monitoring and research is conducted, the related threat assessment can be updated to take account of new information. It should be noted that the developed metric may be less applicable where the source or vent of the volcanic product is not known, such as for volcanic fields (e.g. Campi Flegrei, Italy; Auckland Field, New Zealand; Michoacán-Guanajuato, Mexico).

Another benefit of utilising a semi-quantitative methodology such as the one developed here, is the possibility of incorporating the participation of non-expert stakeholders within the assessment process. Additionally, by avoiding the complex numerical calculations, or computer modelling required in quantitative risk evaluations, this method provides a conceptualisation of risk that may be simpler to grasp amongst lay members of the public, as well as non-specialist hazard and emergency managers. One of the over-riding objectives of this aspect of the study was to produce an assessment technique that would allow frequently limited mitigation resources to be directed towards the most threatened communities, in terms of both their physical exposure to the hazard(s) and their physical vulnerability. By ranking at-risk communities according to their threat score, hazard and emergency managers can priorities mitigation resources, and target the most vulnerable communities. At the two volcanoes considered here, Baños was identified as the most threatened by volcanic activity from Tungurahua, when compared to Riobamba, whilst Sumner, was identified as the most threatened by Mount Rainier, followed by Carbonado, with Ellensburg the least threaten. Another explicit aim of this research was to identify groups *within* these communities who may be most vulnerable, not only as a function of their physical exposure to the hazards, but as a result of their social, cultural and economic characteristics; i.e. their social vulnerability, and this was tackled during the second phase of the research.

6.1.2. Vulnerability Assessment

The second phase of this study utilised two questionnaire surveys to explore social vulnerability. Specifically, the beliefs and attitudes people have towards volcanic risk, as well as measuring elements of their socio-economic status. The aim was to discover which of these factors were most important in shaping an individuals social vulnerability, and use these results to add a supplementary component to the threat assessment metric to measure *vulnerability factors*. Some limited empirical studies suggest that individuals with certain socio-economic characteristics incur greater losses during a disaster (Buckle *et al.*, 2000; Chou *et al.*, 2004; Cutter & Finch, 2008). In contrast, the theoretical underpinnings of this research suggest that how an individual responds or behaves during a hazardous event may be influenced by perceptions of risk, levels of trust, information seeking and preparedness, as well as previous experience, thereby increasing or decreasing vulnerability (Rogers, 1983; Lindell & Perry, 2000; Grothmann & Reusswig, 2006). By exploring these psychological qualities and how they differ between individuals who exhibit different socio-economic characteristics, the relationships between these factors and vulnerability was explored.

An initial pilot study was conducted in Baños, Ecuador, which provided the basis for a significantly more comprehensive exploration of social vulnerability carried out in the USA. The survey conducted in Ecuador provided some evidence for the importance of different social, cultural and behavioural factors in determining vulnerability, and highlighted additional areas for research. The approach was modified accordingly for the survey conducted in the USA, and considered a more comprehensive spread of variables, specifically these were; risk perception, self-efficacy, trust, access to information, and preparedness, as well as socio-economic variables such as; age, gender, income, education, property ownership and sense of community. This latter study employed methods and techniques used in psychological research, supporting the interdisciplinary nature of this study. In particular, PMT provided the theoretical basis for investigating the importance of socio-economic features and psychological characteristics in promoting protective behaviour, and in turn their role in determining vulnerability. For the participants surveyed, the results appear to indicate that socio-economic status plays a very minor role in whether an individual is likely to respond to a volcanic eruption with self-protective behaviour. Rather, it was found that psychological characteristics, particularly risk perception, self-efficacy, information seeking and levels of preparedness contributed far more significantly in determining whether someone was likely to adopt an appropriate response to the threat of volcanic activity. Although these findings prohibited the integration of the two research phases, they have some important implications for social vulnerability research, and provide valuable insight into self-protective behaviour, which may be useful in informing risk communication and education strategies in those communities most at risk.

6.1.2.1. Summary of Results - Ecuador

Comprising a total of 56 items, the questionnaire tool was designed to record specific demographic and socio-economic characteristics, and to measure attitudes and beliefs regarding volcanic risk at Tungurahua. The aim was to explore the relationships between socio-economic status and various facets of risk perception, as well as the current knowledge environment amongst participants. The planning and design phase was informed by past empirical research (Lindell & Whitney, 2000; Becker *et al.*, 2001; Paton *et al.*, 2001b; Tobin & Whiteford, 2001; Whiteford *et al.*, 2002) and theoretical work relating to risk perception and hazard preparedness (Paton, 2003). Practical issues prohibited the use of a pilot study, whilst a purposive, convenience sampling methodology was employed to select the 47 participants, the majority of whom were interviewed face-to-face over approximately 30 minutes. Some surprising results were obtained with regards risk perception, with the majority of respondents reporting low levels. This was despite continuing volcanic unrest, frequent ashfall in the town, and that 45 of those surveyed had been evacuated in 1999. It was speculated that these results may demonstrate the existence of 'normalisation bias' (Johnston *et al.*, 1999; Gregg *et al.*, 2003), whereby the community has been exposed to relatively non-damaging effects, fostering the belief that future activity will be similarly benign. The low levels of reported risk perception may also be explained by respondents beliefs and attitudes regarding the behaviour of the volcano.

Regarding the behaviour of the volcano, the majority of those questioned thought the volcano erupted on average once every one hundred years, whilst almost four-fifths thought it would not erupt again for 'years'. This was despite almost all participants being resident in the town during the previous eruption in 1993, and being exposed almost daily to the effects of the current period of on-going activity. Several explanations for this result were considered. Firstly, how an individual defines an 'eruption' will impact how they respond to this question. The almost continuous light dusting of volcanic ash fall experienced in the town may not be considered evidence of an eruption. Secondly, the summit of Tungurahua, and the visual spectacle of ash plumes and incandescent ejecta, are obscured from the town by topographic features and frequent cloud cover. Thirdly, perceptual biases may have resulted in non-protective responses being adopted, such as denial of the threat or wishful thinking regarding the ongoing activity, as suggested by PMT (Rogers, 1975; Grothmann & Reusswig, 2006). Comparisons of preparedness with levels of risk perception indicate that this may not be the case, but in order to explore this further, more explicit questions relating to protective behaviour were required, and were subsequently included in the US questionnaire to address this issue.

Risk perception was found to correlate significantly with willingness to evacuate. Knowledge of self-protective behaviour, specifically regarding evacuation and safe routes, was very high, most likely as a consequence of the high levels of information accessed, as well as past experience. A comprehensive communication strategy has been developed by the DCB and OVT scientists from the IGEPN. This comprises reports regarding current activity read during the daily radio news broadcasts, and weekly bulletins summarising activity, presented on radio by OVT staff. This constant link between the community and scientists involved in monitoring, as well as the involvement of members of the community in reporting local lahar activity, in conjunction with the DCB, has helped foster a positive relationship between all stakeholders. This is demonstrated in the results of the survey, which suggest high levels of trust in these officials, despite years of political and economic unrest, and institutional corruption within Ecuador.

For hazard managers in Baños, this study provides positive encouragement regarding the high levels of preparedness amongst residents within the town to deal with the consequences of future volcanic unrest. However, no conclusions can be draw as to whether individual hazard-knowledge is high due to past experience, or as a direct result of the education and communication strategies undertaken by the authorities in consultation with scientists. It might be speculated that a combination of these factors is responsible for the high levels of knowledge, given that over six years had elapsed between the last evacuation and the date of the survey, and the frequency and extent of the communication program. Since the survey, Baños has been evacuated again, whilst several of the smaller hamlets at risk from pyroclastic flows have been evacuated several times. The author could find no negative reports regarding these evacuations, unlike those for the initial evacuation in 1999 (Larrea *et al.*, 1999; BBC News Online, 2000; Tobin & Whiteford, 2002b; Lane *et al.*, 2003), and despite several periods of intense activity, the death toll and economic impact remain limited.

Although both the local community and the hazard managers are at an advantage, compared to other areas at risk from volcanic eruptions, as a result of the long period of time they have had to hone their emergency strategies, this research suggests that the combination of frequent information bulletins regarding volcanic activity, and the involvement of the local community in hazard preparedness (in particular the recruitment of civilians in the lahar observation network), has had a positive impact on the community's overall preparedness. Such a response may only be applicable in other areas subject to ongoing volcanic activity but the work carried out by the OVT, IGEPN and DCB provides a useful template for such localised hazard management.

Overall few correlations were found between socio-economic characteristics and the psychological and behavioural factors which theory suggests amplify or attenuate vulnerability. However, the relationships that were observed provide some interesting insight into these factors. Firstly, income was significantly correlated with voluntary evacuation during the 1999 emergency, indicating that as income increased, individuals were more likely to have evacuated voluntarily. For the survey sample, low income was associated with agricultural employment, or farm ownership. The economic wellbeing of these people and their families are closely tide to the land. Leaving their farms would adversely impact their current income, and their ability to maintain that income in the future. In contrast, those with higher incomes would be better able to absorb any negative economic consequences associated with leaving home, and would therefore be more likely to respond positively to an evacuation order. Secondly, the strength of an individual's social network was negatively correlated with whether the 1999 evacuation was thought necessary at the time, i.e. those with greater social ties were less likely to think the evacuation necessary. This supports previous research into strength of community bonds, which found PSOC was negatively correlated with heeding evacuation advice in relation to hurricane warnings (Riad & Norris, 1998). Thirdly, respondents living in larger households were less worried about the volcano, but conversely felt the volcano was a greater risk to themselves and their families, compared to smaller households.

Given the very small sample size, conclusions regarding the importance of these findings have to been drawn with caution. Nevertheless, the lack of consistent significant relationships between socio-economic factors and psychological variables, may suggest that some of the theoretical assumptions which underlie discourse on vulnerability (Degg, 1992; Murck *et al.*, 1997; Corotis & Enarson, 2004; Wisner *et al.*, 2004), and cited by empirical studies (e.g. Cutter *et al.*, 2000; King & MacGregor, 2000; Cutter *et al.*, 2003), are not supported by these findings. Most interestingly, the findings relating to past experience and income suggest that those on lower incomes may not adopt protective responses to volcanic risk, not because they are unaware of what they should do, but because by taking appropriate action, e.g. evacuating, they will adversely impact their current and future livelihoods. Conversely, those on higher incomes are better equipped to absorb any adverse consequences, e.g. they have greater resilience. Therefore, although income does not affect an individuals risk perception, or preparedness, and therefore their vulnerability, it does directly affect a persons ability to cope with an adverse event. This suggests that whilst psychological constructs may directly affect pre-event behaviour, and in turn vulnerability, socio-economic factors may more accurately be seen to determine post-event vulnerability; or more specifically *resilience*.

6.1.2.2. Summary Results - USA

A modified survey instrument, comprising 39 items, was used to explore issues of vulnerability within three communities, at varying levels of risk from volcanic activity at Mount Rainier. This semi-structured questionnaire was devised to elicit an individual's beliefs and attitudes towards volcanic risk and to explore the relationships between socio-economic status and key psychological characteristics. Adapted from the original survey tool used in the initial Ecuador study, measures of several additional psychological variables were incorporated, as well as more explicit questions relating to protective behaviour. The inclusion of these additional elements was guided largely by PMT, and in particularly the work of Grothmann & Reusswig (2006). In retrospect there remained several shortcomings with the survey instrument utilised in this study (which are discussed later). However, significant improvements were made following the lessons learnt in Ecuador, not only with the structure and wording of the questionnaire and the inclusion of additional elements, but also in the distribution method. By not relying on surveys completed during face-to-face interviews, the sample size obtained was significantly larger for the US study. This was partially the result of the appreciably easier working environment, the lack of a language barrier and the use of community centre drop-boxes, as well as the distribution of the questionnaire to several local employers within the three communities surveyed (schools, a university and civic offices).

A total of 242 surveys were completed, two-thirds during face-to-face interviews, which took approximately 30 minutes, utilising a selective (only residents of Carbonado, Sumner or Ellensburg), purposive, convenience sampling methodology. The relatively large sample size allowed more complex statistical analysis to be applied to the data, and this followed a three step process. Firstly, the results of questions relating specifically to seven key psychological indicators were explored by location. As expected, significant differences in the beliefs and attitudes measured by these indicators were found for residents from each of the three communities. The key indicators identified by the literature as important in the formulation of individual vulnerability and considered during this study were; (i) risk perception, (ii) self-efficacy, (iii) trust, (iv) access to information, and (v) preparedness, as well as two novel issues; (vi) understanding of risk, and (vii) appropriate action. Following on from this, and utilising a single collapsed scale for each of the seven indicators, differences in socio-economic characteristics were considered. As inferred from the Ecuador case study, no consistent significant relationships were found between the psychological constructs and socio-economic factors. In the final stage of the analysis, regression analysis was used to discover which factors were responsible for differences in the vulnerability indicators. This series of analytical stages incorporated a reductionist strategy, and aimed to successively reduce the complexity of the analysis of such a large dataset. The statistical processes and methods employed here, followed recommended best practice for psychological research, and that utilised in other similar studies (Weinstein *et al.*, 1998; Gregg *et al.*, 2003; Grothmann & Reusswig, 2006; Martin *et al.*, 2007).

Unsurprisingly given their relative difference in exposure to volcanic phenomenon, the three communities differed significantly, on almost all psychological variables, and a contextual illustration of the differences between the communities has previously been discussed. Generally, these differences would appear to be the result of the communities relative proximity to the volcano and their possible exposure to varying levels of threat from different volcanic phenomena. In addition, differences in optimistic bias and PSOC were uncovered, and it is thought these may have been important in shaping the varying levels of self-efficacy found between the three communities. Levels of preparedness and information accessed were also impacted by outcome expectancy, with Ellensburg significantly less well prepared than either of the other two communities. Outcome expectancy is a facet of self-efficacy, and is where the perceived costs of taking precautionary action are weighed against the perceived benefits (Grothmann & Reusswig, 2006). If levels of perceived risk are low, the cost will outweigh any perceived benefit, resulting in the adoption of non-protective behaviour (e.g. wishful thinking, denial of the threat or fatalism).

Although some relationships between specific socio-economic characteristics were observed, these were not consistent across variables and no clear pattern emerged. Gender differences were found for self-efficacy, information accessed and trust, with men exhibiting significantly higher levels of self-efficacy and information seeking, but lower levels of trust in officials than women. Differences in self-efficacy, trust and preparedness were also found for property ownership, with homeowners displaying significantly higher self-efficacy and preparedness, but lower levels of trust.

Differences in risk perception were restricted to age, elderly in the home and household size, all negatively correlated with perception, except household size, which exhibited a positive relationship. As well as gender and property ownership, self-efficacy was positively correlated with children in the home. Both age and level of education were positively correlated with risk understanding. As well as higher levels of self-efficacy, households with children were significantly more prepared and more likely to respond appropriately. Whilst those with elderly in the home displayed lower risk perception, lower levels of trust, were less prepared and less likely to take appropriate action. Household size correlated positively with all psychological variables, except self-efficacy and risk understanding which did not differ significantly. Perhaps surprisingly, income did not correlate significantly with any of the vulnerability indicators. Previous research has found levels of poverty and lower income to be associated with increased risk to natural hazards (Chou *et al.*, 2004; Kahn, 2005; Cutter & Finch, 2008; Zahran *et al.*, 2008). However, these studies considered vulnerability at a global, country or regional scale and not at the individual level.

In the final stage of the analysis, a series of regression analyses were conducted to determine which variables where predictors of risk perception, risk understanding, preparedness and appropriate action. Here appropriate action (measured by the number of correctly identified mitigation responses mentioned by a respondent) was used as a proxy measure for vulnerability; if a respondent knows what action to take in the event of a volcanic eruption (appropriate for their given location), they may be less vulnerable to negative impacts. Location and property ownership were the only socio-economic variables found to be significant predictors of appropriate response. Although homeowners were more prepared than tenants, they were less likely to adopt the appropriate protective behaviour, despite being more prepared. Again, outcome expectancy may be responsible for this result, i.e. the perceived benefits (avoiding a hazard that has been perceived as low risk) were outweighed by the perceived costs (of leaving their home). Residents of Sumner were less likely to adopted the appropriate response, even when controlling for differences in perceived risk and self-efficacy, and a possible explanation for this are the higher costs associated with evacuation (an appropriate response in Sumner) compared to avoiding ashfall (an appropriate response in Ellensburg). The effects of both location and property ownership only became significant when both information accessed and preparedness were included in the model. This indicates a possible moderator effect (Baron & Kenny, 1986), whereby the protective responses (information accessed and preparedness) alter the strength of the relationship of both ownership and location to appropriate action.

Overall, the psychological variables were significantly better predictors of the adoption of protective hazard adjustment then socio-demographic factors. The most important perceptual factors were risk perception and self-efficacy, whilst information accessed and preparedness were the most important protective behaviours. These findings are consistent with theories of planned behaviour (Ajzen, 1985) and PMT (Mulilis & Lippa, 1990; Lindell & Perry, 2000; Grothmann & Reusswig, 2006). The lack of significant socio-economic predictors, prohibited the integration of census data into the threat assessment metric on empirical grounds. However, these results help elucidate why individuals may behaves as they do in the face of volcanic threat, specifically in the communities around Mount Rainier and Ecuador.

6.2 INTEGRATION OF HAZARD AND SOCIAL VULNERABILITY

Although one of the main aims of this research was to develop a methodology for integrating socio-economic indicators of vulnerability into an assessment of volcanic risk, the findings of the vulnerability survey failed to provide evidence of any clear relationships between the psychological constructs, which are thought to be important in promoting protective behaviour, and in turn in reducing vulnerability (Johnston *et al.*, 1999; Lindell & Perry, 2000; Davis *et al.*, 2006; Grothmann & Reusswig, 2006). Although some correlations between the psychological variables and socio-economic status were found, no single defining relationship was uncovered. As suggested by

PMT pre-eruptive mitigation plans are adopted as a result of perceptual processes and not because of a persons gender, age, or income. Figure 6.1 is an attempt to visualise the relationships between the variables included in the psychological model of vulnerability developed in the latter stages of the US vulnerability assessment.

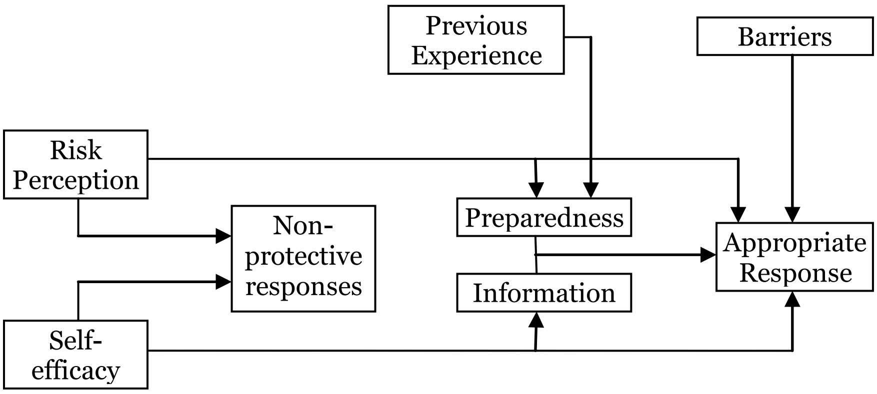


Figure 6.1 Diagram indicating the relationships between various factors which influence protective behaviour in response to volcanic activity.

For simplicity, location and homeownership (the only socio-economic variables found to be significant, but minor, predictors of vulnerability) have been excluded from the schematic. Varying levels of risk perception and self-efficacy can lead to the adoption of either non-protective or protective responses (in the form of preparedness and/or information seeking). If risk perception is too high and self efficacy too low, non-protective responses such as denial of the threat, wishful thinking or fatalism, will be adopted. Risk perception must be balanced in order for a protective response to be adopted, i.e. if an individual's risk perception is low, no benefit will be perceived from taking precautionary action. If risk perception is sufficient, and self-efficacy high, protective responses, such as information seeking and preparedness will be stimulated, and in the event of an eruption, appropriate action will be taken. As indicated by the results from the US and Ecuador surveys, previous experience was found to be important. Although an explicit measure of this was not included in the US survey, as there has been no significant activity at Mount Rainier in living memory, respondents from Ellensburg spontaneously mentioned past experience of the 1980 Mt St Helens eruption, and felt this had provided them with the necessary knowledge to protect themselves in the event of a future eruption at Mount Rainier. Past experience of evacuation was also thought to play a significant role in the high levels of preparedness reported in the Baños sample.

PMT suggests possible barriers to the adoption of protective behaviour (Baron & Kenny, 1986), and from the results of the Ecuador survey, income was found to be negatively associated with evacuation. Although, those on lower income still evacuated (by force), the negative impact on their livelihoods was seen as a disincentive to taking action. From the findings of this study and the empirical evidence from previous research discussed in the literature (Buckle *et al.*, 2000; Cutter *et al.*, 2000; King & MacGregor, 2000; Waite, 2000; Ngo, 2001; Mustafa, 2003; Chou *et al.*, 2004; Kahn, 2005; Bosher *et al.*, 2007; Toya & Skidmore, 2007; Cutter & Finch, 2008; Zahran *et al.*, 2008), it may be that socio-economic factors are important determinants of resilience post-event, rather than in shaping pre-event vulnerability. As indicated by Wisner *et al.* (2004), the most vulnerable groups in society are those who find it most difficult to reconstruct their lives *following* a disaster.

Much of the empirical support for socio-economic determinants of vulnerability is based on the level of negative outcomes experiences by specific social groups, e.g. women, those on lower incomes, or the elderly, following a disaster. Although emergency managers could focus their efforts on these specific social strata's, identifying these people within an at-risk community is problematic and would require a combination of census data and mapping. However, once identified, how can mitigation measures be targeted to address these individual's or group's increased vulnerability? As the results of the US survey demonstrate, being on a lower income, or a woman does not make you less likely to adopt precautionary behaviour, but your relative level of risk perception and self-efficacy does. This suggests a more appropriate goal for risk managers would be to tailor education programmes and communication strategies, which address levels of risk, and provide information regarding what action individuals can take, in order to foster constructive attitudes towards risk, and to engender positive feelings about a persons own ability to protect themselves.

More specifically, the empirical contributions of this work are what it reveals about vulnerability, and the relative threat from volcanic activity in the five case study communities surveyed. Of the communities studied, those most threatened by volcanic activity were identified using the developed threat assessment methodology. In addition, those factors most important in shaping an individual's response to a possible eruption at Mount Rainier and Tungurahua were uncovered. This work builds upon the limited previous work focusing on the social vulnerability of communities around these two volcanoes. At Tungurahua, previous survey work has looked at the health consequences of volcanic ashfall and evacuation (Tobin & Whiteford, 2002a; 2002b; Whiteford *et al.*, 2002), and the vulnerability of women following their evacuation during the 1999 eruption (Tobin & Whiteford, 2001). Previous surveys focusing specifically on differences in risk perception have been conducted amongst school children in the town of Orting near Mount Rainier (Davis *et al.*, 2006; Johnston *et al.*, 2006), and since the work outline in this research was conducted, Wood & Soulard (2009) have considered aspects of a populations physical vulnerability to the lahar hazard at Mount Rainier, specifically in terms of population type (resident, employee or tourist), and the exposure of sensitive care-facilities (such as schools, hospitals, elderly care-homes).

6.3. KEY FINDINGS OF THE RESEARCH

Explicitly, the key findings of the research described in this thesis in relation to the case study volcanoes, the communities surveyed and some of the inferences that can be drawn in relation to the wider research field, are:

- A simplistic volcanic threat assessment methodology has been developed that considers both geophysical hazards and physical vulnerability.

- The developed assessment metric adds to current research by further demonstrating the importance of considering both the geophysical hazards associated with volcanism and the physical vulnerability of at-risk communities.

- For any volcano, but particularly those with limited research regarding past activity, the designed assessment metric would represent minimum threat values. But new data may be incorporated as it becomes available.

- The threat assessment scores obtained here provide a conceptualisation of risk that may be simpler for non-specialists to understand.

- Of the communities surveyed, Baños was identified as the community most at risk from Volcán Tungurahua, and Sumner the most threatened by Mount Rainier.

- The experiences and methods employed by hazard managers in Baños, in particular their communication strategy and recruitment of members of the community into a lahar monitoring network, provide a positive template for mitigation strategies in other communities threatened by ongoing volcanic activity.

- Results from the Ecuador vulnerability survey indicate the importance of income in people's willingness to evacuate. They tentatively point to a distinction between pre-event vulnerability and post-event resilience, further supported by the results of the US survey.

- Risk perception and self-efficacy, as well as information accessed and preparedness were all found to be significant predictors of whether an individual had knowledge of the appropriate action to take in the event of an eruption, findings consistent with theories of planned behaviour and PMT.

- The vulnerability assessment indicated that socio-economic factors were not important in determining levels of preparedness or knowledge of appropriate response to possible future volcanic activity, and these findings prohibited the integration of the two research phases.

- Despite this inability to combine the two assessments on empirical grounds, important contextual knowledge was gained about what motivates an individual to respond to volcanic risk. This provides useful insight for mitigation specialists in the design and implementation of risk and hazard-response communication and education strategies.

- Compared to much hazard research, which focuses on vulnerability at the national or regional level, this study provides evidence of what factors are important in shaping vulnerability at the *individual* level.

6.4. LIMITATIONS OF THE STUDY

The usefulness of the results obtained from both questionnaire surveys, in terms our ability to draw generalisations about each community, citizens from each country, or vulnerable individuals in general, should be considered with care. Research subjects should be similar in all other aspects apart from the variables forming the focus of study (Van de Vijver & Leung, 1997). However, social and cultural factors are important in forming people's understandings of risk (Boholm, 1998). Therefore, information about different events or phenomena are socially processed (Rappaport, 1996), and human social existence is culturally variable, which makes drawing conclusions across national or cultural boundaries problematic. These may not result from common processes or structures, but rather from specific historical, social or cultural circumstances (Boholm, 1998). In addition, methodological procedures for comparative studies require the use of the same survey instrument (Enders, 2001), which was not the case here.

Similarly, generalising from survey work conducted with limited resources, restricted time scales, and insufficient data (as in the case of the work conducted in Baños) is particularly difficult where a case study approach has been employed (Bell, 1999b). The extent to which the findings from a case study can be generalised to other examples depends upon how similar the case study is to these examples. For this research, comparison of results should be restricted to the three US communities, which are similar in terms of their socio-economic characteristics and cultural experiences, and differ only in the criteria we are interested in measuring; i.e. their exposure to volcanic risk and how this might influence their attitudes, beliefs and behaviour. However, such relatively small-scale studies carried out systematically and critically, are valid forms of research (Bassey, 1981), which can inform and illuminate contextual features of the communities studied. The results from the work carried out here may be sufficient and appropriate for hazard managers working in similar communities to relate to, providing a basis for policy development and decision making.

> *"… generalisation may be unlikely, but relatability may be entirely possible…[and] can be invaluable." (Bell, 1999b, p. 172)*

Although significant work was carried out in the planning, consultation and preparation phase before designing both questionnaire instruments, some methodological issues arose. As demonstrated by the extent of the literature reviewed in chapter two, the field of risk and vulnerability research is vast. In order to encompass as many of these aspects as possible, the questionnaires attempted to include items to cover as many of these features as possible. Recommendations for questionnaire design highlight the need for discipline in abandoning questions that are superfluous to the main task (*ibid*). If resources and time had allowed pilot studies to be conducted in both countries, such superfluous questions could have been recognised and removed prior to the main study. The benefits of reducing the length of both survey instruments are two fold. Firstly, data input for analysis would have been simplified. More importantly, the amount of time required to complete the questionnaire would have been reduced. This would have allowed the researcher to maximise the limited time available to collect responses, and may have resulted in larger sample sizes. Additionally, the time burden for participants would have been reduced, response rates may have been improved, premature termination of self-completed questionnaires may have been avoided, and the quality of responses particularly to later questions may have been improved. Various studies have considered the effect of questionnaire length on response rate and quality, but the results are inconclusive (Bogen, 1996), with some reporting no effect (Sheth, 1975; Subar *et al.*, 2001; Rothman *et al.*, 2009), some a small but non-significant negative effect (i.e. longer questionnaires elicited less responses) (Ronckers *et al.*, 2004), or a strong significant negative relationship (Burchell & Marsh, 1992; Jepson *et al.*, 2005). Although empirical support is not conclusive, common sense seems to suggest that the shorter the questionnaire, the higher the response rate, and the personal experiences of the researcher during face-to-face administration of the survey instrument in the USA indicated that some participants, when informed how long the interview would take, declined to participate.

Re-evaluation of the survey instrument utilised in the US study (which benefited from a review following the initial Ecuador study), indicate several areas for improvement. Questionnaire items could have been restricted to only those specifically related to hazard salience, risk perception, trust, information accessed and preparedness. Questions relating to knowledge about past activity could have been removed (Q7, Q8, Q10), as could those items relating to official preparedness (Q11, Q18, Q19,), inclusion of the SCI negated the need for Q23 to Q26, relating to social networks, and the statements section at the end of the questionnaire proved unnecessary (Q39). In addition, a particularly sensitive question regarding socio-economic status could have been excised (Q30; ethnicity), along with those relating to property type, age and value

(Q34 to Q36; which were included to provide a measure of the physical vulnerability of a respondent's property). This would have resulted in a more focused questionnaire containing 23 items, making it approximately 40% shorter, and therefore significantly quicker and easier to administer and complete.

An additional obstacle encountered during the Ecuador study was the need to translate the questionnaire into Spanish. This was delayed until arrival in Baños, reducing the time available to conduct the actual survey distribution and interviews. The methodological justification for this was to utilise local knowledge regarding volcanic activity and hazards to ensure the implied meaning of each question was not 'lost in translation'. Although survey time was encroached, it is felt the benefits in retaining the correct question meaning outweighed any negative impact upon time.

6.5. RECOMMENDATIONS FOR FUTURE WORK

One important finding of the research conducted in Mount Rainier, was the lack of correlation between socio-economic indicators and vulnerability (as theorised by among other Degg, 1992; Cutter *et al.*, 2000; King & MacGregor, 2000; Cutter *et al.*, 2003; Corotis & Enarson, 2004; Wisner *et al.*, 2004). The findings of this study suggest two facets of vulnerability; *pre-event vulnerability*, which may largely be determined by perceptual processes, and *post-event resilience*, which may largely be determined by socio-economic status and demographic characteristics. The literature cited above largely considers *post-event vulnerability* at the global, national or regional scale, whilst no empirical data to support the theory of socio-economic determinants of vulnerability at the community or individual level were found. Current research appears to take little account of how perceptual processes may be modified in order to reduce vulnerability by fostering resilience to volcanic threat. Therefore, several recommendations for future work include:

i) Further empirical research into the victims of disasters, including those following volcanic eruptions, to explore the socio-economic profile of those affected, and to measure the short and long term impacts of disaster. This would determine whether the effects of a natural disaster are unequally felt at an individual level, as they appear to be at the national level.

ii) Building on the previously recommended study could be an exploration of the preparedness measures adopted by disaster victims prior to the hazard event, and how successful these were at mitigating the consequences. This would address one of the limitations of the approach adopted within this thesis, e.g. problems associated with using self reported measures of preparedness, which may reflect perceptions rather than actual behaviour.

iii) Further work to more accurately measure self-protection amongst individuals, rather than infer this from other measures, e.g. perceived preparedness.

iv) This research indicates the importance of coping appraisal or self-efficacy in determining people's decision to respond to a threat, and although this approach has been utilised in some risk perception studies, more consideration of how people estimate their own options and abilities to react to, and cope with a threat should be adopted within behavioural research into natural hazards.

v) Additionally, research should be conducted into the different risk communication and education strategies to determine if, and how, they might address the perceptual factors, which this study found to be important in predicting the adoption of self-protective behaviour, particularly risk perception and self-efficacy.

vi) The threat assessment metric developed here took no account of institutional mitigation measures, which may already be in place, and would (hopefully) act to moderate vulnerability within the communities where they exist. Firstly, the ability of such mitigation measures, including emergency planning, education and communication strategies, evacuations routes etc, could be evaluated in terms of their ability to reduce community vulnerability. Secondly, account of any mitigation could be incorporated with the threat assessment metric to provide an additional measure of physical vulnerability (exposure factors).

vii) To further test the validity of the threat assessment metric developed here, it could be applied to a single volcano, and used to rank the relative threat to all settlements and communities sighted within the volcanic hazard zones.

It is important to state that the recommendations for further research are in no way meant to be exhaustive or comprehensive. They refer to issues that may improve knowledge and understanding amongst risk practitioners about the many complex, interrelated elements which determine vulnerability to volcanic hazards – and by extension other natural hazards.

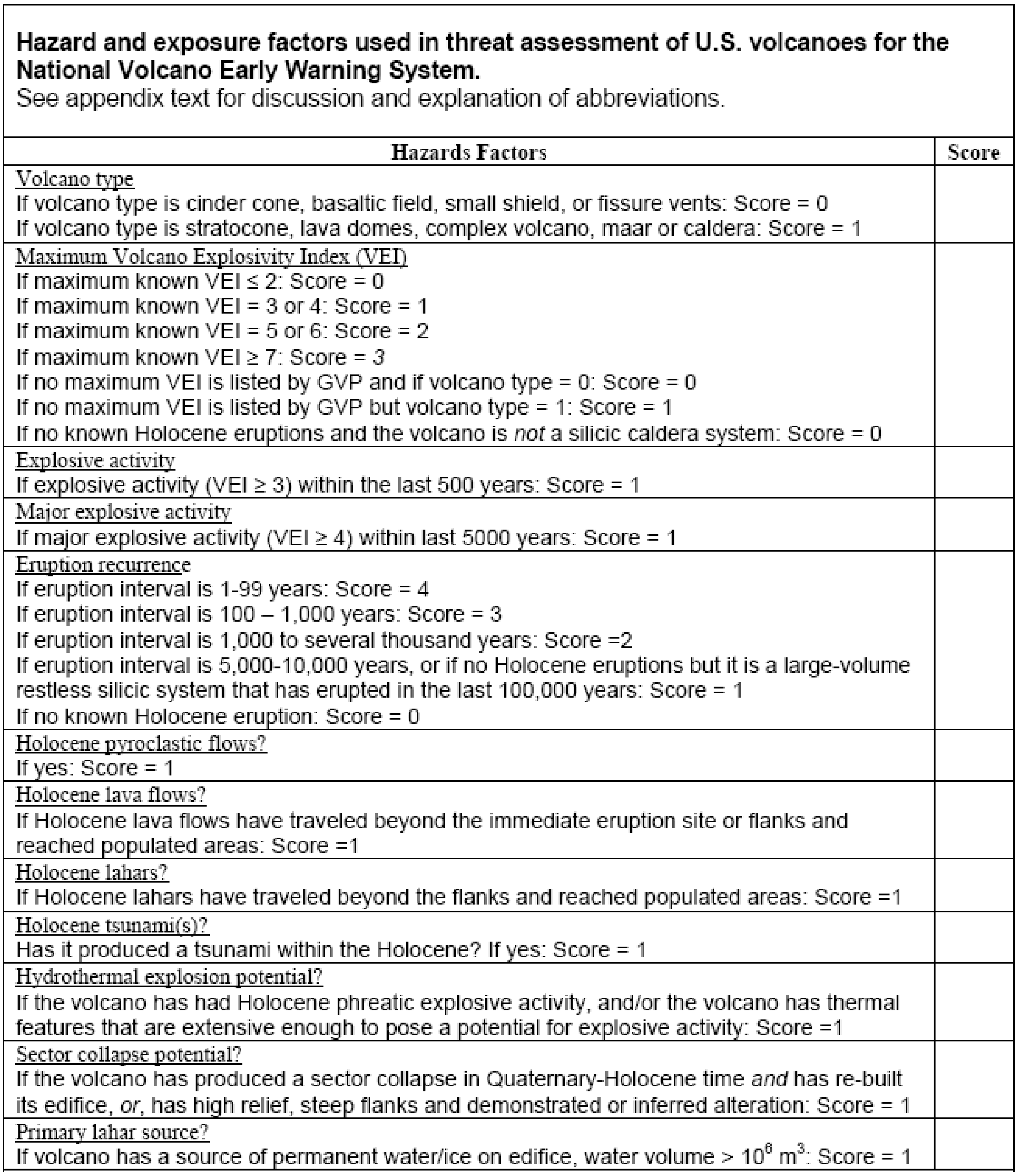
Perhaps most importantly for future work is the need to conduct more collaborative research between the many and varied disciplines involved in the study of risk. It is clear from the work conducted here that both the geophysical hazards, and the social and cultural dimensions of risk are of equal importance in determining vulnerability. Academics should move away from the current trend to overspecialise, and the resulting interdisciplinary researchers should then attempt to bridge the gap, which limits discourse between natural and social scientists, particularly through the development of a shared language and methodologies.

6.6. CONCLUDING REMARKS

As well as providing an approach to quantify the relative threat to at-risk communities based on readily available data, this study has provided valuable insight into the attitudes and beliefs that shape social vulnerability. It provides empirical evidence for the importance of perceptual processes in shaping an individual's response to volcanic risk at the two case study volcanoes. It has identified preparedness, access to information, risk perception and self-efficacy as important predictors for the adoption of appropriate self-protective behaviour to volcanic risk, as well as identifying barriers to this. Although no socio-economic indicators were identified to allow the integration of these factors into a micro-scale analysis of community vulnerability, the study has helped reveal why individuals respond as they do, and how this behaviour may be modified through appropriately targeted risk communication and education strategies.

Although it has long been recognised in psychological research that beliefs and attitudes play a much greater role in determining how a person behaves, work continues to be done by social scientists and more qualitative risk researchers that assumes the importance of socio-economic characteristics is over-riding, and that these can be used as a measure of vulnerability. Although empirical evidence exists at the national scale that disasters unfairly affect poorer nations, or women within a society, little evidence exists at the individual level. Although one could say that women or the poorest in society are more vulnerable, what can emergency managers do to mitigate these characteristics? These are issues that can only be addressed through national development policies. However, this research has identified that differences in risk perception and self-efficacy play a significant role in whether someone seeks information about risk, or adopts precautionary behaviour to prepare for an emergency event. Advancing hazard science through this understanding of vulnerability at the individual level, the knowledge gained from this study can be used by emergency managers to tailor education and communication strategies that will inform and empower individual’s to protect themselves, and begin to break the over-reliance on state intervention during an emergency, or international aid in the aftermath of a disaster.

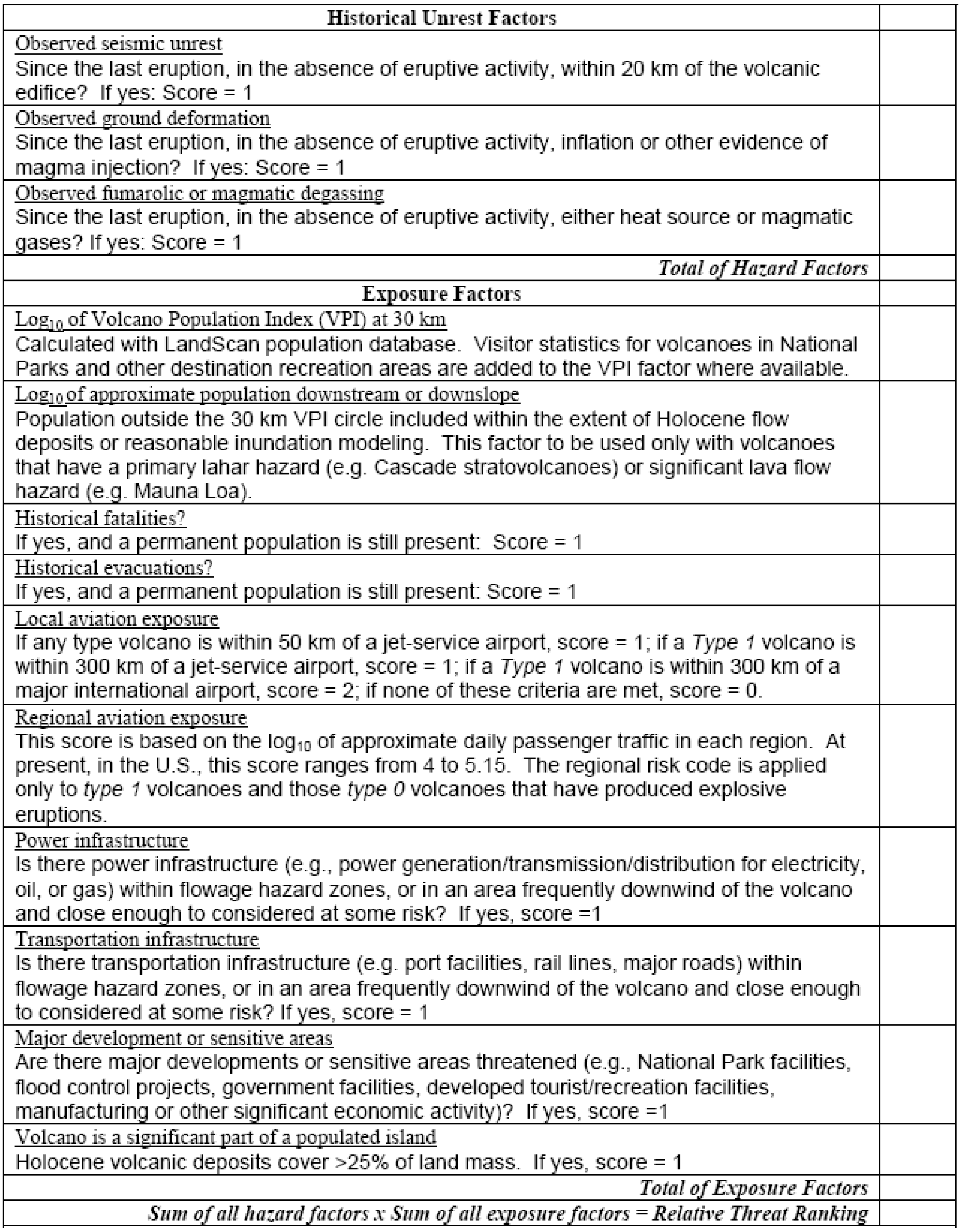
APPENDIX 1: USGS VOLCANO THREAT ASSESSMENT CRITERIA



Hazard and exposure factors used in threat assessment of U.S. volcanoes for the National Volcano Early Warning System.
See appendix text for discussion and explanation of abbreviations.

Hazards Factors	Score
Volcano type If volcano type is cinder cone, basaltic field, small shield, or fissure vents: Score = 0 If volcano type is stratocone, lava domes, complex volcano, maar or caldera: Score = 1	
Maximum Volcano Explosivity Index (VEI) If maximum known VEI ≤ 2: Score = 0 If maximum known VEI = 3 or 4: Score = 1 If maximum known VEI = 5 or 6: Score = 2 If maximum known VEI ≥ 7: Score = *3* If no maximum VEI is listed by GVP and if volcano type = 0: Score = 0 If no maximum VEI is listed by GVP but volcano type = 1: Score = 1 If no known Holocene eruptions and the volcano is *not* a silicic caldera system: Score = 0	
Explosive activity If explosive activity (VEI ≥ 3) within the last 500 years: Score = 1	
Major explosive activity If major explosive activity (VEI ≥ 4) within last 5000 years: Score = 1	
Eruption recurrence If eruption interval is 1-99 years: Score = 4 If eruption interval is 100 – 1,000 years: Score = 3 If eruption interval is 1,000 to several thousand years: Score =2 If eruption interval is 5,000-10,000 years, or if no Holocene eruptions but it is a large-volume restless silicic system that has erupted in the last 100,000 years: Score = 1 If no known Holocene eruption: Score = 0	
Holocene pyroclastic flows? If yes: Score = 1	
Holocene lava flows? If Holocene lava flows have traveled beyond the immediate eruption site or flanks and reached populated areas: Score =1	
Holocene lahars? If Holocene lahars have traveled beyond the flanks and reached populated areas: Score =1	
Holocene tsunami(s)? Has it produced a tsunami within the Holocene? If yes: Score = 1	
Hydrothermal explosion potential? If the volcano has had Holocene phreatic explosive activity, and/or the volcano has thermal features that are extensive enough to pose a potential for explosive activity: Score =1	
Sector collapse potential? If the volcano has produced a sector collapse in Quaternary-Holocene time *and* has re-built its edifice, *or*, has high relief, steep flanks and demonstrated or inferred alteration: Score = 1	
Primary lahar source? If volcano has a source of permanent water/ice on edifice, water volume > 10^6 m^3: Score = 1	

Cont'd.



Historical Unrest Factors	
Observed seismic unrest Since the last eruption, in the absence of eruptive activity, within 20 km of the volcanic edifice? If yes: Score = 1	
Observed ground deformation Since the last eruption, in the absence of eruptive activity, inflation or other evidence of magma injection? If yes: Score = 1	
Observed fumarolic or magmatic degassing Since the last eruption, in the absence of eruptive activity, either heat source or magmatic gases? If yes: Score = 1	
Total of Hazard Factors	
Exposure Factors	
Log$_{10}$ of Volcano Population Index (VPI) at 30 km Calculated with LandScan population database. Visitor statistics for volcanoes in National Parks and other destination recreation areas are added to the VPI factor where available.	
Log$_{10}$ of approximate population downstream or downslope Population outside the 30 km VPI circle included within the extent of Holocene flow deposits or reasonable inundation modeling. This factor to be used only with volcanoes that have a primary lahar hazard (e.g. Cascade stratovolcanoes) or significant lava flow hazard (e.g. Mauna Loa).	
Historical fatalities? If yes, and a permanent population is still present: Score = 1	
Historical evacuations? If yes, and a permanent population is still present: Score = 1	
Local aviation exposure If any type volcano is within 50 km of a jet-service airport, score = 1; if a *Type 1* volcano is within 300 km of a jet-service airport, score = 1; if a *Type 1* volcano is within 300 km of a major international airport, score = 2; if none of these criteria are met, score = 0.	
Regional aviation exposure This score is based on the log$_{10}$ of approximate daily passenger traffic in each region. At present, in the U.S., this score ranges from 4 to 5.15. The regional risk code is applied only to *type 1* volcanoes and those *type 0* volcanoes that have produced explosive eruptions.	
Power infrastructure Is there power infrastructure (e.g., power generation/transmission/distribution for electricity, oil, or gas) within flowage hazard zones, or in an area frequently downwind of the volcano and close enough to considered at some risk? If yes, score =1	
Transportation infrastructure Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within flowage hazard zones, or in an area frequently downwind of the volcano and close enough to considered at some risk? If yes, score = 1	
Major development or sensitive areas Are there major developments or sensitive areas threatened (e.g., National Park facilities, flood control projects, government facilities, developed tourist/recreation facilities, manufacturing or other significant economic activity)? If yes, score =1	
Volcano is a significant part of a populated island Holocene volcanic deposits cover >25% of land mass. If yes, score = 1	
Total of Exposure Factors	
Sum of all hazard factors x Sum of all exposure factors = Relative Threat Ranking	

APPENDIX 2: CHRONOLOGY OF MAJOR VOLCANIC ACTIVITY AT VOLCAN TUNGURAHUA

Age/Date	Event	Comment
~700,000 years BP	Construction of Tungurahua I	Characterised by andesitic lava flows and tephra fall, followed by major flank collapse.
30,000 years BP	Collapse of Tungurahua I	Major eruption resulting in flank collapse and associated debris avalanche.
30,000 years BP to 9,000 years BP	Tungurahua II	Up to four main eruptions identified centred around the same conduit as the current edifice. Lava flows, pyroclastic flows and tephra fall.
9,700 years BP	Guano pyroclastic deposits	Large eruption accompanied by ejection of large scoria clasts up to 15km to the SW. Pyroclastic flows travelled a maximum of 20km reaching the outskirts of the current town of Guano.
2,950 years BP	Collapse of Tungurahua II edifice	Volcanic blast originating from the central vent. Produced a sub-plinian column reaching 25km above the summit. Resulting massive debris avalanche filled Chambo River valley to a maximum depth of 300m. Associated pyroclastic flows, lava flows and lahars down all flanks of the volcano. Tephra production 1.3km^3, estimated VEI 5; largest eruption during the Holocene period.
2,300BP-1,400 BP	Construction phase of Tungurahua III	First main period of activity at current edifice. Characterised by lava flows and the emplacement of a lava dome within the amphitheatre created following the collapse of Tungurahua II. Debris flows descended W and N flanks.
1,200 BP	Las Juntas pyroclastic flow deposits	Beginning of second period of activity of current edifice. Pyroclastic flows generated and lava flows reached 5 to 7km from the crater.
950 BP	P1 tephra unit	Explosive central vent eruption; VEI 4. Tephra volume approximately 9.5 x 10^{7}m^3.
1534	Central vent eruption	Small eruption, possibly generated pyroclastic flows.
1640	Central vent eruption	Historical records describe damage to land and property from pyroclastic flows. Also block and ash flows and lava flows. Collapse of NW summit cone caused debris avalanche down Vazcún valley.

cont'd.

Age/Date	**Event**	**Comment**
1773	P2 tephra unit	Explosive central vent eruption, with lava flows, lahars and pyroclastic flows descending the Vazcún valley reaching Baños. Evacuation of affected area and damage to land/property recorded. Estimated VEI 3.
1886	Central vent eruption	Pyroclastic flows, lava flows (volume 8.9 x 10^{7}\m^{3}) and lahars. First recorded fatalities directly associated with an eruption (although archaeological evidence suggests prior fatalities). Estimated VEI 4.
1916-1918	Last recorded period of activity prior to current eruptive phase	VEI 3 explosive eruption accompanied by pyroclastic flows down all flanks, lava flows, lahars, phreatic explosions, ash plumes, ballistic projectiles and intermittent strombolian activity.
1999 to date	Current ongoing eruptive activity.	Increased seismicity, fumarolic activity, explosions, lava flows and numerous lahars down the W, NW and N flanks. Ash-fall to the west, including in the provincial capital Ambato, and Riobamba. Evacuations in both 1999 and 2006. During 2006 period of increased activity, first pyroclastic flows generated, at least five fatalities recorded. Ongoing ashfall mainly to the W and SW, steam emissions and ballistic ejecta.

Compiled from Hall *et al.* (1999) and Le Pennec *et al.* (2004, 2006 & 2008).

APPENDIX 3: CHRONOLOGY OF MAJOR VOLCANIC ACTIVITY AT MOUNT RAINIER

Eruptive Period	**Age/Date**	**Event**
Historic activity	1980s to present	Many glacial outburst flood, rain, stream capture and drainage diversion induced small to moderate sized debris flows in most river valleys which head on mountain, none extending beyond park boundaries.
	1963	Rock avalanche from Little Tacoma Peak, with debris flow extending down White River as far as White River campground (7km).
	1947	Multiple debris flows in Nisqually River valley
	1910-1927	Rock avalanche on Tahoma Glacier extent below glacier terminus in Puyallup River valley, small debris flow.
	1894	Possible small phreatic explosions, no physical evidence found but eyewitness accounts.
	500 years ago	Electron Mudflow in Puyallup/Nisqually River, extended >50km (to outskirts of Sumner). Max height within park >100m. Volume 0.26 km^3. No evidence of associated volcanism, likely cause; massive avalanche or series of avalanches from collapse of hydrothermally altered rock within Sunset Amphitheatre on west flank.
Fryingpan Creek eruptive episode	1,050 to 1,000 years ago	Last confirmed magmatic eruption; pyroclastic flow, tephra and lahars in White River valley as far as Kautz Creek. Lahar down Puyallup River, extent at least to confluence with Mowich River, possibly to Puget Sound lowland. Estimated volume >0.30km^3.
Twin Creeks eruptive episode	1,500 years ago	Explosive magmatic eruptions producing tephra and lahars, no lava flows. Lahars in valleys of White River and Kautz Creek (Deadman Flats Lahar Assemblages). Travelled at least 11km onto Puget Sound lowland, may have reached Puget Sound. National Lahar possibly a close or synchronous correlative of Dead Man Flat lahar, traveled down Nisqually River, inundating valley above Alder Reservoir and extending into Puget Sound.
Summerland eruptive period	2,000	Lava flows formed present summit cone. Eruption of tephra layers. One or two magmatic eruptions producing east summit crater lava flows.
	2,170 to 2,710	Round Pass Mudflow following flank collapse, descends Puyallup River, Tahoma Creek and Nisqually River to Puget Sound lowland.
	2,200	Subplinian eruption of tephra layer C, deposits blanket park to average depth of 15cm, estimated volume 0.3km^3. Largest known tephra eruption of Mount Rainier. VEI 4.
	2,350	Pyroclastic flow in South Puyallup River valley extending at least 24km beyond terminus of Tahoma Glacier.

cont'd.

Eruptive Period	**Age/Date**	**Event**
Summerland eruptive period cont…	2,200 to 2,700	Lahar in Nisqually River valley and multiple lahars in White River valley extending >30km. Lava flows, phreatic and phreatomagmatic tephra and minor pumice eruptions.
	>3,400	Lahar extends down Carbon River valley as far as current boundary of national park, deposits up to 3m thick.
Osceola eruptive period	> 4,500 years ago	Eruption of tephra layer B to south and southeast of summit. Deposits to maximum depth of 7cm, containing bombs and lapilli.
	5,600 years ago	Explosive phreatic and phreatomagmatic eruptions, lateral blast, massive flank collapse of hydrothermally altered rock leading to Osceola Mudflow, which extended at least 110km down main and West Fork of the White River valley to the Puget Sound lowland area. Volume estimated at 3km^3. Paradise lahar, thought to be contemporaneous with Osceola Mudflow, extended down Nisqually River valley to at least the community of National (~ 30km)
	< 5,700 years ago	Eruption of tephra layer H east of summit over Summer Land south to Cowlitz Park, during several small eruptions.
	5,700 years ago	Magmatic eruption of tephra layer F (possibly steam blast in part), deposits extends north, east and south of volcano beyond park boundaries (possibly synchronous with Osceola Mudflow). Greenwater Lahar flowed down main fork of White River at least 50km from volcano (probably initial part of Osceola Mudflow).
	5,900 years ago	Eruption of tephra layer S to the northeast. Deposits in Yakima Park to Sunrise Ridge up to 1.25m thick, containing blocks measuring up to 45cm. Possibly part blast in origin, pyroclastic eruption caused by one or more steam explosions.
Cowlitz eruptive period	6,300 years ago	Eruption of tephra layer N deposits found in small tongue to east of summit, not extending outside national park.
	6,600 years ago	Rock avalanche induced lahar down the Nisqually River valley covering Van Trump Park.
	6,800 years ago	Eruption of tephra layer D extends east well beyond park boundaries, includes abundant bombs (~15cm diameter) to the east and southeast of the summit crater up to 10km distance (Stevens Ridge).
	6,800 to 7,200 years ago	Reflection Lakes lahar flowed to the south, overtopping 60m ridge to enter the lake, raising its level by up to 6m.
	7,200 to 7,400 years ago	Eruption of volcanic bomb-bearing rocks. Lahars in the White River valley.

cont'd.

Eruptive Period	**Age/Date**	**Event**
	7,300 years ago	Eruption of tephra Layer L, found mainly in a narrow lobe to the southeast of the summit crater particularly in Cowlitz Park to a depth of 25cm.
	7,400 years ago	Eruption of Layer A in broad arc over much of eastern area of national park.
	7,500 years ago	Avalanche of clayey rock debris covered Paradise Park in the Nisqually River Valley.
Sunrise eruptive period	9,800 years ago	Eruption of oldest recognised post-glacial tephra (Layer R), extended over most of park to east of summit and beyond.
	9,500 to 10,000 years ago	Large cohesive lahar to the south; the Van Trump debris flow.
Period of increased activity	40,000 to 15,000 years ago	Most of upper head walls and ridges on volcano constructed. Period characterised by simultaneous lava effusion and glacial erosion.
Period of waning eruption rates	180,000 to 40,000 years ago	Lava flows from dikes and vents on upper east flank construct Little Tahoma. Pyroclastic flow filled headwaters of Kautz Creek. Erosion incised upper edifice removing much of the upper north and south flanks reducing summit elevation.
	105,000 years ago	Basaltic lava flows erupted across Spray Park and Mist Park from vents on lower northeast flank.
	130,000 years ago	Flank vent at Windy Gap flowed against ice filling present Carbon River valley, producing Bee Flat lava flow north of volcano.
Period of rapid lava accumulation	280,000 to 180,000 years ago	Many voluminous eruptions, extensive lava flows including from vents on flanks of volcano, dike emplacement. Volcano grew to its highest elevation.
Reduced rate of lava accumulation	400,00 to 300,000 years ago	Infrequent, small eruptions, including Rampart Ridge lava flow to northwest. Substantial erosion leading to reduction in volcano height.
Onset of modern volcano	500,000 to 420,000 years ago	Highly active period with rapid accumulation of lava capping a thick apron of pyroclastic flows. Volcano built to height similar to that of current edifice

Compiled from Crandell (1971), Mullineaux (1974), Scott *et al.* (1995), Driedger *et al.* (2005), John *et al.* (2008) and Sisson & Vallance (2009).

APPENDIX 4: THE MAY 1980 MOUNT ST HELENS ERUPTION

The volcano

Mount St Helens is located in Washington State, approximately 80km south of Mount Rainier and forms part of the northern end of the Cascade Range of mountains. Situated within the Mount St Helens National Volcanic Monument area, rising to 2,549m, its summit is over 1,800m lower than Mount Rainier's; the "giant of Cascades volcanoes" (Foxworthy & Hill, 1982). A composite volcano, Mount St Helens' steep sides are built of alternating layers of lava, ash, cinders and other volcanic products. This form of volcano is typical of convergent plate margins and is characterised by relatively frequent, small to medium sized, explosive eruptions (Davidson & De Silva, 2000). Prior to the 1980 eruption, the volcano was admired for its beautiful symmetrical, conical shape and perennial cap of snow and ice. Due to its resemblance with its Japanese cousin, it was known as the Fuji-san of America.

Eruptive history (pre-1980)

Nine "pulses" of activity prior to the 1980 eruption have been identified, beginning about 40-50,000 years ago (Siebert & Simkin, 2002-). Active periods lasted from between 5,000 years to less than 100 years, with dormant periods of between 15,000 years to just 200 years. The visible cone of the volcano formed during the past 2,200 years, making it the youngest of the major Cascade volcanoes (Tilling *et al.*, 1990; Siebert & Simkin, 2002-). There have been 4 major explosive eruptions and many smaller eruptions since the late 15th century, starting in 1480 with an eruption 5 times larger than that of 1980 (Wolfe & Pierson, 1995). Prior to 1980, Mount St Helens' last eruptive period occurred from 1800 to 1857, and was observed and documented by early settlers. It is thought that an explosive eruption in 1800 was followed by intermittent minor explosions and extrusions of lava, ending in 1857 (Tilling et al., 1990).

The 1980 eruption

Extensive scientific study of the volcano and its geological deposits, led to the publication of a booklet in 1978 that outlined the potential hazards from, and likely frequency of, future volcanic activity at Mount St Helens (Crandell & Mullineaux, 1978). The report suggested that an eruption was likely within the next 100 years and perhaps before the end of the century. The report correctly predicted the plinian and sub-plinian activity, tephra deposition and mudflow paths of the 1980 eruption but the massive landslide and lateral blast were substantially larger than anticipated (Newhall, 2000). Given the scientific knowledge at the time, the report was remarkably prescient. However, predicting the actual timing of the climactic eruption was not possible given the triggering mechanism (an earthquake induced landslide), but pre-cursory earthquakes and phreatic eruptions warned of the volcanoes re-awakening.

During the middle of March 1980, several small earthquakes were detected beneath the volcano, followed on 20th March by a magnitude 4.2 (Richter scale) earthquake. The number of daily earthquakes increased, peaking towards the end of March with 8 ≥ magnitude 4 events on the 25th March (McNutt, 2000). On the 27th March, an explosion occurred followed by an eruption of ash and steam, rising to almost 2,000m above the volcano. The ash erupted during this phreatic phase, was derived from the shattered and pulverized rock of the summit cone. Driven by steam produced from melting snow and ice finding its way into cracks in the volcano, which was then superheated and expanded explosively (Tilling *et al.*, 1990). Seismic activity continued with over 10,000 earthquakes recorded, located at depths of 3 to 7kms beneath the north flank of the volcano (McNutt, 2000). For the following month, intermittent phreatic eruptions continued. Towards the end of April and into early May, bulging of the north flank of the volcano, caused by the intrusion of magma, was clearly visible.

Combined with the detection of volcanic tremor, this indicated the subsurface movement of magma and associated gases within the volcano (Tilling *et al.*, 1990). Inflation of the north flank of the volcano, forming the prominent bulge, raised some areas by as much as 150m above pre-eruption topography, with measuring stations detecting continued and relatively constant rates of movement towards the north, of up to 2.5m per day (Murray *et al.*, 2000).

On the morning of 18th May, activity seemed to be progressing much as it had for the preceding 2 months until a magnitude 5.1 earthquake initiated a sector collapse of the north flank of the volcano. The failure of the bulging north flank caused the largest recorded debris avalanche in historical times. Travelling northwards at speeds of up to 120 to 240km per hour, the avalanche covered an area approximately 62km^2 and travelled more than 24km down the North Fork of the Toutle River. The deposits of volcanic debris, glacial ice and water displaced from Spirit Lake, filled the valley to a depth of up to 50m (Tilling *et al.*, 1990).

This uncapping of the volcano caused the sudden realise of pressure within the volcanic system. The rapidly expanding steam and volcanic gases produced a laterally directed blast, which devastated 600km^2 of land (Cioni *et al.*, 2000) within a 120^o arc from the northwest to the east-northeast (Schuster, 1981). Occurring seconds after the sector collapse, the lateral blast quickly overtook the debris avalanche, increasing in speed from an initial velocity of 100m/s to over 300m/s (Kieffer, 1981). The direct blast zone reached up to 13km from the volcano, where almost everything was completely destroyed. Beyond this, within an intermediate zone extending to a radius of between 18 to 24km, vegetation, including old growth forest, was completely flattened. A halo on the outer edges of the intermediate zone, approximately 2 to 3km wide, was marked by scorched vegetation, killed by the thermal effects of the blast (Schuster, 1981; Tilling *et al.*, 1990).

Following within minutes of the laterally directed blast, a vertically directed eruption, fed by a continuous discharge of magma lasting 9 hours, created the characteristic plinian eruptive column. Rising within hours to a height of around 20km above the volcano (Cioni *et al.*, 2000), this caused localised pumice-fall and lightening. Fluctuating in intensity, the eruption generated numerous, but relatively minor, pyroclastic flows that travelled down the flanks of the volcano. Prevailing winds carried volcanic ash to the east-northeast of the volcano, depositing tephra over an area of more than 57,000km^2. The thickest deposits occurred within a 100km swath immediately downwind of the volcano, but deposits of up to 50mm occurred almost 300km away (Tilling *et al.*, 1990).

From the beginning of the eruption, lahars and debris flows were generated, sweeping down most river drainages. Initially, lahars with high peak flow velocities of between 30 to 40m/s were generated by pyroclastic surges melting snow and ice high on the volcano (Munoz-Salinas *et al.*, 2007). These were largely confined close to the volcanic cone or proximal river channels. The largest and most destructive lahar, originated from slumping and flowing of water saturated parts of the debris avalanche deposits in the North Fork of the Toutle River. Occurring during the afternoon of 18th May, this lahar was relatively slow moving with peak flow velocities of between 4 to 12m/s (Janda *et al.*, 1981). The larger lahars left mud-lines up valley walls indicating peak flow depths of between 10 to 20m, however, deposits were considerably less, averaging between 1 to 3m in depth (Lombard *et al.*, 1981; Tilling *et al.*, 1990). Travelling up to 120km downriver (Janda *et al.*, 1981), parts of the Cowlitz and Columbia river beds were elevated by up to 5m by deposits of sediment, reducing carrying capacity to less than 10% of its former volume (Cummans, 1981).

Impacts of the eruption

The precursory activity of the volcano, leading to the closure of the surrounding area, undoubtedly reduced the death toll but 57 people lost their lives during the eruption.

Most victims were within the lateral blast zone and died by asphyxiation from inhaling hot volcanic ash (Tilling *et al.*, 1990). Extensive damage was confined to the large area of forest and recreational land immediately surrounding the volcano. At greater distances from the volcano, serious damage was restricted to river channels; mudflows and lahars destroyed more than 200 homes and damaged many others within the Toutle River valley. Bridges, roads, logging camps, water supplies and sewage disposal systems were also destroyed. Ashfall across a broad band of eastern Washington, northern Idaho and western Montana caused major disruption, forcing the closure of highways, county roads and airports. Immediately impeded by the ash cloud, air transport was further disrupted, with airports closed for up to 2 weeks to allow for the removal of ash deposits.

Situated 90km east-northeast of the volcano, ashfall deposits in Yakima were reported from between 20mm (Schuster, 1981) up to almost 80mm (Zais, 2001). The clean-up operation lasted for a week, with volunteer residents, city and government agency officials and private contractors working 24 hours a day. The city estimated the cost of the emergency at $5.4 million (Zais, 2001). The total cost of the eruption across the region was estimated at $1.5 billion (Tilling *et al.*, 1990; Zais, 2001), but this excludes indirect, intangible costs. Initially unemployment rose within the region surrounding the volcano and a loss of tourism was reported across a wider area of both Washington and Oregon states. Although long term concerns for economic activity within the region were initially expressed, particularly for agriculture and tourism, these proved unfounded. Agricultural production in 1980 was above average, and the site of the volcanic eruption has become a major tourist destination (Tilling *et al.*, 1990).

Size of the eruption

The Volcanic Explosivity Index (VEI) is used to describe both the volume and plume height of a given eruption (Pyle, 2000). Defined by Newhall & Self (1982), the VEI is a system developed to estimate the magnitude and intensity of a volcanic eruption, it contains nine categories with eruption volume increasing logarithmically from 0; less than 10^4 m^3 to 8; greater than 10^{12} m^3. The 18th May 1980 eruption of Mount St Helens has been rated a VEI score of 5 (Siebert & Simkin, 2002-). The total tephra volume ejected was 1.2×10^9 m^3, and the peak eruption plume height was between 19 and 20km (Cioni *et al.*, 2000; Pyle, 2000). For comparison, the AD 79 eruption of Vesuvius that destroyed Pompeii and Herculaneum, also rates a VEI score of 5. There have been 12 eruptions rated VEI 5 or greater (10 VEI 5 and 2 VEI 6) since 1900, including that at Mount St Helens in 1980 (Siebert & Simkin, 2002-). However, the VEI score is no indication of human risk from volcanic activity, as some of the most devastating eruptions are rated as moderate on the index. The 1902 eruption of Mount Peleé, Martinique, rated a VEI 4, killing 28,000 inhabitants of a single city when pyroclastic surges swept down the flanks of the volcano. Similarly, a catastrophic lahar killed over 23,000 people in the town of Armero, Columbia, during a VEI 3 eruption of Nevado del Ruiz. For comparison, the largest eruption of Mount Rainier has been estimated as a VEI 4.

APPENDIX 5: ECUADOR CASE STUDY QUESTIONNAIRE - ENGLISH

Hello, my name is Sara and I am a research student from the University of Plymouth in England. I am doing a survey in Baños to learn about how different communities are affected by volcanic activity and hope this information may help develop better mitigation plans. The information you give me will provide the basis for my research and is completely confidential. This survey should not take long. I really appreciate you taking the time to speak to me.

Demographics – Individual

1. Indicate the gender of the participant ☐ Male ☐ Female

2. How old are you? ______________________________

3. What is your marital status?
☐ Married
☐ Single
☐ Widowed
☐ Divorced/Separated
☐ Other _________________

4. Do you work for a living? ☐ Yes ☐ No – Skip to #12

5. What do you do for a living?
☐ Agriculture
☐ Independent store
☐ Business
☐ Café/Restaurant
☐ Hotel/Guest house
☐ Other __________________

6. If you work in agriculture, do you work
☐ Permanently
☐ Occasionally
☐ Seasonally

7. Is the land you work
☐ Your own
☐ Rented/leased
☐ The families
☐ An employer's

8. Who do you work for?
☐ Self
☐ Employer
☐ Another family member
☐ Other __________________

9. Are you paid for the work you do? ☐ Yes ☐ No – skip to #12

10. How are you paid?
☐ By the hour
☐ By the day
☐ By the week
☐ By the month
☐ Piecework or product

11. If possible, please indicate your average monthly income. $ ____________

Household

12. What is the main source for the family's income?

    ____

13. Including you, how many people in the household contribute to the family's income? ______________________

14. How do they contribute?
    - ☐ With money
    - ☐ Planting
    - ☐ Raising animals
    - ☐ Working in the family business
    - ☐ Other ______________

15. Do you receive help from family/friends out of the country?

    ☐ Yes ☐ No - skip to #17

16. Do they help you with
    - ☐ Money
    - ☐ Clothes
    - ☐ Other ______________

17. If possible, please indicate your household's average monthly income: ________

18. Including you, how many other people live in your household? __________

19. Please complete the following information for each person living in your household:

Relationship to you (family members or friends)	Age	Gender (M or F)	Occupation (if applicable)

20. Which of the following best describes the type of accommodation in which you live?
    - ☐ Flat/apartment
    - ☐ House
    - ☐ Room
    - ☐ Villa
    - ☐ Hotel
    - ☐ Other ______________

21. Approximately how old is your home?________________________

22. Is your home owned by:
    - ☐ You
    - ☐ Your family
    - ☐ Rented
    - ☐ A friend
    - ☐ Other ______________

23. Please give details of your home address (the roads were you live; e.g. Ambato y J.L.Mera)

    ____

Perceptions – Risk

24. How long have you lived in Baños? ______________________________

25. Are you worried about Volcán Tungurahua?
☐ Not worried
☐ Slightly worried
☐ Very worried
☐ Extremely worried

26. Do you think that the volcano is a risk to you and your family?
☐ No risk
☐ Low risk
☐ Moderate risk
☐ High risk
☐ Very high risk

Perceptions - Hazards

27. On average, how often do you think Tungurahua erupts?
☐ Never
☐ Once a century
☐ Once every 10 years
☐ Once a year
☐ Once a month
☐ Constantly

28. What types of hazards do you think might occur during an eruption?
☐ Ash fall
☐ Lava flows
☐ Pyroclastic flows
☐ Lahars
☐ Explosions
☐ Earthquakes

29. What do you think is the greatest hazard from an eruption?
☐ Ash fall
☐ Lava flows
☐ Pyroclastic flows
☐ Lahars
☐ Explosions
☐ Earthquakes

30. When do you think Volcán Tungurahua will next erupt?
☐ Within days
☐ Weeks
☐ Months
☐ Years
☐ Never

31. How big do you think the next eruption will be?
☐ Insignificant
☐ Small
☐ Moderate
☐ Large
☐ Very large

Assessment of mitigation

32. Do you know what you should do if there is an eruption?
☐ Yes ☐ No – skip to #34

33. If yes, what? ____
____

34. Do you know your evacuation routes in the event of an eruption?
☐ Yes ☐ No

35. What types of information have you had access to regarding what to do in the event of an eruption?
☐ None - skip to #37
☐ Leaflet/pamphlet
☐ Poster
☐ Map
☐ Community meeting
☐ Radio
☐ Other _____________

36. If you have had access to information was it useful?
☐ Yes
☐ A little
☐ No

37. What sources have provided you with information regarding what to do if there is an eruption?
☐ National government
☐ Local officials
☐ Scientists
☐ Newspapers
☐ Television/Radio
☐ Friends or family
☐ Church
☐ None
☐ Other _____________

38. What plans have you made should there be an eruption?
☐ None
☐ Stockpile food
☐ Practice evacuation
☐ Relocate to another place
☐ Other ___________________

39. How much do you trust the following people to inform you about a possible eruption?
(i) National government
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely
(ii) Local officials
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely
(iii)Scientists
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely
(iv) Media (newspapers, television, radio)
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely

(v) Friends and family
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely

(vi) Church/other social group
☐ Not at all
☐ Somewhat
☐ Mostly
☐ Completely

Experience of previous eruption

40. Did you live in Baños during the eruption of 1999? ☐ Yes ☐ No – skip to #48

41. Did you have to evacuate? ☐ Yes ☐ No – skip to #48

42. If yes, did you leave voluntarily? ☐ Yes ☐ No

43. Where did you go?
☐ Shelter
☐ Relatives
☐ Friends
☐ Rented accommodation
☐ Other ____________________

44. For how long where you away from your home?
☐ Less than 2 weeks
☐ 2 weeks to 1 month
☐ 1 to 3 months
☐ 3 to 6 months
☐ More than 6 months

45. What made you return home?
☐ Economic reasons
☐ Friends and family returned
☐ Volcano no longer a threat
☐ Official evacuation order lifted
☐ Other ____________________

46. At the time, did you think the evacuation was necessary? ☐ Yes ☐ No

47. How do you feel about the evacuation now? ___________________________
____
____

Social Networks

48. Do you have any close family members who live near by?
☐ None – skip to #50
☐ Grandparents
☐ Parents
☐ Brothers/sisters
☐ Other __________

49. If yes, how often do you see them?
☐ Never
☐ Occasionally
☐ Monthly
☐ Weekly
☐ Daily

50. Do you have friends living close by? ☐ Yes ☐ No – skip to #52

51. If yes, how often do you see them?
☐ Never
☐ Occasionally
☐ Monthly
☐ Weekly
☐ Daily

52. Do you belong to any social groups or organisations (sports, church, friends etc)?

☐ Yes ☐ No – skip to #55

53. If yes, please indicate what? ________________________________

54. How often do you attend any meetings/services?
☐ Never
☐ Occasionally
☐ Monthly
☐ Weekly
☐ Daily

55. Who do you turn to for assistance in a crisis situation?
☐ Husband/wife
☐ Parents
☐ Grandparents
☐ Sisters/Brothers
☐ Friends
☐ Priest/
spiritual advisor
☐ Other _________

56. What kind of assistance have you received from them?
☐ Financial
☐ Emotional
☐ Company
☐ Spiritual
☐ Other

Thank you very much for your time and assistance.

APPENDIX 6: ECUADOR CASE STUDY QUESTIONNAIRE - SPANISH

Hola, mi nombre es Sara y soy una estudiante graduada de la Universidad de Plymouth en Inglaterra. Estoy realizando una encuesta en Baños para aprender cómo las diferentes comunidades son afectadas por el Volcán Tungurahua y espero que esta información pueda ayudar a desarrollar mejores planes para manejar este problema. Su información me dará la base para mi investigación y es completemente confidencial. La encuesta no llevará mucho de su tiempo. Le agradecería mucho si me puede proporcionar algo de su tiempo.

Demografia - Individual

1. Indique el sexo del participante ☐ Hombre ☐ Mujer
2. ¿Qué edad tiene usted? ____________________________
3. ¿Cuál es su estado civil?
   - ☐ Casado/a
   - ☐ Soltero/a
   - ☐ Viudo/a
   - ☐ Divorciado/a
   - ☐ Separado/a
   - ☐Otro ________________
4. ¿Usted trabaja? ☐ Sí ☐ No – Pase a la #12
5. ¿Cuál es su ocupación?
   - ☐ Agricultura
   - ☐ Tienda independiente
   - ☐ Negocios
   - ☐ Cafetería/restaurante
   - ☐ Hotel/posada
   - ☐ Otra ____________________
6. Si usted trabaja en agricultura ¿como trabaja?
   - ☐ Permanentemente
   - ☐ Ocasionalmente
   - ☐ Por temporada
7. ¿La tierra que usted trabaja es?
   - ☐ Propia
   - ☐ Alquilada
   - ☐ De la familia
   - ☐ Del empleador
   - ☐ Otra _______________
8. ¿Usted para quién trabaja?
   - ☐ Para usted mismo/a
   - ☐ Patrón o empleador
   - ☐ Miembro de la familia
   - ☐ Otro _______________
9. ¿Le pagan por el trabajo que hace? ☐ Sí ☐ No – Pase a la #12
10. ¿Cómo le pagan?
    - ☐ Por hora
    - ☐ Por diá
    - ☐ Por semana
    - ☐ Por mes
    - ☐ a destajo, producto, contrato

11. ¿Cuánto gana mensualmente, aproximadamente? $__________________

Familia

12. ¿Cuál es la principal fuente de sustento para la familia? _________________

13. Incluyendo usted, cuantos miembros trabajan para mantener a la familia? ________________________

14. ¿Cómo contribuyen ellos?
☐ Con dinero
☐ Cultivando
☐ Criando animales
☐ Trabajando en el negocio familiar
☐ Otro __________________

15. ¿Recibe ayuda de familiares o amigos en el exterior?
☐ Sí ☐ No – Pase a la #17

16. Le ayudan con
☐ Dinero
☐ Ropa
☐ Otro_________________

17. ¿Cuánto es la ganacia mensual de la familia, aproximadamente?
$__________________

18. ¿Cuántas personas viven con usted en la casa, incluyendo usted?
____

19. Por favor, complete la siguiente información para cada persona que viven con usted:

Relación con usted (familia o amigos)	Edad	Sexo (H o M)	Ocupación/trabajo

20. ¿En qué tipo de vivienda vive usted?
☐ Departamento
☐ Casa
☐ Cuarto
☐ Villa
☐ Hotel
☐ Otra _______________

21. ¿El lugar donde usted vive tiene cuántos años aproximadamente? __________

22. Su vivienda es
☐ Propia
☐ De la familia
☐ Arrendada
☐ Prestada
☐ Otra ____________________

23. Por favor, escriba su dirección, que calles exactamente (ejemplo; Ambato y J.L. Mera) ____

Percepciónes - Riesgos

24. ¿Hace cuánto tiempo vive en Baños? ______________________________

25. ¿Está preocupado/a por el Volcán Tungurahua?
☐ No
☐ Un poco preocupado
☐ Muy preocupado
☐ Extremádamente preocupado

26. ¿Piensa quel el volcán es un peligro para usted y su familia?
☐ Ningún riesgo
☐ Poco riesgo
☐ Riesgo moderado
☐ Alto riesgo
☐ Muy alto riesgo

Percepciónes - Peligros

27. Aproximadamente, cada cuánto tiempo piensa usted que erupciona el volcán?
☐ Nunca
☐ Cada 100 años
☐ Cada 10 años
☐ Cada año
☐ Cada mes
☐ Constantemente

28. ¿Qué tipo de riesgos piensa usted que podría ocurrir durante una erupción?
☐ Caída de ceniza
☐ Flujos de lava
☐ Flujos de piroclásticos
☐ Lahares
☐ Explosiones
☐ Temblores

29. ¿Qué piensa usted sería lo más peligroso de una erupción?
☐ Caída de ceniza
☐ Flujos de lava
☐ Flujos de piroclásticos
☐ Lahares
☐ Explosiones
☐ Temblores

30. ¿Cuándo piensa usted que el volcán Tungurahua tendrá su proxima erupción?
☐ Dentro de unos días
☐ Dentro de unas semanas
☐ Dentro de unos meses
☐ Dentro de unos años
☐ Nunca

31. ¿Cuan grande piensa usted que será la proxima erupción?
☐ Insignificante
☐ Pegueña
☐ Moderada
☐ Grande
☐ Muy grande

Manejo de riesgos

32. ¿Sabe usted que hacer en caso de una erupción?
☐ Sí ☐ No – Pase a la #34

33. Si es así ¿Qué haría en caso de una erupción? ______________________
____

34. ¿Usted conoce las rutas de evacuación en caso de una erupción? ☐ Sí ☐ No

35. ¿Qué tipo de información ha recibido usted para un caso de erupción?
☐ Ninguna – Pase a la #37
☐ Panfletos/volantes
☐ Posters
☐ Mapas
☐ Reuniones comunitarias
☐ Radio
☐ Otra ________________

36. ¿La información fué útil?
☐ Sí
☐ Un poco
☐ No

37. ¿De qué fuente ha recibido usted la información de qué hacer durante una erupción?
☐ Gobierno nacional
☐ Autoridades locales
☐ Científicos
☐ Periódicos
☐ Televisión/Radio
☐ Amigos o familia
☐ Iglesia
☐ Ninguna
☐ Otra ________________

38. ¿Qué planes tiene usted para prepararse en caso de una erupción?
☐ Ninguno
☐ Tener comida en conservas
☐ Hacer simulacros de evacuación
☐ Ir a vivir en otro lugar
☐ Otro ________________

39. ¿En caso de una posible erupción, cuánto usted confía en la información de:

(a) Gobierno nacional?
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

(b) Autoridades locales?
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

(c) Científicos?
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

(d) Medios de comunicación?
(periódicos, radio, televisión)
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

(e) Amigos y familia?
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

(f) Iglesia/otros grupos sociales?
☐ Nada
☐ Un poco
☐ Bastante
☐ Completamente

Experiencias de la erupción en 1999

40. ¿Viviste en Baños durante la erupción de 1999?
☐ Sí ☐ No – Pase a la #48

41. ¿Tuvo que ser evacuado? ☐ Sí ☐ No – Pase a la #48

42. ¿Salió por su propia voluntad? ☐ Sí ☐ No

43. ¿A dónde fue?
☐ Albergue
☐ Familia
☐ Amigos
☐ Vivienda alquilada
☐ Otro ____________________

44. ¿Por cuánto tiempo estuvo evacuado?
☐ Menos de 2 semanas
☐ 2 semanas a 1 mes
☐ 1 mes a 3 meses
☐ 3 a 6 meses
☐ Mas de 6 meses

45. ¿Por qué regresó?
☐ Razones económicas
☐ Su familia y amigos regresaron
☐ La actividad del volcán bajó
☐ La orden de evacuación terminó
☐ Otro _________________________

46. ¿En ese momento, pensó que era necesario evacuar? ☐ Sí ☐ No

47. ¿Qué piensa ahora acerca de la evacuación? _________________________
____
____

Relaciones sociales

48. ¿Tiene parientes viviendo cerca de usted?
☐ Nadie – Pase a la #50
☐ Abuelos
☐ Padres
☐ Hermanos
☐ Otros ______________

49. Si es así ¿con qué frecuencia se ve con ellos?
☐ Nunca
☐ Ocasionalmente
☐ Mensualmente
☐ Semanalmente
☐ Diariamente

50. ¿Tiene amigos viviendo cerca de usted? ☐ Sí ☐ No – Pase a la #52

51. Si es así ¿con qué frecuencia se ve con ellos?
☐ Nunca
☐ Ocasionalmente
☐ Mensualmente
☐ Semanalmente
☐ Diariamente

52. ¿Usted pertenece a algún grupo u organización social ?
(ejemplo; deportivo, religioso, amigos)
☐ Sí ☐ No – Pase a la #55

53. Si es así ¿A qué grupo pertenece? ________________________

54. ¿Con qué frequencia usted tiene reuniones de su grupo social?
☐ Nunca
☐ Ocasionalmente
☐ Mensualmente
☐ Semanalmente
☐ Diariamente

55. ¿A quién pide ayuda en casos de tener problemas?
☐ Esposo
☐ Padres
☐ Abuelos
☐ Hermanos
☐ Amigos
☐ Párroco, consejero espiritual
☐ Otro __________________

56. ¿Qué clase de ayuda ha recibido de ellos?
☐ Economico/financiero
☐ Emocional
☐ Compañía
☐ Espiritual
☐ Otro __________________

Muchas gracias por su tiempo y su ayuda.

APPENDIX 7: US CASE STUDY QUESTIONNAIRE

Volcanic Risk Perceptions Survey

This survey is being carried out as part of a research project at the University of Plymouth, UK, on people's views of volcanic risk in the region. All views will remain anonymous and will only be used for purposes directly related to this research. The survey should not take more than 20 minutes to complete. Please answer all questions by marking an 'x' in the box next to **one** of the options only, unless otherwise indicated. Please read through all possible answers before selecting your choice. I would like to thank you for taking the time to complete this survey.

1. How often do you think about the possibility of volcanic activity at Mt Rainier?

☐ 1 Never
☐ 2 Rarely
☐ 3 A few times a year
☐ 4 Once a month
☐ 5 Once a week or more

2. Compared to a volcanic eruption, how concerned are you about the following?

	Less concerned	The same	More concerned
Earthquakes	☐ 1	☐ 2	☐ 3
Floods	☐ 1	☐ 2	☐ 3
Severe storms	☐ 1	☐ 2	☐ 3
Landslides	☐ 1	☐ 2	☐ 3
Tsunamis	☐ 1	☐ 2	☐ 3
Wild fires	☐ 1	☐ 2	☐ 3

3. How worried are you about possible future volcanic activity at Mt Rainier?

☐ 1 Not at all worried ☐ 2 Slightly worried
☐ 3 Quite worried ☐ 4 Very worried

4. If there is an eruption, how likely do you think it is that this will affect your town?

☐ 1 Not at all likely ☐ 2 Somewhat likely
☐ 3 Quite likely ☐ 4 Very likely

5. If there is an eruption, how serious do you think the affects would be for your community?

☐ 1 Not at all serious ☐ 2 Somewhat serious
☐ 3 Quite serious ☐ 4 Very serious

6. If there is an eruption, how serious do you think the affects would be for you and your family?

☐ 1 Not at all serious ☐ 2 Somewhat serious
☐ 3 Quite serious ☐ 4 Very serious

7. When do you think the next eruption of Mt Rainier is likely to occur?

☐ 1 Within the next 12 months
☐ 2 Within the next 1 to 5 years
☐ 3 5 to 10 years from now
☐ 4 10 to 50 years from now
☐ 5 More than 50 years from now
☐ 6 Never

8. What types of hazards do you think might occur during an eruption?
(mark ☒ in more than one box if necessary)

☐ 1 Volcanic ash
☐ 3 Lava flows
☐ 5 Debris avalanches
☐ 2 Pyroclastic flows and surges
☐ 4 Lahars/mud flows
☐ 6 Explosions/lateral blasts

9. Please rate how serious a threat you think the following hazards would be to your town/community during an eruption:
(for each line check one box which best indicates your opinion)

	Not serious	Somewhat serious	Quite serious	Very serious
Volcanic ash	☐ 1	☐ 2	☐ 3	☐ 4
Pyroclastic flows and surges	☐ 1	☐ 2	☐ 3	☐ 4
Lava flows	☐ 1	☐ 2	☐ 3	☐ 4
Lahars/mud flows	☐ 1	☐ 2	☐ 3	☐ 4
Debris avalanches	☐ 1	☐ 2	☐ 3	☐ 4
Explosions/lateral blasts	☐ 1	☐ 2	☐ 3	☐ 4

10. Do you know when Mt Rainier last erupted?
☐ 1 No
☐ 2 Yes *(please state when)* ______________________________

11. Do you know of any plans or strategies the authorities have put in place to help protect your community from future volcanic activity?
☐ 1 No
☐ 2 Yes *(please state)*______________________________
____

12. In the event of a volcanic eruption affecting your town, do you know what action you should take to help protect yourself and your family?
☐ 1 No
☐ 2 Yes *(please state)*______________________________
____

13. Have you made any plans to help protect yourself and your family in the event of an eruption?
(mark ☒ in more than one box if necessary)
☐ 1 No
☐ 2 Yes, purchased insurance
☐ 3 Yes, planned an evacuation route
☐ 4 Yes, stored emergency supplies of food and water
☐ 5 Yes, other *(please state)* ______________________________
____

14. What types of information have you had access to regarding what action you should take in the event of an eruption? *(mark ☒ in more than one box if necessary)*
☐ 1 None → *skip to 16*
☐ 2 Leaflet/pamphlet
☐ 3 Poster
☐ 4 Map
☐ 5 Community meeting
☐ 6 Radio/TV program
☐ 7 Other *(please state)* ______________________________

15. Please rate how useful you found the information:

☐ 1 Not at all useful☐ ☐ 2 Slightly useful
☐ 3 Quite useful ☐ 4 Very useful

16. Thinking about what you know about the volcano, where have you obtained this information from?

☐ 1 FEMA
☐ 2 Washington State Department of Emergency Management
☐ 3 County Department of Emergency Management
☐ 4 Mt Rainier National Park Service (NPS)
☐ 5 United States Geological Survey (USGS)
☐ 6 Cascades Volcano Observatory (CVO)
☐ 7 Newspapers
☐ 8 Television/radio
☐ 9 Internet
☐ 10 Family or friends
☐ 11 Other *(please state)* ________________________________

17. How would you rate the amount of information you have received about what you should do to help protect yourself and your family during an eruption?

☐ 1 Not enough
☐ 2 Enough
☐ 3 Too much

18. How prepared [are] do you think the authorities in your town to deal with a potential eruption?

☐ 1 Not at all prepared ☐ 2 Somewhat prepared
☐ 3 Quite prepared ☐ 4 Very prepared

19. How prepared [are] do you think the County Emergency Management Department to deal with a potential eruption?

☐ 1 Not at all prepared ☐ 2 Somewhat prepared
☐ 3 Quite prepared ☐ 4 Very prepared

20. How much trust do you have in each of the following to provide you with accurate information about future eruptions?

	None	Some	A lot	Complete
FEMA	☐ 1	☐ 2	☐ 3	☐ 4
Washington State DEM	☐ 1	☐ 2	☐ 3	☐ 4
County DEM	☐ 1	☐ 2	☐ 3	☐ 4
Mt Rainier NPS	☐ 1	☐ 2	☐ 3	☐ 4
Emergency Services	☐ 1	☐ 2	☐ 3	☐ 4
Scientists (USGS/CVO)	☐ 1	☐ 2	☐ 3	☐ 4
Media(TV/Radio/Newspaper)	☐ 1	☐ 2	☐ 3	☐ 4
Internet	☐ 1	☐ 2	☐ 3	☐ 4
Family/Friends	☐ 1	☐ 2	☐ 3	☐ 4
Church/Community Group	☐ 1	☐ 2	☐ 3	☐ 4

21. How well do you feel you would cope in protecting yourself and your family, if there were a volcanic eruption?

☐ 1 Not at all ☐ 2 Somewhat
☐ 3 Quite well ☐ 4 Very well

22. How well prepared do you think you are to deal with the effects of a potential volcanic eruption?

☐ 1 Not at all prepared ☐ 2 Somewhat prepared
☐ 3 Quite prepared ☐ 4 Very prepared

23. Do you have any family members living nearby?
    - ☐ 1 No → *skip to 25*
    - ☐ 2 Yes *(please state relationship)* ____________________________________

24. How often do you see them?
    - ☐ 1 Never
    - ☐ 2 Several times a year
    - ☐ 3 Once a month
    - ☐ 4 Once a week
    - ☐ 5 Every day

25. Do you belong to any social groups/organisations (e.g. sports, church, community)?
    - ☐ 1 No → *skip to 27*
    - ☐ 2 Yes *(please state)* ____

26. How often do you attend meetings/services with the above group?
    - ☐ 1 Never
    - ☐ 2 Several times a year
    - ☐ 3 Once a month
    - ☐ 4 Once a week
    - ☐ 5 Every day

27. The following statements might be said by people about their community. Please read each of the following statements and indicate if it is mostly true or mostly false about your own community by answering "true" or "false".
    (for each line mark ☒ in the box which best indicates your opinion)

	True	False
I think my community is a good place to live	☐ 1	☐ 2
People in this community do not share the same values	☐ 1	☐ 2
My neighbours and I want the same thing from the community	☐ 1	☐ 2
I can recognise many of the people who live in my community	☐ 1	☐ 2
I feel at home in this community	☐ 1	☐ 2
Very few of my neighbours know me	☐ 1	☐ 2
I care about what my neighbours think of my actions	☐ 1	☐ 2
I have no influence over what this community is like	☐ 1	☐ 2
If there is a problem in this community, people who live here can get it solved	☐ 1	☐ 2
It is very important to me to live in this particular community	☐ 1	☐ 2
People in this community generally don't get along with each other	☐ 1	☐ 2
I expect to live in this community for a long time	☐ 1	☐ 2

28. Gender ☐ 1 Male ☐ 2 Female

29. What is your age? ________________________ years

30. How would you describe your ethnicity?

☐ 1 White/Caucasian
☐ 2 Spanish/Hispanic/Latino
☐ 3 Black/African American
☐ 4 American Indian/Alaska Native
☐ 5 Other (*please state)* ____

31. What is your approximate annual household income (before deductions)?

☐ 1 Less than $20,000
☐ 2 $20,000 - $39,999
☐ 3 $40,000 - $59,999
☐ 4 $60,000 - $79,999
☐ 5 $80,000 - $99,999
☐ 6 more than $100,000

32. What is the highest degree or level of schooling you have COMPLETED?
(mark ☒ in ONE box only)

☐ 1 No schooling completed
☐ 2 12th Grade – no diploma
☐ 3 High school graduate *(high school diploma or equivalent)*
☐ 4 Associate degree *(for example: AA, AS)*
☐ 5 Bachelor's degree *(for example: BA, AB, BS)*
☐ 6 Master's degree *(for example: MA, MS, Meng, Med, MSW, MBA)*
☐ 7 Professional degree *(for example: MD, DDS, DVM, LLB, JD)*
☐ 8 Doctorate degree *(for example: PhD, EdD)*

33. Is the property in which you live:

☐ 1 Owned by you or someone in the household with a mortgage or loan?
☐ 2 Owned by you or someone in the household free and clear (without a mortgage or loan)?
☐ 3 Rented?
☐ 4 Occupied without payment of cash or rent?

34. Which best describes the type of property in which you live:

☐ 1 A mobile home
☐ 2 A one family house detached from any other house
☐ 3 A one family house attached to one or more houses
☐ 4 An apartment
☐ 5 Other *(please state)* ____

35. What is the approximate age of the property in which you live?

________________________________ years old

36. How much do you think your property would sell for if it were for sale?

☐ 1 Less than $50,000
☐ 2 $50,000 to $99,999
☐ 3 $100,000 to $149,999
☐ 4 $150,000 to $199,999
☐ 5 $200,000 to $299,999
☐ 6 $300,000 to $499,999
☐ 7 $500,000 or more

37. Please give the name of the street and town in which you live:

____

38. Please complete the following information for each person living in your home:

Relationship to you	Age	Gender (M or F)

39. Please read each of the following statements and describe the extent to which you agree or disagree with each:
(for each line mark ☒ in the box which best indicates your opinion)

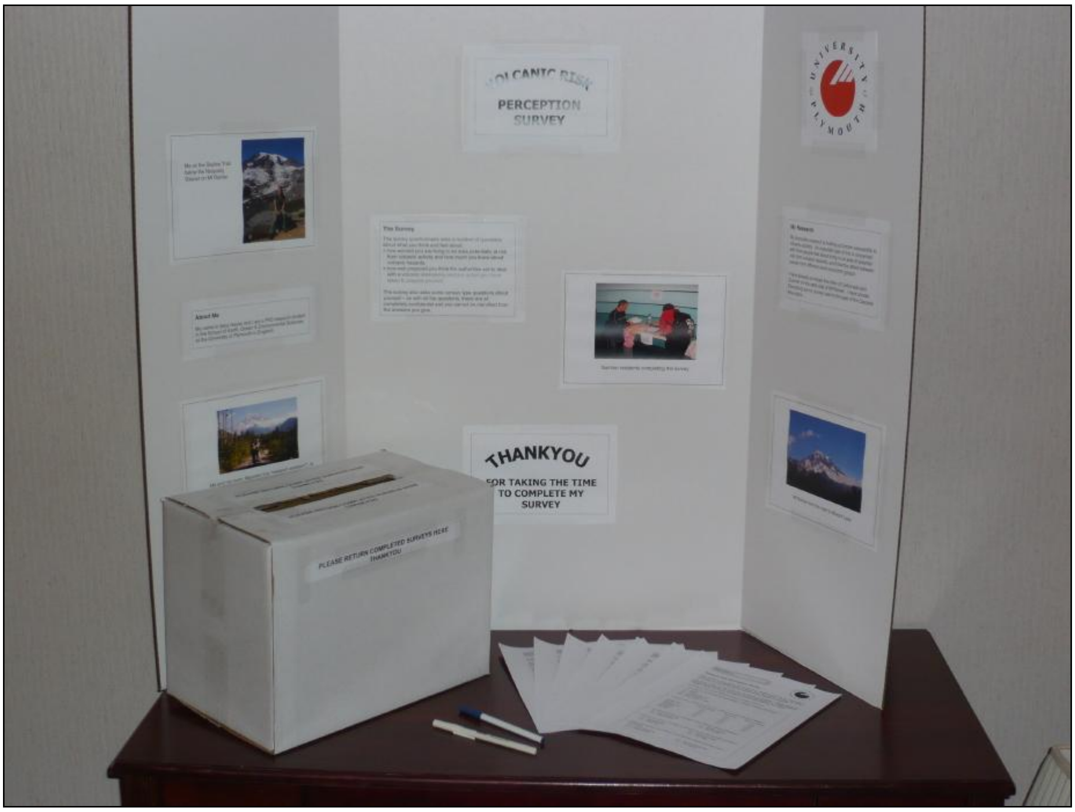
	Strongly agree	Slightly agree	Slightly disagree	Strongly disagree
An eruption poses a threat to my home or property	☐ 1	☐ 2	☐ 3	☐ 4
The effects from an eruption will be located far away from here and will have little impact on me	☐ 1	☐ 2	☐ 3	☐ 4
The authorities are doing all they can to help protect us from a future eruption	☐ 1	☐ 2	☐ 3	☐ 4
An eruption poses a threat to the personal safety of most residents in my community	☐ 1	☐ 2	☐ 3	☐ 4
I know enough about what to do in a volcanic emergency	☐ 1	☐ 2	☐ 3	☐ 4
The threat from a future volcanic eruption has been exaggerated	☐ 1	☐ 2	☐ 3	☐ 4
An eruption poses a threat to my personal safety	☐ 1	☐ 2	☐ 3	☐ 4
More work needs to be done by the scientists to fully understand the volcano	☐ 1	☐ 2	☐ 3	☐ 4
I don't need to make any preparations now because there will be lots of warning before an eruption	☐ 1	☐ 2	☐ 3	☐ 4
An eruption poses a threat to daily life activities (e.g. work, leisure) in my community	☐ 1	☐ 2	☐ 3	☐ 4
There wont be any long term effects from a volcanic eruption	☐ 1	☐ 2	☐ 3	☐ 4
The authorities are ready to respond to a volcanic eruption	☐ 1	☐ 2	☐ 3	☐ 4
An eruption poses a threat to the homes or property of most residents in my community	☐ 1	☐ 2	☐ 3	☐ 4
The scientists will be able to predict when an eruption is going to happen	☐ 1	☐ 2	☐ 3	☐ 4

THANK YOU VERY MUCH FOR YOUR TIME AND ASSISTANCE IN COMPLETING THIS SURVEY

APPENDIX 8: DETAILS OF KEY PSYCHOLOGICAL INDICATORS

Vulnerability Indicator	**Scale alpha**	**Survey Item**	**Description**
(i) Risk perception	.811	Q1, Q3, Q4, Q5, Q6	- time spent thinking about hazard - level of worry about hazard - rating likelihood and severity of future eruptions - rating likely effects and severity for community and for self/family
(ii) Self-efficacy	.769	Q21, Q22	- rating ones ability to protect ones self/family in the event of a volcanic eruption
(iii) Trust	.871	Q20	- rating level of trust in official sources of information
(iv) Access to information	.572	Q14	- number of sources of information accessed about what to do in the event of an eruption
(v) Preparedness	.678	Q13	- number of protective measures already adopted
(vi) Understanding of risk	.640	Q9	- discrepancy score between subject's risk rating for different hazards and the threat assessment rating
(vii) Appropriate action	n/a	Q12	- knowledge of appropriate response to volcanic activity based on current mitigation advice for their given location

APPENDIX 9: PHOTOGRAPHS OF US SURVEY METHODOLOGY



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