Standardising the USGS volcano alert level system: acting in the context of risk, uncertainty and complexity

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I, Carina Jacqueline Fearnley confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Standardising the USGS Volcano Alert Level System: acting in the context of risk, uncertainty and complexity.

A volcano alert level system (VALS) forms a key component of a volcano early warning system, which is used to communicate warning information from scientists to civil authorities managing volcanic hazards. In 2006, the United States Geological Survey (USGS) standardised its VALS, replacing all locally developed systems with a common standard. The emergence of this standardisation, and resulting implications, are charted here, in the context of managing the scientific complexities and diverse agencies involved in volcanic crises. The VALS concept embodies a linear reductionist approach to decision-making, designed around warning levels that correspond to levels of volcanic activity. Yet, complexities emerge as a consequence of the uncertain nature of the physical hazard, the contingencies of local institutional dynamics, and the plural social contexts within which each VALS is embedded, challenging its responsiveness to local knowledge and context. Research conducted at five USGS managed volcano observatories in Alaska, Cascades, Hawaii, Long Valley, and Yellowstone explores the benefits and limitations standardisation brings to each observatory. It concludes that standardisation is difficult to implement for three reasons. Firstly, conceptually, natural hazard warning systems are complex and non-linear, and the VALS intervenes in an overall system characterised by emergent properties and the interaction of many agents, for which forecasting and prediction are difficult. Secondly, pragmatically, the decision to move between alert levels is based upon more than volcanic activity and scientific information, with broader social and environmental risks playing a key role in changing alert levels. Thirdly, empirically, the geographical, social and political context to each volcano observatory results in the standardised VALS being applied in non-standard ways. It is recommended that, rather than further defining a standardised linear product, VALS should focus on developing systems based upon processes and best practice designed to facilitate communication and interaction between scientists and users in context.

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List of symbols, abbreviations and nomenclature

AFM	Acoustic Flow Monitor
AVO	Alaska Volcano Observatory
CAA	Civil Aviation Authority
CAP	Common Alerting Protocol
CAS	Complex Adaptive System
CDMG	California Division of Mines and Geology
CUSVO	Consortium of U.S. Volcano Observatories
CVO	Cascades Volcano Observatory
DHS	Department of Homeland Security
DM	Deliberative Mapping
DOI	U.S. Department of Interior
EAS	Emergency Alert System
EWS	Early Warning System
FAA	U.S. Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GST	General Systems Theory
HVO	Hawaii Volcano Observatory
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IAVW	International Airways Volcano Watch
ICAO	International Civil Aviation Organisation.
IDNDR	International Decade for Natural Disaster Reduction
ISDR	International Strategy for Disaster Reduction
KVERT	Kamchatka Volcanic Eruption Response Team
LVO	Long Valley Volcano Observatory
MCM	Multi-Criteria Mapping
NIMS	National Incident Management System
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice To Airmen
NVEWS	National Volcano Early Warning System
NWS	National Weather Service

OSHA	Occupational Safety and Health Administration
PNS	Post-Normal Science
PPW	Partnership for Public Warning
QDA	Qualitative Data Analysis
SCOT	Social construction of technology
SIC	Scientist in Charge
SIGMET	Significant Meteorological Information
SSK	Sociology of scientific knowledge
UAF	University of Alaska Fairbanks
UAFGI	University of Alaska Fairbanks Geophysical Institute
UN	United Nations
UNDHA	United Nations Department of Humanitarian Affairs
UNISDR	United Nations International Strategy for Disaster Reduction
U.S.	The United States of America
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Centres
VALS	Volcano Alert Level Systems
VAN	Volcanic Activity Notice
VAWSG	Volcanic Ash Warnings Study Group
VDAP	Volcano Disaster Assistance Program
VEWS	Volcano Early Warning System
VHP	Volcano Hazard Program
VONA	Volcano Observatory Notices for Aviation
WMO	World Meteorological Organization
WOVO	World Organisation of Volcano Observatories.
YVO	Yellowstone Volcano Observatory

It is in the admission of ignorance and the admission of uncertainty that there is a hope for the continuous motion of human beings in some direction that doesn't get confined, permanently blocked, as it has so many times before in various periods in the history of man.

Richard P. Feynman

Chapter 1. Introduction

The explosive eruption of Eyjafjallajökull volcano in southern Iceland on 15-20 April 2010 caused an unprecedented closure of UK, European, and North Atlantic air space, grounding commercial flights in many parts of the world. Once the relatively small volcanic eruption pierced its overlying glacier, it resulted in an explosive phreatomagmatic eruption (triggered by water-magma interaction), generating significant quantities of ash that covered most of Europe, trapped by unusual weather patterns. The decision to close commercial airspace followed international protocols that guided responses to the presence of volcanic ash clouds along established flight paths (Prata and Tupper, 2009, p.305, ICAO, 2004). These guidelines were developed following two significant aircraft encounters with ash in regions prone to explosive volcanic activity. In 1982, a British Airlines Boeing 747 lost all four engines flying though the volcanic plume of Mt. Galunggung in Indonesia falling over 7 kilometres before restarting the engines (Miller and Casadevall, 2000). Shortly after in 1989, during the eruption of Mt. Redoubt in Alaska, another 747 also had full engine failure, restarting them only minutes before colliding with mountains, and costing US$80 million in damage to the aircraft; the second costliest volcanic eruption after Mt. St. Helens in 1980 (Neal et al., 1997, Casadevall, 1994, Brantley et al., 1990). Since these near-disasters, the aviation industry has worked for over thirty years to develop internationally standardised protocols and procedures to prevent aircraft encountering ash (Casadevall et al., 1994). A policy of 'if ash, no fly' was adopted internationally by the International Civil Aviation Organisation (ICAO) (ICAO, 2004). However, this policy was eventually disregarded during the Eyjafjallajökull ash crisis, raising fundamental questions, discussed later, about the application of standardised protocols in volcanic ash hazard management.

According to the International Air Transport Association (IATA), the cost of the flight ban of 15-20 April to the European aviation industry is estimated at over £1.1billion (IATA, 2010) without taking into account the wider costs to the European economy, loss to travel companies, and the chaos caused for travellers globally. The ICAO standardised rule of 'avoiding ash' generally assumes that aircraft can divert or re-route and still access the country of destination, as is commonly done when volcanoes erupt in Alaska. However, in Europe, the context is completely different, with crowded flight paths and small countries that can be 'locked in' by disperse ash clouds. In retrospect, it is clear that the development of standardised protocols did not consider significant economic loss resulting from closure of large air spaces over many countries, or the realisation that countries that do not host active volcanoes can be extensively affected by volcanic activity. The initial response of UK aviation agencies relied heavily on international protocols developed from experience elsewhere as decision-makers were unfamiliar with volcanic activity. This initial response was later modified, however, resulting in the UK Civil Aviation Authority (CAA), changing the protocols to accommodate changes in perception in relation to flight through dilute ash clouds.

It took nearly three decades to establish a sophisticated volcanic ash plume / cloud warning system therefore, it is no surprise that there was scepticism and concern that, within three weeks of the Eyjafjallajökull event, the CAA established a ‘safe’ concentration of ash and removed the buffer zone based on 'evidence gathering', when this had not been achieved in thirty years (CAA, 2010b, CAA, 2010a, CAA, 2010c). The composition, size and reactivity of ash is different for each volcano, making it difficult to establish how much ‘ash’ damages aircrafts and their engines, and the effects of different levels of exposure to ash on aircraft engines. The distinct lack of scientific information to enable a quantitative ‘risk assessment’ is precisely why, historically, a precautionary approach had been adopted by the aviation sector. However the effect of adopting the precautionary approach during the Eyjafjallajökull eruption by closing European airspace was more than a financial inconvenience; it raises a number of fundamental questions relating to internationally standardised early warning systems (EWS) for aviation and ash hazards:

i. What are the roles of social and economic risk factors in managing natural hazards?
ii. How are decisions made in complex, uncertain and risky situations, particularly when there are issues of accountability?
iii. How efficient are standard protocols if they do not consider local contexts?

It is important that these questions are addressed, not only for the aviation sector who will review how effective their standardised early warning system is for ash hazards, or for the UK and Europe to be better prepared for future ash clouds in their airspace, but also because early warning systems are becoming increasingly standardised, it seems, with inadequate knowledge of the consequences. To address these concerns, this thesis charts the emergence and implications of the standardisation of Volcano Alert Levels Systems (VALS) as a strategy for managing the scientific complexities and diverse agencies involved in volcanic crises. VALS are a key component of a volcano early warning system (VEWS), used to communicate warning information from scientists to civil agencies managing volcanic hazards. The thesis focuses on the VALS standardised by the United States Geological Survey (USGS) in 2006 and applied at all five of their volcano observatories in the United States (U.S.). The standardised VALS replaced three different locally developed VALS that existed at three volcano observatories, with a common standard, including the internationally adopted VALS for ash hazards used during the Eyjafjallajökull eruption. This thesis thus is a timely investigation into the aforementioned questions: the role of social and economic factors in managing hazards, decision-making in uncertainty, and the function of standardisation in the use and apparent effectiveness of VALS.

In this introductory chapter, the problems that volcanic crises present are addressed, demonstrating the need for mitigatory actions such as EWS to help mobilise scientific knowledge to prevent loss of life and reduce socio-economic impact. In addition, the research objectives of this thesis are justified, alongside the reasoning underpinning the choice of case study, the United State Geological Survey (USGS). Finally, the arguments proposed in this thesis are introduced and presented along with the key research questions.

1.1 Volcanoes and Society

If the management of a volcanic crisis is unsuccessful, the resulting disaster can cause significant loss of life, socio-economic impact, and damage to the environment. This section reviews the hazards volcanoes produce, their power to kill large populations and cause considerable socio-economic losses, why people live near to volcanoes, and how scientists try to understand volcanic behaviour to provide warnings by establishing volcano observatories that use EWS to reduce the impact of volcanic activity on society.

1.1.1. The impacts of volcanic activity on society

Volcanic activity can produce a range hazards arising from both fall (ash, ballistics) and flow processes (pyroclastic flows, surges, lateral blasts, debris flows / lahars, floods and lava flows), to volcanic gases, earthquakes and tsunamis (Francis and Oppenheimer, 2004), driven by the unique combination of underlying geochemical and geophysical processes, and tectonic location (Sigurdsson and Houghton, 2000). All these hazards have potential to kill and affect people's livelihoods, while post-eruption erosion and sedimentation can lead to disruption of existing systems of provision and sanitation, contributing to famine and disease.

Over the last century, one incident in particular stands out as an anomaly; the tragedy that struck Armero, Columbia in 1985 when a small eruption at Nevado del Ruiz generated a lahar that killed over 25,000 inhabitants. Despite numerous recent large eruptions including the Mt. St. Helens in Washington State, U.S. in 1980 and Mt. Pinatubo in the Philippines in 1991, Nevado del Ruiz stands out as tragedy because, rather than a failure of scientific knowledge or technology, local government and decision-makers failed to act on warnings issued by scientists monitoring the volcano (Barberi et al., 1990). It was caused 'purely and simply, by cumulative human error - by misjudgement, indecision and bureaucratic short-sightedness' (Voight, 1990, p.383). This event highlighted the limitations of scientific knowledge in preventing volcanic disasters, and resulted in a paradigm shift within the volcanological community towards developing an understanding of local contexts when issuing volcanic warnings. More than 20 years later, major disasters caused by natural hazards are still occurring; also not because of unclear scientific evidence or advice, but due to failures in other areas. Examples are the failure to have an EWS in place for the 2004 Boxing Day tsunami (UN ISDR PPEW, 2006); neglect of civil defences and full consideration of risks involved in Hurricane Katrina, 2005 (Select Bipartisan Committee, 2006); and the 2010 earthquake of Chile that scientific studies had anticipated (Ruegg et al., 2009). The consequences of not having a EWS can be very costly and damaging to local cultures.

Measuring the real socio-economic impacts of volcanic hazards is difficult since the effects can take years to occur and are often difficult to isolate from other social or political events. Sometimes the impact is visible and in some cases quantifiable, as exemplified by the ongoing eruptions of the Soufriere Hills volcano in Montserrat, which has resulted in the permanent evacuation of the capital city of Plymouth and two-thirds of the island's population (Aspinall et al., 1998, Druitt and Kokelaar, 2002, Young et al., 1998). The Emergency Disasters Database (EM-DAT) archives essential data from 1990 to present, on the occurrence and effects of over 18,000 mass disasters, defined as when so many persons are injured that local emergency medical services may be overwhelmed. Their data includes total number of people affected by volcanic activity (see Table 1.2) and economic costs (Table 1.3).

Country	Year	Number of Total Affected
Mt. Pinatubo, Philippines	1991	1,036,065
Cerro Negro, Nicaragua	1992	300,075
Tungurahua, Ecuador	2006	300,013
Galunggung, Indonesia	1982	300,000
Merapi, Indonesia	1969	250,000
Mt. Karthala, Comoros	2005	245,000
Mayon, Philippines	1993	165,009
Rabaul, Papua New Guinea	1994	152,002
El Reventador, Ecuador	2002	128,150

Table 1.1 Top ten most important volcano disasters for the period 1900 to 2010 sorted by numbers of total affected people at the country level (EM-DAT, 2008)

Country	Year	Damage (000 US$)
Nevado del Ruiz, Colombia	1985	1,000,000
Mt. St. Helens, U.S.	1980	860,000
Mt. Pinatubo, Philippines	1991	211,000
Galunggung, Indonesia	1982	160,000
Tungurahua, Ecuador	2006	150,000
Colo, Indonesia	1983	149,690
El Chichón, Mexico	1982	117,000
Rabaul, Papua New Guinea	1994	110,000
Usu, Japan	1945	80,000

Table 1.2 Top ten most important volcano disasters for the period 1900 to 2010 sorted by economic damage costs at the country level (EM-DAT, 2008)
N.B Damage is the cost that corresponds to the damage value at the moment of the event, i.e. the figures are shown true to the year of the event

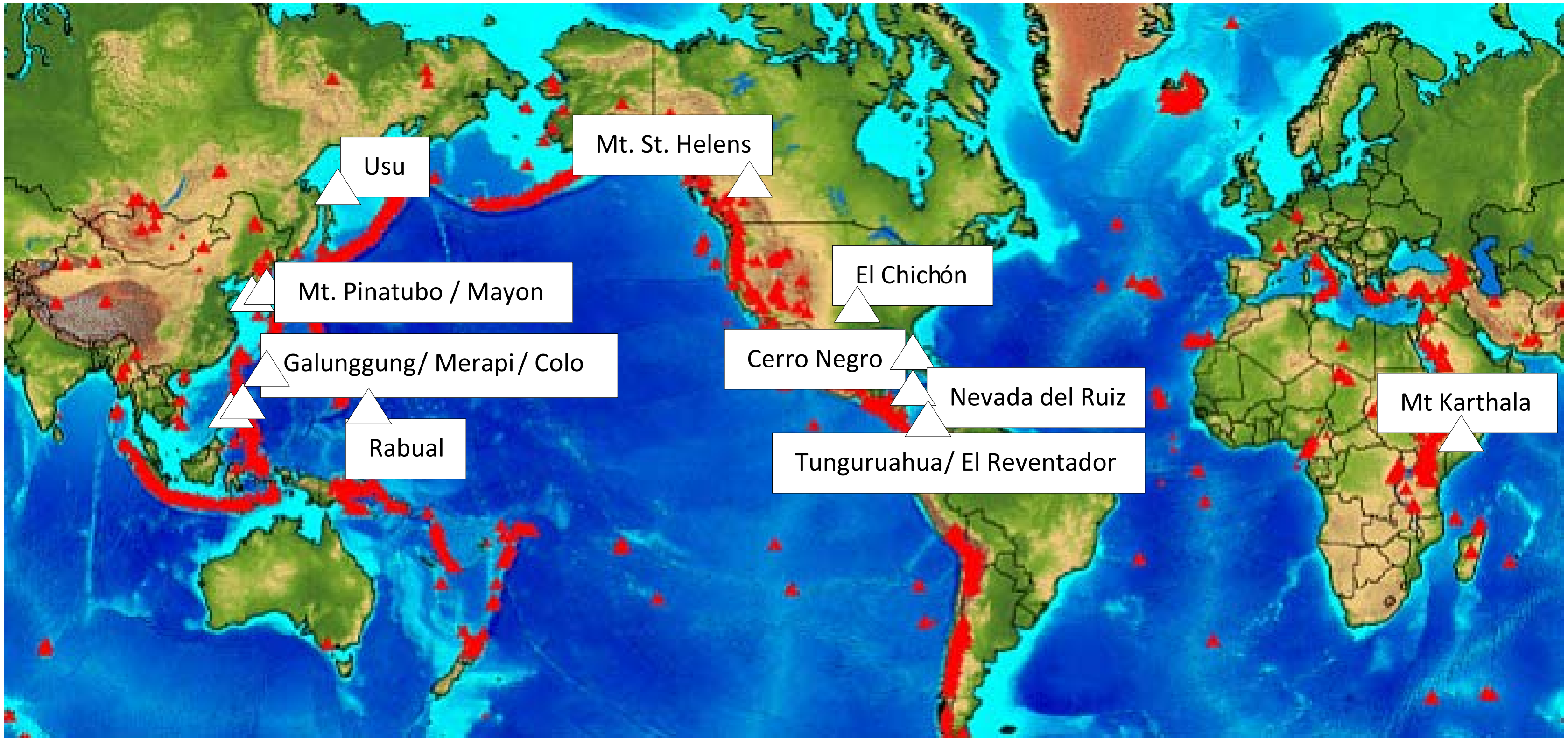

Figure 1.1 Location of the volcanoes listed in Table 1.2 and 1.3. Image courtesy of Smithsonian Institute Global Volcano Program.

Although more than 350 people died as a result of the Mt. Pinatubo eruption (see Table 1.1), Table 1.2 indicates that it affected over one million people, many of whom were saved by evacuations (discussed below), however it was also an extremely costly disaster (Table 1.3). The U.S. suffered considerable economic losses as a consequence of the burial of Clark Air Base (Philippines) under several metres of ash (Newhall and Punongbayan, 1997), as well as from the 1980 eruption of Mount St. Helens (Washington State) that killed over sixty people and levelled the surrounding area (Foxworthy and Hill, 1982). The data from EM-DAT reveal that volcanic hazards continue to affect large populations and cause significant economic losses. This data does not include the Eyjafjallajökull eruption, which as mentioned previously cost over £1.1billion in lost business for the aviation sector in Europe alone (IATA, 2010). It is very difficult to determine the true economic cost of volcanic hazards as it depends of a number of factors relating to ‘the precise nature of volcanic activity; the timing of various eruptive phases relative to climatic seasons and agricultural and other cyclical economy (e.g. tourism); population density and types of economic significance for the rest of the country’ (Benson, 2005), as well as secondary impacts generated by the volcano’s activity. Whilst only 0.02% of deaths from disasters in 2006 were the result of volcanic activity (Hoyois et al., 2007), often secondary volcanic hazards such as tsunamis or debris flows generated by volcanic activity are classified under different hazard categories. Therefore, volcanic disaster figures, such as those from EM-DAT, sometimes do not capture the often-devastating consequences of volcanic activity and consequently volcanoes should still be regarded as potentially large killers. Benson (2005) suggests that relating the damage to the Gross Domestic Product of the Country at the time of event can be a more accurate measure of cost.

Increased global trading, growing economies, and ever-expanding critical infrastructure make the function of society more vulnerable to volcanic hazards, even those that occur remotely, as exemplified the Eyjafjallajökull ash crisis in Europe. Given the movement of people from rural areas to cities, Chester et al (2000, p.89) argue that that ‘urbanisation, particularly in developing countries, has led to increasing global exposure to a variety of natural hazards, not the least of which are risks posed to large cities by volcanoes’. Volcanic hazards can destroy or reduce the facilities that enable business, infrastructure, and commerce to function. Economic damage potential is not just confined to populated areas; agricultural lands can be damaged, and essential infrastructure such as pipelines, electricity, rail lines and communication cables can be destroyed causing regional and national disruption (Keys, 2007). The aviation sector is particularly vulnerable to ash, often from remotely located volcanoes that can result in millions of pounds worth of damage to aircraft and place the lives of the passengers in danger (Miller and Casadevall, 2000). Ash can also present severe health concerns such as respiratory problems or poisoning to local or distal populations (Baxter, 2004). Thus whilst absolute loss of life in volcanic disasters have reduced, they are still the cause of considerable disruption.

There are currently 1,511 known active volcanoes globally (volcanoes known to have erupted during the Holocene (the last 10,000 years) (Simkin and Siebert, 1994)) with over 10 per cent of human population living within close proximity to an active volcano (Francis and Oppenheimer, 2004, McGuire and Kilburn, 1997). Given the unpredictable nature of volcanoes and their hazards, it is difficult to manage crises at volcanoes where large populations live in close proximity. Unfortunately, rising populations, particularly within large urban areas near active volcanoes such as Mexico City (Popocatepetl) and Tokyo (Mt. Fuji), increase the exposure of these populations to volcanic hazards. These hazards can have significant impacts on differing spatial and temporal scales. Populations, tens to hundreds of kilometres away from volcanoes, can remain unaware of volcanic activity, yet be devastated by lahars, mudflows, debris flows (Mothes et al., 1998, McGuire and Kilburn, 1997), or ashfall (Tilling et al., 1990). On a global scale, the emission of sulphur gases can cause global cooling (Newhall and Punongbayan, 1997, McGuire, 2002). What defines a vulnerable population, in the context of volcanic activity, depends upon the characteristics of the potential hazards, the geographical location of the population, and meteorological conditions at time of the hazard's activity as rainfall, snow and high winds can exacerbate problems (Sigurdsson and Houghton, 2000). In some respects, humanity has been lucky during the last century since many recent large eruptions occurred in uninhabited regions such as the 1912 eruptions of Katmai volcano (Alaska), and the 1955-6 eruptions at Bezymianny (Kamchatka, Russia). In contrast, there were three episodes of major caldera unrest at Long Valley (U.S.) 1980-4, Campi Flegrei (Italy) 1982-4, and Rabaul (Papua New Guinea) 1983-5, that did not result in eruptive activity, yet caused major social and economic disruption; including the evacuation of 40,000 people at Campi Flegrei (Chester et al., 2005, Tilling and Lipman, 1993).

Despite the damage potential of volcanic hazards, human settlements continue to grow on and around volcanoes, attracted by potentially fertile soils, a more pleasant climate, reservoirs for the storage of ground waters, high scenic values, tourism, and sources of heat and mineral resources. Often, many do not realise the mountain they live near is a volcano, and those that do may be willing to take the risk based upon past frequencies and scales of eruption. There are both demands and benefits in relation to mitigating against volcanic hazards as fully as possible, driven by both vulnerable populations and government authorities. Conversely, given the existing advantages of living within a volcanic area, there can be a perception that too much money is being spent on a precautionary approach for a hazard that is unlikely to occur within the population's lifetime, or even within the next thousand years. Therefore, not only is knowledge of volcanic behaviour uncertain, but also divergent attitudes to risks in different contexts (Slovic, 2000), make it difficult to prevent building or developing lands that may be identified as hazardous.

1.1.2 Mitigating against volcanic hazards

Since 10 percent of the human population lives on and around volcanoes, there is a need to reduce the risks that volcanic hazards pose. Historically this has been accomplished using traditional disaster preparedness and mitigative actions, commonly used in natural hazard disaster management. Following a number of volcanic crises, some handled successfully; others not, groups of scientists began thinking about how best to manage volcanic risk drawing on lessons learnt. In 1989, Tilling designed an effective program of volcanic hazard mitigation. Based on a foundation of basic studies of physical processes, the program recommends volcano monitoring and research programs to understand a volcano's behaviour. This program also promotes integration between scientists and civil authorities, and the responsibilities that each have, since government bodies have to consider socio-economic and political factors in addition to scientific information in order to make decisions relating to volcanic activity (Fig. 1.1) (Scott and Tilling, 1989, Tilling et al., 2003, Tilling, 1989). One key aspect of mitigation involves educating the local population via outreach programs that teach about the physical hazard, and the appropriate responses relevant for each hazard.

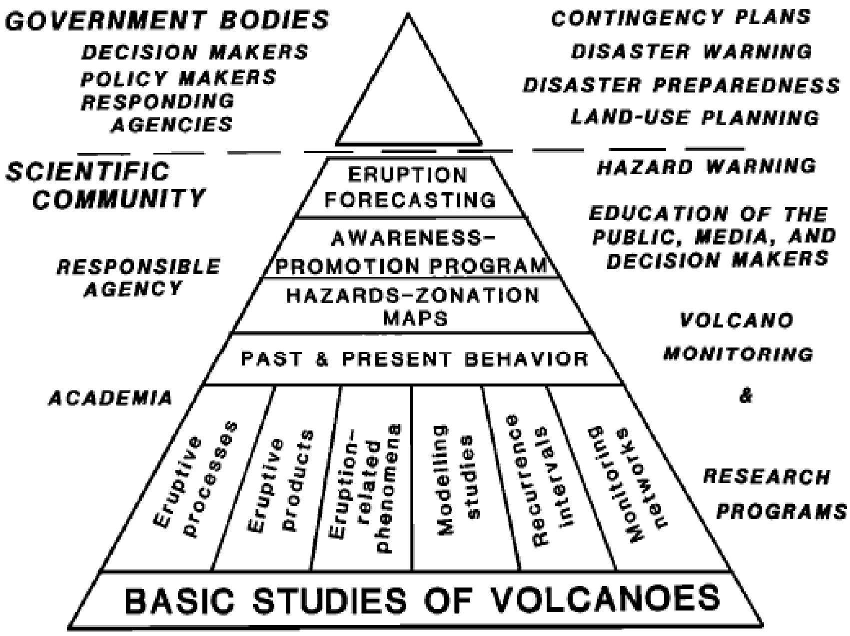

Figure 1.2 Volcano hazard mitigation (Tilling, 1989, p.242)

Five specific measures have been identified (Tilling, 1989) to provide short or long-term mitigation: identification of high-risk volcanoes; hazard identification, assessment and zonation; volcano monitoring and eruption forecasting; engineering-oriented measures, and volcanic emergency management (Table 1.4). In the case of volcanic hazards most mitigation measures involve developing a foundation of knowledge relating to the volcano's behaviour and a programme of monitoring. It is important to note that the critical role of volcanic emergency management is identified as undervalued, partly because of the complexities of society. This suggests that although mitigatory actions are useful, it is important that they are integrated with emergency practitioners during a volcanic crisis, and highlights the importance of local context at such times.

	Mitigation of Volcanic Risks	Description of associated processes
1	Identification of high-risk volcanoes	Only a small fraction of known active volcanoes have been studied in detail. A number of the world's largest and most dangerous volcanoes occur in densely populated countries with limited economic and scientific resources and a lack of political will to study and monitor them.
2	Hazard identification, assessment and zonation	Reconstructing a volcano's past eruptive behaviour and events can provide the basis for assessing potential hazards for future eruptions. Hazard zonation maps are useful tools for decision-makers and land use planners. GIS has helped to make maps more accessible.
3	Volcano monitoring and eruption forecasting	Short-term eruption forecasts are still predominantly made on seismic and ground deformation data alone. However, optimum monitoring is achieved by integrating a combination of approaches, rather than just relying on any one precursor.
4	Engineering-orientated measures (mitigation)	Volcanic eruptions cannot be controlled, however some hazards can be mitigated or tempered by engineering methods, or structures to reduce impact or extent of damage. To date, engineering countermeasures have mitigated lava and debris flows, floods, and ash fall on buildings.
5	Volcanic emergency management	Emergency management plays a critical role in coping a volcanic crisis, yet receives little attention. This is understandable given that volcanic hazards occur infrequently relative to human life span and to other hazards, and the demands of an increasingly complex society.

Table 1.3 Mitigation of volcanic risks (compiled from Tilling, 1989)

In 1993, Chester also acknowledged the role of social contexts as a contributing factor to volcano crises by reviewing developed and underdeveloped world responses during low magnitude / high frequency and high magnitude / low frequency events (Fig. 1.2). From this study Chester highlights the importance of understanding the vulnerability of affected populations and that bottom-up approaches should be adopted in the development of plans, so local people have ownership over mitigatory activities.

DEVELOPMENT LEVEL

PHYSICAL CHARACTERISTICS	DEVELOPED RESPONSE	UNDERDEVELOPED RESPONSE
High magnitude / low frequency	Examples include: Mount St. Helens, USA (1980) Ruapehu volcano, New Zealand, (1953)	Examples include: El Chichón, Mexico (1982) Agung, Indonesia (1963-64) Arenal, Costa Rica (1968)
Low magnitude / high frequency	Heimaey, Iceland (1973) Mount Etna, Sicily (1983) Kilauea, Hawaii (many)	Nyiragongo, Zaire (1977) Karthala, Comores, Indian Ocean (1972)

Figure 1.3 A classification of responses to historical eruptions based on the physical characteristics of the eruption and the level of economic development attained by the country in question (Chester, 1993, p.247)

Since the 1980 eruption of Mt. St. Helens there have been significant advances in the development of mitigatory approaches and techniques for volcanic hazards, predominantly driven by improvements in instrumentation, data collection and transmission resulting in better data analysis and interpretation, facilitating more refined techniques of volcano monitoring and eruptive forecasting[1] (discussed further in chapter 2). A majority of this progress is the result of improved computer, satellite, data storage and telemetric technologies. Regardless of these advances, they need to be incorporated via 'contingency planning and effective communication between scientists and authorities' to improve warnings (Tilling, 1989, p.237). Volcano observatories typically bring together different mitigatory activities in relation to volcanic hazards and their potential consequences.

[1] Forecasting and prediction are often considered synonymous; however, it is recommended to adopt the following definitions. A forecast is a comparatively imprecise statement of the time, place, and nature of expected activity. Prediction is a comparatively precise statement of the time, place and ideally, the nature and size of impending activity. SWANSON, D. A., CASADEVALL, T. J., DZURISIN, D., HOLCOMB, R. T., NEWHALL, C. G., MALONE, S. D. & WEAVER, C. S. 1985. Forecasts and predictions of eruptive activity at Mount St. Helens, USA: 1975-1984. *J. Geodynamics,* 3**,** 397-423.

1.1.3 The role of volcano observatories

A volcano observatory is essentially a facility wherein monitoring data are assembled and analysed in order to better understand a volcano's behaviour so as to provide warnings to populations that allow them to be better prepared for volcanic hazards. They range from small offices, manned by one person and with limited monitoring equipment, to highly sophisticated offices with a wide range of state-of-the-art monitoring equipment. The functions of a volcano observatory can be broken down into: i) *data collection* via the process of volcanic activity detection using various monitoring techniques; ii) *data analysis*: assessment and interpretation of data; iii) *forecasting:* establishing the volcano's status from the data analysis i.e. quiescent, restless or building to eruption; and in the latter case the likely timing, duration and climax of the eruption and the nature of associated hazards; iv) providing an *alert level* for the volcano's behaviour based upon discussion and consensus, and v) *research* relating to volcanic behaviour and the applicability and effectiveness of monitoring techniques, amongst other areas.

A volcano observatory forms a central focus for the monitoring of volcanic activity and communication, including with civil authorities and local government through emergency plan coordination, the media via, interviews and press releases, and the public, via education and outreach events. As well as the duty to provide warnings, a volcano observatory also provides a research environment. With large archives of monitoring data from previous volcanic activity, research is fundamental to the progress of volcanology and subsequently the ability to analyse data and provide accurate and detailed forecasts in a timely manner. Providing warnings with increased certainty enables civil authorities to make decisions that are more informed, however, many unknowns remain in relation to volcanic processes (see chapter 2) such that significant scientific uncertainties continue to present problems for volcanologists and civil authorities.

Most volcanoes located near large population centres will be subject to extensive monitoring to minimise loss of life or livelihood as much as possible, with civil authorities charged with communicating any changes in volcanic activity to a range of national, regional, and local stakeholders. The necessity to translate scientific knowledge into effective warnings for natural and man-made hazards has generated the need for early warning systems (EWS) that are designed to provide 'timely and effective information, through identifying institutions, that allow individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response' (UN ISDR, 2003). Typically, national governments designate a volcano observatory with the legal responsibility for the provision of warnings about volcanic hazards.

1.1.4 Volcano early warning systems

In many parts of the world, VEWS have been developed by volcanologists and government policy makers to provide warnings to populations at risk from volcanic hazards and to allow them to seek safety, both locally and regionally (Peterson et al., 1993). Key decision-makers, responsible for safety, environment, and socio-economic issues usually require information relating to: when and where the volcano will erupt; the magnitude, style and duration of the eruption; likely hazards and expected location; and the effect of volcanic hazards on the local, regional and global scale. In contrast to many other hazards, such as hurricanes or landslides, scientific understanding of volcanoes remains limited, making it difficult to address these questions. It is imperative to continue researching the processes involved in driving volcanic eruptions and the hazards produced to develop better warning signals and understand the consequences for each hazard (Scarpa and Tilling, 1996, Tilling, 2002). Given limitations in scientists' capability to forecast or predict volcanic activity, however, managing volcanic crises requires careful consideration and understanding of how to take action in the context of uncertainty, both scientifically and socially (Leonard et al., 2008). To operate effectively, a VEWS should therefore be fully integrated to cover everything from monitoring and detection, to analysis and interpretation of the data, to communication and the generation of an effective response.

Despite growing populations near to volcanoes, little research has been devoted to establishing best practice for VEWS to minimise loss of life and socio-economic damage prior to and during volcanic crises. Volcano-related disasters show that the effectiveness of VEWS has been, and continues to be, hindered by institutional weaknesses in: procedures and infrastructures, poor integration and sharing of knowledge between scientists and community, and ineffective communication (Peterson et al., 1993). In addition, the relative impacts of these factors on the effectiveness of VEWS are not fully understood.

Generating effective warnings is particularly challenging for a few key reasons. First, volcanologists and related scientists are still developing theories to understand the origin, processes and eruptive behaviour of volcanoes and their numerous associated hazards. Second, volcanic hazards occur within different social contexts involving different cultures, economic and political circumstances. In addition, volcanic activity tends to occur over long time frames relative to human time-scales and, in particular, periods of political office, and therefore are not normally a political priority. This commonly results in limited funding and resources for research and volcano observatory upkeep, leading to limited volcanic hazard awareness. Finally, institutional influences can lead to increasing levels of bureaucracy so that decisions become complex and take a long time to make. Managing a volcanic crisis can involve numerous institutions making it difficult to maintain communication, both internally and externally. Tilling states that ‘few would dispute that volcanology has arrived as a modern science; yet for me, nagging questions persist about successful application of the science to societal problems. Have the advances in volcanology been fully translated into advances in hazards mitigation?’ (1989, p259). This ‘nagging’ feeling is based both on his personal experiences and historical examples of volcanic crises wherein the failure to provide an effective warning to local decision-makers and vulnerable populations so to prevent or minimise loss of life and reduce economic loss using a VEWS, has been the result of 'societal problems’, rather than a consequence of poor scientific knowledge or certainty in the understanding of the volcano's activity; despite advances in hazard mitigation. Chapter 2 discusses further the influence of 'societal' problems' on the failure of VEWS by demonstrating the influence of political interference at Mt. Pelée, Martinique, 1902 (Scarth, 2002), miscommunication between the scientists and the media in Guadeloupe, 1976 (Fiske, 1984), interactions between scientists and authorities in Montserrat (1995-present) (Druitt and Kokelaar, 2002), and differing levels of trust and understanding of the uncertainties and risks involved in volcanic crises (Haynes et al., 2008a, Haynes et al., 2008b) and the ability for VEWS to successfully fulfil their purpose (Peterson et al., 1993). The case studies outlined support Peterson and Tilling’s (1993) assertion that, hand-in-hand with advances in scientific understanding, understanding the interface between science, decision-making and communication amongst a wide range of public bodies, is critical to reducing volcanic risk. Therefore, although critical evaluation of volcanic crises research has historically focused on the limitations of science, there needs to be further exploration of the social and institutional aspects involved.

1.1.5 Volcano alert level systems and standardisation

A Volcano Alert Level System (VALS) is the part of a VEWS that relates to the processes occurring before and during the issuance of a volcano warning. The United States Geological Survey (USGS) defines a volcano warning as a ‘series of levels that correspond generally to increasing levels of volcanic activity’ (Gardner and Guffanti, 2006). As a volcano becomes increasingly active towards eruption, a higher alert level is issued that offers the public and civil authorities a framework they can use to gauge and coordinate their response to a developing volcanic emergency. VALS are based on a linear design, where the alert level assigned is directly proportional to the volcanic activity. In addition, alert levels carry information from the observatory to those who use it in a uni-directional, manner. Globally, many VALS (also referred to as status levels, condition levels, or colour codes) are used providing volcanic warnings and emergency information in relation to volcanic unrest and eruptive activity based on data analysis or forecasts. Yet, there are only two identified papers that discuss VALS in the context of their role, operation, limitations and benefits (De la Cruz-Reyna and Tilling, 2008, Metzger et al., 1999). VALS remain a 'black box', a concept developed by Bruno Latour, where the inputs and outputs are known but the inner workings remain hidden and are no longer open for debate because they have been accepted by the scientific community and then society alike (1987). Latour stated that this is 'the way scientific and technical work is made invisible by its own success. When a machine runs efficiently, when a matter of fact is settled, one need focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become' (Latour, 1999, p304). VALS are superficially simplistic (one reason they are so easy to black box) and so tend to be treated as such, but they encompass a number of complex issues with a range of physical, social and institutional dynamics as just described. By opening the black box, through establishing how they function in the context of the USGS, this research looks at how these complexities are managed and, sometimes, how they are excluded from these warning tools.

In 2006, the United Nations conducted a Global Early Warning Survey that resulted in five key recommendations, including one to 'develop a globally comprehensive early warning system, rooted in existing early warning systems and capacities' (UN ISDR PPEW, 2006, p.vi). Consequently, VALS in a number of countries (including Japan, New Zealand, the Philippines and the U.S.) have been standardised at a national level so that a single VALS is used for all ground based volcanic hazards. The advantages are provision of consistent warnings for civil authorities required to take action and facilitation of national policies for emergency management. As earlier highlighted, however, the Eyjafjallajökull ash crisis raised important questions about the applicability of standardised VEWS and VALS when operating within local and novel contexts, and the overall robustness of standardisation as a strategy in managing such complexity. It is clear this conflict warrants further investigation. This research thus adds to the understanding of specific functions of the VALS, but also aids the development of broader understanding of the issues involved in managing complex hazards.

1.2 Research objectives

1.2.1 Research questions

In summary, volcanoes are a complex and dangerous phenomena, which, despite many decades of research, leave many scientific questions unanswered. During a volcanic crisis there is a need to protect lives, infrastructure, and the socio-economic fabric of areas at risk. To do this VEWS and VALS have been developed as tools to provide effective warnings to limit loss and disruption. Historically, as discussed further in chapter 2, when VEWS have failed to provide an effective warning (see section 1.1.4) it has frequently been the consequence, not of deficiencies related to of scientific knowledge despite all the uncertainties, but to a lack of consideration of pertinent social contexts and weaknesses in decision-making and communication, highlighting the fact that local context is often critical. Yet many countries are now standardising their VALS in response to the UN's recommendation to develop a global platform for EWS. The 2010 Eyjafjallajökull ash crisis raises questions about the applicability of standardised VALS on a global scale because it was unable to accommodate local context. Therefore, the question arises: ***to what extent are linear, standardised VALS an effective warning tool for volcanic hazards in different contexts of complexity, uncertainty and risk?*** This study addresses this over-arching query through seeking to answer three constituent questions that examine the issues of using VALS to manage complexity, decision-making, and communication that emerge from the literature review in chapter 2.

1. Why and with what implications did a <u>linear VALS</u> emerge as a tool for <u>managing complex</u> volcanic hazards?
2. How are <u>decisions</u> made using the standardised VALS given contexts of complexity, uncertainty and risk?
3. Does the standardised VALS function effectively in <u>communicating</u> information about hazardous volcanic behaviour to a range of users?

In addressing these questions, the USGS VALS is selected as forming the most appropriate case study.

1.2.2 Introducing the USGS volcano alert level system

This study seeks to demonstrate that the current lack of research surrounding the effectiveness of VALS necessitates the development of a deeper understanding in relation to standardising or adopting frameworks for VALS. The chosen case study lends itself best to a detailed analysis of the standardisation process, in relation to managing the complexities involved and, in addition, allows the opening of the ‘black box’ that is VALS.

The USGS is accepted as being one of the world’s leading geological institutions. It supports five well-funded volcano observatories, located in regions of significant volcanic hazard, high population or important infrastructure, and operating in Alaska, the Cascades (north-western U.S.), Hawaii, Long Valley (California) and Yellowstone (Wyoming), as part of the Survey’s Volcano Hazard Program (VHP). The USGS has substantial experience, both within the U.S. and abroad, via the Volcano Disaster Assistance Program (VDAP) jointly funded by the Office of Foreign Disaster Assistance of the U.S. Agency for International Development (USAID) and the VHP. This program supports a team of scientists to respond rapidly to volcanic emergencies in the U.S. and abroad, by deploying portable volcano-monitoring equipment. Since 1986, the VDAP team has responded to 20 volcano emergencies, in Central and South America, the Caribbean, Africa, Asia, and the South Pacific. They have also provided monitoring equipment and technical assistance at 59 volcanoes in 18 countries and maintain close relations with a number of observatories around the world following collaborative work (Ewert et al., 2007). The USGS are a good institution to explore a global emerging shift towards standards, because they have significant experience of designing and operating VALS in other countries. In addition other countries often look to what the USGS are doing and to seek advice from them.

In 2006, the USGS adopted two standardised VALS (one for ground-based hazards, and the other for aviation ash hazards) replacing pre-existing VALS that were locally developed at each volcano observatory (Gardner and Guffanti, 2006). The VALS developed by Alaska Volcano Observatory (AVO) was adopted as the international warning system for volcanic ash by the International Civil Aviation Organisation (ICAO) in 2006, and as such is the first globally standardised VALS in the world. Early warning is an important issue to the USGS, exemplified by their New Volcano Early Warning Systems report (NVEWS) (Ewert et al., 2006, Ewert et al., 2005) that addresses the need to balance monitoring, research capabilities and warning requirements to successfully manage volcanic crises. In 2009, the U.S. American Recovery and Reinvestment Act provided some US$15.2 million to upgrade volcano monitoring as outlined in the NVEWS report to provide state-of-the-art monitoring capabilities, demonstrating that volcanic hazards are taken seriously by the U.S. Government (USGS Newsroom, 2010).

Within the time limitations of this study, only one national case study proved manageable. The U.S. has, and remains, at the centre and forefront of shifts towards standardised emergency and disaster management protocols (see chapter 4). The advantage of comparing the approaches of a number of different observatories / VALS within one country lies in the fact that the broader economic, political, and cultural and communication issues are relatively more closely aligned, differing only on a regional or local level. This results in fewer variables in the study, facilitating focused research on the hazard and social impacts on decision-making within a VALS, rather than broader concerns such as diverse cultural attitudes, political structure and economic capabilities. One additional benefit for selecting the U.S. is the practicalities of using the English language, and the resulting ease of access to the large and varied portfolio of USGS publications.

1.2.3 Thesis outline

In this study, I draw upon literature from the fields of hazard EWS; scientific enquiry, volcanology, uncertainty and risk, and complex systems, to demonstrate how and why the research questions were formulated and to define the framework within which the empirical data were collected (see chapter 2). Literature of VEWS is diverse and fragmented, but this thesis seeks to go beyond the single disciplinary approach to volcano warning through incorporating insights from the philosophy and sociology of science, and approaching issues of risk and uncertainty from a sociological perspective. The role of systems within warnings and the need to understand complex systems are used to reconceptualise what VALS are and to expand upon the aforementioned research questions.

Qualitative research methods and analysis are used in this study to obtain and dissect the data, using a new approach developed to analyse large numbers of interviews conducted during the multi-sited fieldwork. The methodology, methods and analysis are reviewed in chapter 3. This study adopts methods used within disaster management studies and sociology of scientific knowledge studies to provide appropriate qualitative data.

The context of the case study is important, and in chapter 4 the legal mandate of the USGS to issue volcanic warnings is addressed. A number of key volcanic crises in the U.S. over the last

30 years have led to the development of five volcano observatories and three different formal VALS, motivated by local needs and contexts. Lessons learnt during these crises are also dealt with in this chapter. At a national level, different pressures have been exerted on the USGS, most importantly - in the context of this study - the recent requirements to develop a standardised VALS for all five observatories.

The research findings are presented within three empirical chapters focusing upon three key themes that emerge from the data and which specifically address the three constituent research questions. Chapter 5 reviews the progress of the USGS to develop a design for their standardised VALS. The resulting linear VALS is then analysed in the context of its ability to manage the complexities involved within a volcanic crisis, including a diverse range of hazards, and organisational factors. This chapter also raises questions about the ability of VALS, in practice, to manage complex systems using a linear system.

In chapter 6, the role of decision-making in VALS is explored. This includes reviewing the roles of scientific and social information when constructing scientific knowledge, including monitoring data, analytical tools and evaluating the uncertainties involved; deciding which alert level to assign and the associated consideration of local contingencies and risk; and finally the gap between decision-making capabilities that connect the scientists and users.

Chapter 7 investigates the communication processes within VALS, through reviewing communication products and protocols, and whether they fulfil user needs. The impact of the standardised VALS on communication is investigated, considering how it works in practice and the importance of local context. In addition, this chapter explores a diverse range of communication networks, and consequently, how effective VALS are for users.

Finally, in chapter 8, the discussion and conclusion reflects the empirical findings and addresses the key research question. The implications of the research conclusions are considered from both theoretical and practical perspectives and suggestions for future research on VALS are presented.

Chapter 2. Using early warning systems to manage complexity

Studies on volcanic hazards typically focus on the use of scientific information when issuing warnings. The volcanic crises discussed in the introduction chapter demonstrate that in practice, issuing warnings and alerts is far more complex than simply understanding the science of the hazard. Ignorance of the social context in which the hazard is occurring has resulted in numerous crises (e.g. the tragedy of Nevado del Ruiz in 1985 (Voight, 1990)); this includes institutional, political, economic, and cultural circumstances. Civil authorities, with responsibility to take action on the basis of a warning, have to make difficult decisions and so 'busy decision-makers swamped with information tend to gravitate towards reliance on simple, straightforward messages' (Glantz, 2009, p.xv). To reduce volcanic crises, examples have demonstrated that scientific knowledge of the volcanic hazard needs to be integrated with relevant contextual information. Volcano early warning systems (VEWS) typically bridge this gap therefore this chapter aims to understand more about VEWS; how they manage the complexities involved, and how the different actors within them interact.

This chapter divides into four parts. The first part outlines early warning systems (EWS); explaining how they are conceptualised from a theoretical, sociological and institutional perspective. Increasing levels of globalisation are generating multi-platform EWS that are standardised. This process is examined to see how standardisation may affect EWS. The second part will discuss how EWS work in practice, using examples of VEWS and volcano alert level systems (VALS), to demonstrate the issues identified that impact the effectiveness of a EWS. The third part addresses issues of science, uncertainty and risk in volcanic hazards and warning systems. This section reviews how scientists understand volcanic behaviour and the techniques they employ to manage these complexities, including the understanding and operation of decision-making processes. Scientific uncertainty and risk make this a difficult task for scientists. However, understanding how these issues are approached from a social science perspective provide new methods of understanding these problems, whilst also recognising the importance of social context. In the fourth part VEWS and VALS are reconceptualised as tools that aim to manage the many physical and social complexities involved, which are often locally dependent. This is in contradiction to the rising levels of standardisation within EWS. Complexity science can provide theoretical and practical methods to conceptualise and manage the many complexities involved in developing an effective warning. Finally, the four key themes that emerge from this literature review: uncertainty, decision-making, communication, and accommodating local and national users, are reviewed prior to their exploration in the methodology chapter.

2.1 Defining early warning systems

Despite an abundance of EWS related research, there is little consensus about what they are, or how they are defined (Glantz, 2004). EWS are seen as ‘a means of getting information about an impending emergency, communicating that information to those that need it, and facilitating good decisions and timely response by people in danger’ (Mileti and Sorenson, 1990, p.2-1). Whilst this is a simple definition, the operation of a EWS is far more complex, partly due to variations spatially (global, national, regional, local), temporally (rapid onset, slow onset, frequent, infrequent), in function (safety, property, environment), and in hazard (weather, climate, geo-hazard). This chapter only focuses on natural hazards (i.e. geological and meteorological) that are rapid onset (occur within a short period). EWS also operate in different economic, political and social circumstances; use different communicative tools (from technology to word of mouth); and link many different organisations (or actors) such as science (government and private), engineering, technology, government, news / media, and the public. This leads to different perspectives of what EWS are, and what they should do. For Governments, EWS are an important tool for disaster risk reduction (DRR) measures; consequently, EWS tend to be highly centralised. Decisions have to be made about the benefits of EWS relating to: cost-benefit, timeliness (what constitutes a warning, are they a forecast, projection or trend, and how early is early), establishing different levels of warning, and lastly accountability.

Following the Indonesian Ocean tsunami of 2004, Hurricane Katrina in the U.S. in 2005, and the UK floods in 2008, recent publications highlight that EWS are becoming an increasingly topical and important area within disaster risk reduction methods (Glantz, 2009, IFRC, 2009, Hall, 2007). Despite the importance of EWS, research about their application and effectiveness is fragmented, unconsolidated and patchy. Individual studies on EWS review the wide scope of institutions involved, technologies used, decision-making capabilities, and interactions within the system. However, these generally focus on three sub-systems: hazard detection (hazard indicators and monitoring systems), management (of information, communication, and generation of a warning), and response (receiving, believing and acting on the warning) (Mileti and Sorenson, 1990). This study brings into focus a more holistic perspective of EWS, viewing them as a system that attempts to interact with a number of complex systems, such as the physical hazard and society, to provide sufficient warnings for appropriate action to take place. Historically EWS research focused on two key areas: forecasting techniques for natural hazards within the scientific community, and exploring strategies to disseminate warnings effectively and credibly to vulnerable populations, often referred to as the 'last mile' within disaster studies. Studies on the last mile relate to large literatures on risk perception (Slovic, 2000, Gaillard and Dibben, 2008), vulnerability (Wisner, 2004, Birkmann, 2006, Bankoff et al., 2004), resilience (Bankoff, 2007, Kelman and Mather, 2008), and capacity and communication (Tierney and Dynes, 1994). This PhD is different in that it considers the 'first mile' as an overlooked, but key, component in EWS in an increasingly globalised yet patchily standardised world. This 'first mile' relates to the design and operation of EWS and raises questions about how effective they are in communicating warnings and information to all the users of the system. These user groups are growing in diversity as trade and travel becomes increasingly international. Understanding the 'first mile' requires investigation into how scientists understand volcanoes, how they manage the associated uncertainties and risks, and how they attempt to manage them both theoretically and practically, which is explored further in section 2.3.

Institutionally, the EWS literature is seen as problematic due to a diverse range in definitions of concepts and terms, even as basic as disaster, hazards, risk, warning, and vulnerability. Although some glossary style documents have been compiled (UNDHA, 1992, UN ISDR, 2003), the lack of any consistent use of definitions in disaster management has been interpreted as a problem: 'unless we clarify and obtain minimum consensus on the defining feature per se, we will continue to talk past one another on the characteristics, conditions and consequences of disasters' (Quarantelli, 1995, p.225). However, the wide range in definitions for many disaster terms in the United Nations Department of Humanitarian Affairs (UNDHA) glossary highlight diverse views about what is at stake; whether this relates to reducing liability, discharging responsibility and / or protecting values. Contrasting views on how to conceptualise disasters and define terms suggest these terms themselves reflect complex phenomena requiring further exploration.

2.1.1. Theoretical approaches to early warning systems

The diversity in EWS and of the agencies involved results in different ways of conceptualising EWS. The next section first explores theoretical approaches to EWS by reviewing the concept and its evolution from a linear to a complex system. Second, the role of EWS within disaster management studies; and third, institutional approaches towards EWS, including that adopted by the United Nations.

EWS form a relatively new area of inquiry within the context of disaster research, obtaining growing recognition in 1960s. Prior to this, studies typically viewed early warning as a linear process (Gillespie and Perry, 1976); where there is a clear relationship between a hazard occurring and generating a warning forming a cause and effect relationship. Linear processes are characteristically embodied in the Newtonian paradigm, and often referred to as reductionist as it aims to strip relationships to their simplest format. However, in 1969, a study by Barton changed this to view early warnings as a system. Barton's work (1969) on disaster classification generated a paradigm shift from the descriptive to the analytical, by developing four classifying variables in his typology of disasters: scope of impact, speed of onset, duration of impact, and social preparedness. This work influenced Gillespie and Perry who said that 'by adopting a systems perspective, the disaster researcher can not only describe and classify disasters more effectively, but can also move towards a more analytic approach' (Gillespie and Perry, 1976, p.305). A systemic approach enabled the development of models for the prediction of individual, group and organisational behaviours, going beyond the simplistic cause and effect relationships within an early warning.

Although the idea of 'systems' influence on disasters had first been identified in 1958 (Form and Nostow, 1958), it took decades to take hold. General Systems Theory (GST) emerged following the Second World War as an interdisciplinary approach to the field of science and the study of the complex systems in nature and society (Bertalanffy, 1975). The term 'systems' has many definitions, although the one adopted in this research is that of a group of interacting, interrelated, or interdependent elements forming a complex whole, which is nearly always defined with respect to a specific purpose (Kim, 1994). Originating in biological studies in the 1920s, GST recognised that systems are greater than the sum of their parts (Bertalanffy and Woodger, 1933), providing a holistic approach to disaster studies by demonstrating that the processes involved are interrelated. In 1975, models of idealised EWS were developed such as in Fig. 2.1, which does not show EWS as a linear progression through the different stages of disasters in chronological order, but indicated that an EWS comprised of subsystems (in this case evaluation-dissemination and response) that have inputs, outputs and feedback between them.

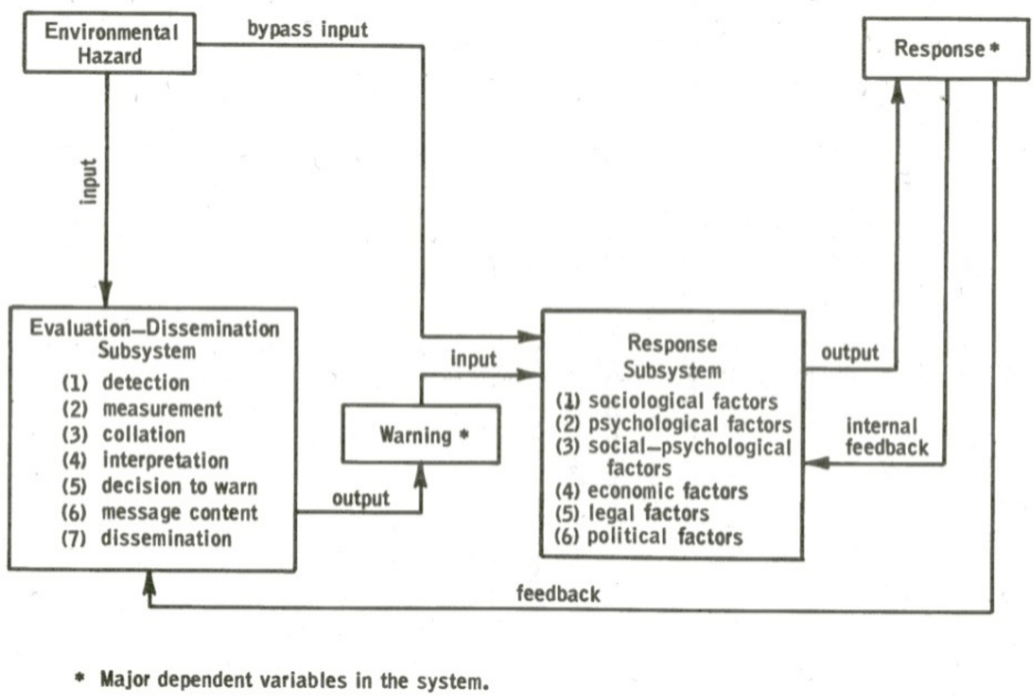

Figure 2.1 Systems model of an early warning system (White and Haas, 1975, p.185)

By the 1980s, Foster (1980) identified that decision-making and communication processes between different actors in EWS were non-linear and could be understood better within the context of systems theory as a dynamic system. Foster also developed an idealised EWS to represent the different stages, using a system style layout as seen in Fig. 2.2. Although this model recognised the role of organisations and policy, it maintains an element of linearity rather than presenting a series of feedback loops that are multi-directional enabling a systems approach, as Foster states 'every warning system should be designed to facilitate a *two-way flow* of information' (Foster, 1980, p.203) (author's emphasis).

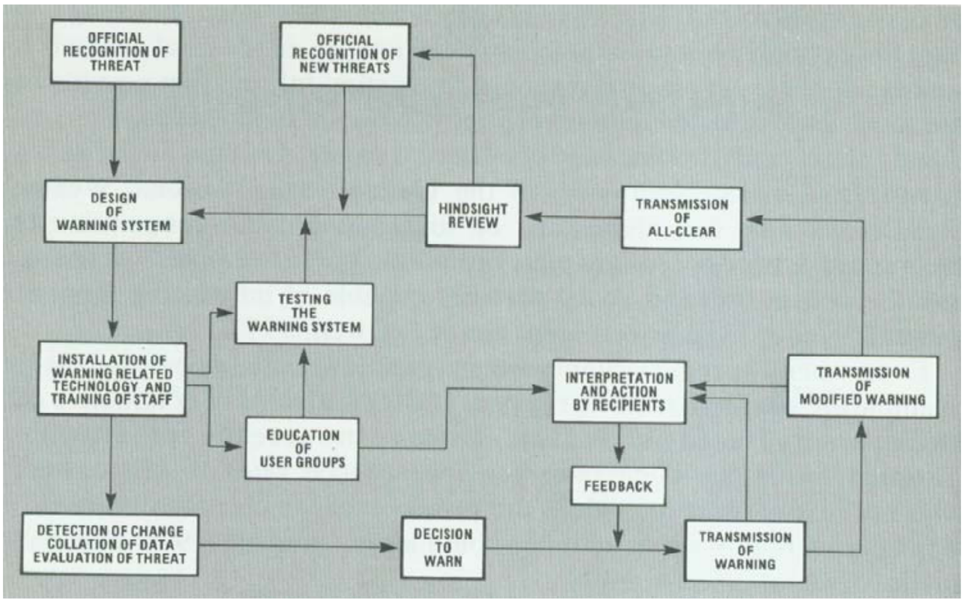

Figure 2.2 Idealised warning systems (Foster, 1980, p.172)

The EWS models developed by White and Haas (1975), and Foster (1980), as shown in Fig. 2.1 and Fig. 2.2, divide EWS into component parts and consider each part separately to ensure their proper function (White, 1995). It is important to note that both these models are idealised and are not descriptive of what actually happens in an EWS. However, the models struggle to view EWS as a system because they fail to 'identify emergent properties arising from interacting elements and because it does not consider that the behaviour of systems is due as much to their external environment as to their internal mechanisms' (White, 1995, p.41). White argues that disaster studies tools which provide a holistic approach, by considering how human behaviour and context can affect the management of risk, should be used.

By the late 1990s, there was growing recognition that interactions between natural environments, human perception, actions and organisations are part of a genuinely 'complex' system (Mileti, 1999). The term 'complex' has become a popular and often misused term both in the physical and social sciences. Complexity can only emerge within a system, but a complexity approach is different to that of systems theory. Systems theory stipulates that systems have rules, a form of control system guiding the elements, rationale and predictable processes, and change their structure according to rule based learning. Complex systems do none of these things as they defy rules, are unpredictable and self-organise (Ramalingam et al., 2008). When a complex systemic approach is adopted it 'focuses on interaction among the elements of a system and on the effects of its interactions; it examines a variety of factors at one time; it integrates time, feedback, and uncertainty' (Mileti, 1999, p.107). It is the reciprocal interactions or feedback amongst variables or subsystems, as well as time delays in seeing the results, that create complexity, making the system difficult to understand (Senge, 1990). As a result complexity highlights serious limitations to our scientific knowledge because it breaks traditional reductionist Newtonian thinking that regards science as infinitely divisible and measurable (Capra, 1996); 'complexity argues against reductionism, against reducing the whole to the parts' (Urry, 2005a, p.401). The concept of complexity and chaos has questioned the naivety that science depends on patterns by establishing a link between determinism and predictability (Sardar and Ravetz, 1994, Nowotny et al., 2001). Therefore it is important that analyses of complex systems are not left to scientists, since these systems are transdisciplinary, involving human agents, science and society (Nowotny, 2005).

Mileti (1999) was not alone in recognising that systems are firmly entrenched in thinking and research on hazards and disasters. According to Gillespie et al. knowing how to mitigate the negative consequences of natural disasters and respond effectively requires three steps: 'understanding the physical and social systems involved in disasters, communicating that understanding clearly to decision-makers, and knowing what interventions may be effective' (Gillespie et al., 2004, p.82). Complex systems theory provides a holistic approach to integrate these three steps and understand how complex interactions generate certain behaviour, although it is difficult to monitor these complex interactions (discussed further in part four). Theoretically, the framing of EWS has evolved through systems thinking throughout the last fifty years with growing recognition of the social systems involved in a EWS.

2.1.2 Early warning systems within disaster management

Individuals, who developed theories on how disasters and EWS operate, as outlined above, were not alone in recognising that social systems have a significant role in disaster management. In the last century, human geographers have influenced disaster management thinking by challenging top-down expert-driven approaches, by instead suggesting bottom-up locally integrated ones. In the 1930s and 1940s the 'dominant approach' was widely accepted (Wisner, 2004), stating that factors such as 'material wealth, experience of hazardous events, systems of belief, and psychological considerations are all important in controlling how individuals, social groups, and indeed, whole societies respond to disasters' (Chester et al., 2005, p.416). This approach implied there are adjustments that individuals and societies can make to deal with natural hazards. In the 1980s, Kenneth Hewitt (1983) discussed the inherent complexities in natural-disaster planning in 'Interpretations of Calamity' disputing the dominant approach. This new approach adopted the view that most disasters in developing countries are the result of poverty and deprivation rather than extreme natural hazard events, and so those economically or geographically marginalised suffer the most (Susman et al., 1983). Radical alternatives changed the way natural hazards are studied by scientists, social scientists, and policy-makers to emphasise the uniqueness of the location, suggesting that successful hazard reduction is dependent on not only understanding the physical environment and hazards, but also the socio-economic and cultural conditions of the society. To be successful, adjustments to hazards should be sensitive to the local environment and be intercultural. The common acceptance of this alternative way of thinking did not occur until the World Conference on Natural Disaster Reduction in 1994, where the published Yokohama Strategy reviewed, in part, how we could transform society to reduce disasters using radical alternatives (UN ISDR, 2004).

By the 1990s, EWS became an area of focused research within disaster management studies. EWS are difficult to understand because they encompass the physical hazard and the context of the 'society' affected. Mileti & Sorenson (1990) provide one of the first detailed reviews of EWS from a social science perspective. Based on 200 studies in the U.S., they established three key findings. First, variation in the nature and content of warnings has a large impact on whether the public responds. Second, the characteristics of the population receiving the warning affect the response (i.e. gender, ethnicity and age, and other social, psychological and knowledge characteristics). Third, many current myths about public response to emergency warnings are at odds with field investigation results, for example 'cry-wolf' syndrome, public panic and hysteria. These results indicate there is a difference between 'ideal' models and those in practice. Drawing on case studies the authors outline guidance for what information warning messages should contain: the hazard, location, guidance, time, and sources. For many hazards, including volcanoes, this is extremely challenging to achieve since hazards have different levels of predictability, detectability, certainty, lead time, duration of impact, and visibility as scientific capabilities remain limited, making it difficult to generate 'specificity, consistency, accuracy, certainty and clarity' (Mileti and Sorenson, 1990, p.3-11) in warnings. Mileti and Sorenson (1990) state it is not possible to review EWS in a comprehensive manner by just isolating the social and physical elements since there is a need to establish organisational effectiveness, work with other organisations, and maintain flexibility during warnings. The report presents a model of EWS (see Fig. 2.3) with a detection component (monitoring and detection, data assessment and analysis, prediction and informing), emergency management component (interpretation, decision to warn, method and content of warning, and monitoring of response), and response component (interpretation and response). This builds on the White and Haas (1975) model (Fig. 2.1) by emphasising the different subsystems and their relationships and institutional roles, rather than only focusing on the relationship between the hazard, warning and response.

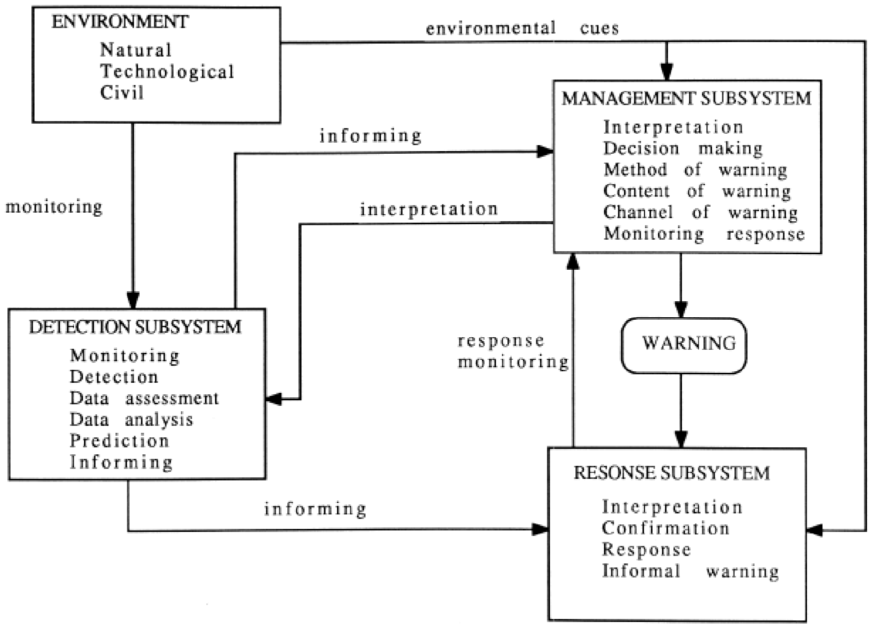

Figure 2.3 The general components of an integrated warning system (Mileti and Sorenson, 1990, p.2-4)

2.2.3 Institutional approaches and issues

In recent decades, global institutions that provide guidelines and best practices for EWS have increasingly recognised the role of EWS in disaster management. The largest institution concerned with EWS is the United Nations (UN). The UN General Assembly designated the 1990s as the International Decade for Natural Disaster Reduction (IDNDR), which in 2000 the International Strategy for Disaster Reduction (ISDR) replaced. Throughout the 1990s and 2000s, the UN held a number of EWS conferences resulting in a number of publications (Kuppers and Zschau, 2002, UN ISDR, 2006b, UN ISDR, 2006a). In 2005, the UN established the Hyogo Framework, a global blueprint for disaster risk reduction (DRR) efforts during the next decade with the goal to substantially reducing disaster losses by 2015. One of its' five key priorities for actions is to 'identify, assess and monitor disaster risks and enhance early warning' (UN ISDR, 2005, p.6), highlighting growing awareness of the role EWS has within institutional governance.

Following the catastrophic Indian Ocean tsunami of 2004, the Secretary-General of the United Nations called for the development of a global EWS for all natural hazards and communities. It was felt that if an EWS were in place when the tsunami struck the Indian Ocean region, many thousands of lives could have been saved (230,000 are estimated to have been killed in eleven countries (Thieren, 2005)). In March 2005, the UN ISDR Platform for the Promotion of Early Warning (PPEW) undertook a global survey to identify existing capacities and gaps in EWS. The report was intended to provide a wake-up call for governments and other agencies about the role of EWS in reducing human and economic loss from natural hazards. Published in 2006 the 'Global Survey of Early Warning Systems' was the culmination of this research, and a number of EWS conferences conducted in over 23 countries with 20 international agencies (UN ISDR PPEW, 2006). The report advocated that EWS should be 'people-centred' (i.e. community based) in that it requires many systematic approaches and diverse activities spanning four key elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability (see Fig. 2.4).

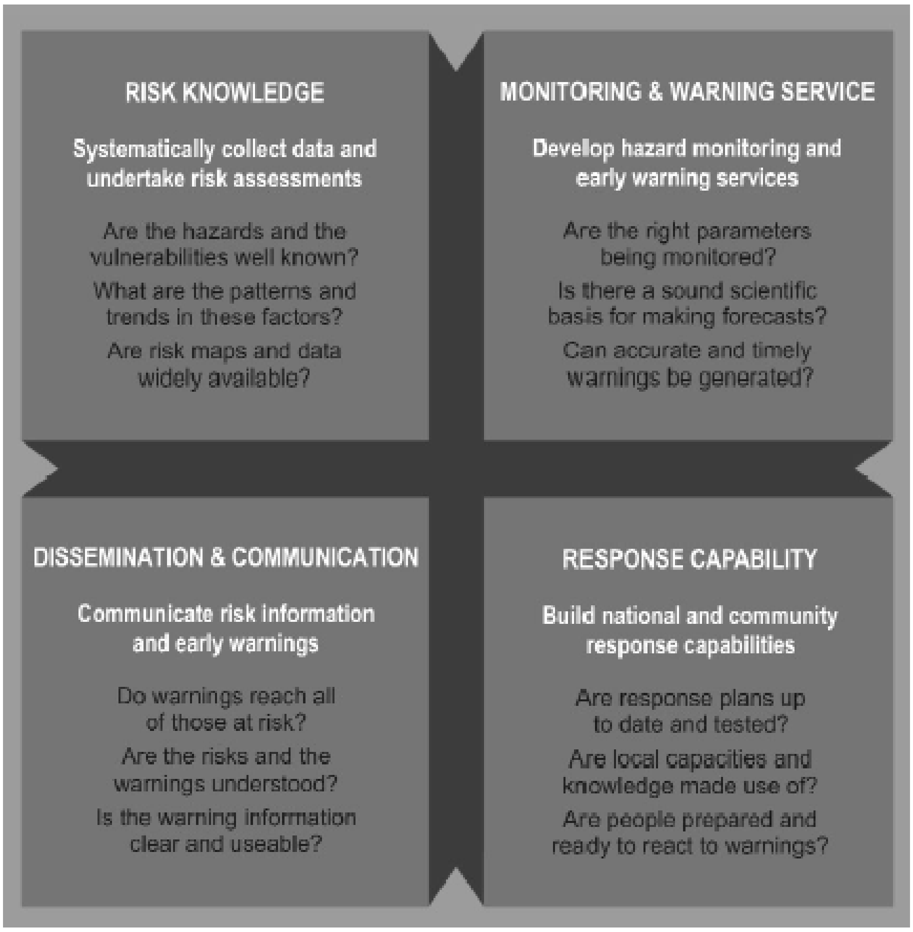

Figure 2.4 The elements of a people-centred early warning system (UN ISDR PPEW, 2006, p.2)

According to the UN an EWS 'can only be effective if the element and the linkages are well-understood, well-designed and well-operated' (Basher, 2006, p.2176). Yet, the model presented in Fig. 2.4. does not indicate what these linkages are. Aside from presenting an idealised EWS the survey concludes that the world is far from having the global system for all hazards and communities called for by the UN Secretary-General, but it does make five key recommendations (UN ISDR PPEW, 2006, p.vi):

1. Develop a globally comprehensive EWS, rooted in existing EWS and capacities
2. Build national people-centred EWS (i.e. community based)
3. Strengthen the scientific and data foundation for early warnings
4. Fill the main gaps in global early warning capacities
5. Develop the institutional foundations for a global EWS

These recommendations illustrate the difficulties and contradictions involved in developing a globally comprehensive EWS. First, they raise questions about the viability of developing a global VEWS, the transferability of the four identified elements of EWS, and their compatibility in one globalised system. With different hazards, countries, varying levels of scientific capabilities and communication technologies available, and different local decision-making structures, and institutions, uniformity is likely to be difficult to achieve. Second, it is appears contradictory to develop a system that can be globally comprehensive, yet built by the local community. Third, the role of 'scientific and data foundation' in preventing EWS failure is questionable given this thesis has already reviewed examples that have shown that frequently it is not scientific or technological deficiencies that cause failure, but social and institutional elements, as this literature review will go on to demonstrate further in part two (e.g. the Nevado del Ruiz tragedy). Fourth, the UN state it is important to identify what the major gaps are in EWS, but identifying these gaps may be difficult given that what may be a gap in resources and capabilities for one country, may not pose a problem in another, due to differing social and institutional contexts such as available funding. Therefore, consideration of the local resources, knowledge and capabilities to prevent failure in EWS is required. Last, there may be issues with developing institutional foundations for a global EWS when the requirements for emergency response vary in different nations. Hall (2007) has commented that despite the efforts by the UN events focused on early warning systems, there still lacks 'coordinated, collaborative international action' (p.32) to make the move from debate to tangible results. Additionally Hall outlines that the emphasis within EWS has consequently been more to do with funding of current capabilities and development in science and technology, which has 'distracted us from the central issue of address the real needs of the communities and people at risk' (Hall, 2007, p.32). Some scientists agree, suggesting that they must step outside their 'ivory tower' and try to anticipate the consequences of developing warning tools and to make sure they will actually lead to hazard reduction (Malone, 2008). Discussions with a number of disaster practitioners at conferences attended during the research imply that grassroots organisations and NGOs find the UN's suggestions somewhat utopian given the reality in which these groups have to operate.

To improve EWS, the UN has called for more effective procedures via standardisation and the application of new technologies and enhanced scientific understanding (UN ISDR PPEW, 2006). Such a strategy poses two potential weaknesses. First, standardisation, by definition, tends to exclude the importance of incorporating local factors into a global procedure (discussed below). Second, the focus on science and technology implicitly assumes that social and cultural variations are secondary factors, when the introduction and this chapter illustrate the importance of social context in making EWS effective. Hence, even if standardisation may yield improved strategies for gathering and interpreting warning signals, it will still favour inflexible procedures not designed to accommodate local social and cultural constraints. The UN has not developed new approaches to EWS that consider the complexities involved; instead they focused on the need for developing global platforms and standardising. Standardisation is reductive, and so counteracts systematic approaches to managing crisis. Despite this, frequently standardised methods are used to manage hazards or complex situations.

2.1.4 The emergence and challenge of standardisation

Globally, the levels of standardisation in protocols and procedures for disasters and emergency management have risen, including the development of an Indian Ocean Tsunami EWS following the 2004 Boxing Day tsunami. Within the U.S., the 9/11 terrorist attacks led to a significant change in government policy resulting in the standardised National Incident Management System (NIMS), the Homeland Security Alert Level, and other alerting and warning protocols for electronic technological warning capabilities. Standardising warnings is not a new concept, but as disaster practitioners learn more about the complexity of natural disasters, concerns are being raised that it is increasingly difficult to use 'nonlinear' methods of communication and that 'faced with the nature and complexity of challenges involved in societal responses to hurricanes [or disasters], interdisciplinary work that, for example, integrates appropriate meteorological and social science research will be critical' (Gladwin et al., 2009, p.4). In addition, there appears to be insufficient literature on the effectiveness of standardisation as a tool to manage complex disaster-related issues; subsequently there is minimal understanding of what benefits or limitations standardisation can bring. Within disaster studies guidelines and models for applying standards have been developed, such as consistency and quality control, for developing and using emergency plans (Alexander, 2005). Alexander argued that whilst viewing standards as unnecessarily restrictive and overly prescriptive, they could also help guarantee the quality, content and relevance of these plans. Given the lack of other data around the standardisation of EWS, reviewing other standardised processes such as medical procedures or technological processes can demonstrate issues that standardisation raises as a method of managing complexity. This section draws on these examples to review issues that standardisation raises that may be relevant to standardising EWS.

Whilst some regard standardisation as a constraint, a number of features also make standardisation attractive. First, it improves the ‘doability’ of work. Fujimura argues that ‘doability’ enables scientists to ‘constrain work practices and define, describe, and contain representations of nature and reality’, and enables a ‘dynamic interface to translate interest between social worlds’ (Fujimura, 1987, p.205). Second, it enables simpler procedures for people to learn from and carry out. Third, in a number of spheres, particularly medical and ethical, it provides answers to concerns relating to the processes or procedures by the public (Hogle, 1995). Medical practices regard standardisation as necessary to control processes and make outcomes more effective and reproducible. Fourth, standardisation provides political ordering and control. In summary, standardisation offers a tool to communicate in compatible ways (via language or protocols), ensure minimum quality, and provide a reference point (David and Greenstein, 1990).

A number of factors influence the standardisation of a process, when and where it is standardised, and how the process occurred previously. Standardisation may benefit policy makers or the people who manage the process and require legal accountability, but provide few benefits to users of the process. To standardise there is an element of persuasion, coercion or even force required to obtain consensus or compromise, usually dependent on what is being standardised and the rationale; for example within computer technology it is clear that standardisation was preferable as it enabled greater flexibility for users (Hanseth et al., 1996).

Standardising a process is difficult, predominantly because it fixes the process in an ever changing and dynamic world. In addition, there is no guarantee that researchers or users in different locations will use them in the same way. Scientists tend to ‘tinker’ with standard procedures, often making assumptions of the standard application, so although standardisation can increase 'doability' it does not guarantee reproducibility (Fujimura, 1987). In fact, it can create problems that begin to work against the benefit of standardisation, creating tension between the efforts to rationalise work, and changes in the local conditions, which affect the work (Fujimura, 1987). Often local practice can render a process less standard, rather than more predictable and uniform (Hogle, 1995). Since the cultural, organisational and institutional relations that characterise a process change, it seems difficult to remove contingency and national variation; for example, medics acting within a standard process bring their own experience and technical contingencies that mean local cultural meanings and categories remain. It is difficult for standardised technologies to be flexible, unless black boxed like a computer, because once a standardised system is in place it already has a number of users geographically and organisationally that are difficult to change (Hanseth et al., 1996).

One key practical problem in creating standards or universalities is the relationship that occurs with pre-existing infrastructures, procedures and practices. To some extent, new standards need to incorporate and extend the old ones. Timmermans and Berg (1997), believe that universality is always local universality, depending on how standards manage the tension of transforming work practices whilst simultaneously being grounded in those practices. Whilst many scientific laboratories have standard procedures that ‘work’ successfully, studies have shown that ‘the successful working of a standard procedure is built out of painful processes of adaption and learning to ‘fit’ techniques to settings, and scientists to their methods’ (Knorr-Cetina et al., 1995, p.157). In a dynamic, uncertain reality, stability is a consequence of continuous balancing of temporary agreement, beliefs and mini-social contracts. Therefore, the progression of a standardised system or process is not always one way, it can resist changes and stabilise into diverse cultures and adaption's; often corporate sponsors of a standardisation not only standardise the product or process, but also the intra-organisational links and organisational regime that optimises the standard process (Jordan and Lynch, 1998). Another key complication, seen particularly within the technology sector, is constant destabilisation due to new developments often triggered by cost-benefit and risk-benefit analysis (Webster, 2004). Consequently, standardised processes are viewed as ‘open-ended; closure is never truly achieved’ (Timmermans and Berg, 1997, p.287).

The historical development of technology provides an example as to how standardisation is a social construct, shaped by the local and relevant contexts. Pinch and Bijker (1987) developed the theory of the social construction of technology (SCOT). They argued that human action shapes technology rather than it being technology that determines human action. They argued that the ways in which a technology is used cannot be understood without understanding how that technology is embedded in its social context (Bijker et al., 1987). A technology's success cannot be achieved by just saying it is 'best'; an understanding of what is defined as best and the groups and stakeholders that participate in defining it is required. Pinch and Bijker (1987) use an excellent example of the success of the chain-driven bicycle, relative to the 'primitiveness' of the Penny Farthing. Historically bicycles were valued according to different standards than today; men valued the speed, thrill, and spectacularity of the Penny Farthing, in contrast to the security and stability of the chain-driven Safety Bicycle, and there was concern as to how women could ride a Safety Bicycle wearing a skirt or dress. The SCOT research methodology aims to reconstruct and analyse how technology developed by reviewing the problems and conflicts that occurred by connecting them to the design features of the artefact, in this case a bicycle. A key paper on standardisation, or 'making things the same' focused around the adaptation, development and standardisation of weapons during the French Revolution. The paper used the theory of SCOT to demonstrate that what can appear as 'objective' artefacts can be 'coordinated across vast physical, temporal and cultural boundaries' (Alder, 1998, p.499). Standardisation can be implemented in different ways; based on a number of assumptions, or via groups that create a number of boundary objects, but frequently it is automations and commercialisation that drives the process (Jordan and Lynch, 1998).

Standardisation requires establishing boundaries, often in complex scenarios, making it difficult to decide what to leave outside of standardisation, and what to include. Most studies on standardisation across different practices have demonstrated it is not possible to factor in uncertainty or ignorance when designing a standard, and that knowledge, practices and technologies of the present shape the standardisation. Clearly, these aspects are not static, but to reflect this within the tool of standardisation is not easy. Standardising something like EWS that are diverse and pluristic is challenging. This section has demonstrated that despite institutional recommendations to standardise EWS, other examples of standardisation highlight there are many potential problems that warrant further investigation before applying them in practice. The next section reviews how EWS work in practice, focusing on VEWS to demonstrate the importance of local context, and the challenges of standardising them.

2.2 Early warning systems in practice

Globally there is recognition that EWS are an essential tool for disaster risk reduction (DRR), yet, many institutions still view them solely as warning provider, for example taking form of a siren or issuing or an alert. A majority of advances in EWS over the last twenty years come from improved technology for monitoring, instrumentation, data collection, and data processing (Sorensen, 2000). This resulted in significantly improved prediction and forecasting, in addition to facilitating more widespread warnings using sophisticated technology for example, using phone and mobile-phone automatic ring systems, automatic television warning messages and internet messages. However, numerous examples such as Guadeloupe in 1976 (Fiske, 1984) and Nevado del Ruiz in 1985 (Voight, 1990) illustrate that in practice, warnings are not useful if based on poor scientific data, and / or communicated ineffectively, and do not generate the required response due to lack of understanding of the message. Therefore, recent research on warning systems argue that integrated warning systems that merge scientific, managerial, technological and social sub-systems maximise public protection (UN ISDR, 2006a, UN ISDR PPEW, 2006, IFRC, 2009).

Important practical research has been conducted on sub-systems of EWS (i.e. hazard monitoring, risk assessments and forecasting tools), yet numerous case studies indicate that is not the individual components of EWS that are causing failure, but the processes that link them (Garcia and Fearnley, 2011). These vital processes include effective decision-making processes (Leonard et al., 2008), communication (Solana et al., 2008), trust building and participatory activities (Haynes et al., 2008a), and defining accountability and responsibility so people know what to do clearly (Glantz, 2004). This section uses examples from VEWS to first review the significance of decision-making; second the need for effective communication; and last, the importance of local context that helps establish trust and accountability. Finally, volcano alert level systems, the focus of this study, will be discussed.

2.2.1 Decision-making

Every aspect of a EWS involves a decision, from interpreting monitoring information, to issuing a warning, to deciding to evacuate a town, to the person on the street deciding what to do. Decision-making is still considered under a systemic approach, using a logical sequence between the definitions of the problem, the risk assessment, and its solution, rather than considering the complexities involved (UNDRO, 1990). A wide range of institutions have to make decisions about appropriate actions and the conventional view is these move along a linear chain as shown in Fig. 2.5, taking a top-down approach. Some countries, such as the U.S., adopt this top-down approach to decision-making wherein populations turn to their local civil authorities for information and advice to make informed decisions. Countries that adopt a bottom-up approach place greater responsibility on the individual or community.

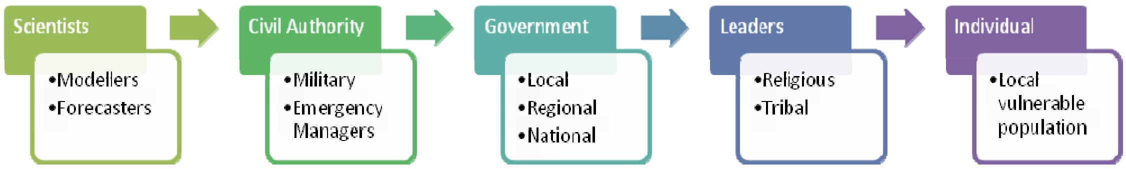

Figure 2.5 The decision-makers within EWS from one extreme to the other

In 2004, the Humanitarian Practice Network developed a model of EWS (see Fig. 2.6) that shows EWS as a more complex system, with feedback loops and variables, but also identifies the need for risk assessment, understanding vulnerability, and public education. Unlike the linear models shown in Figs. 2.1-2.3, this model illustrates that decision-making is a core component of EWS and is not a linear process, but the result of feedback from different actors involved in the EWS.

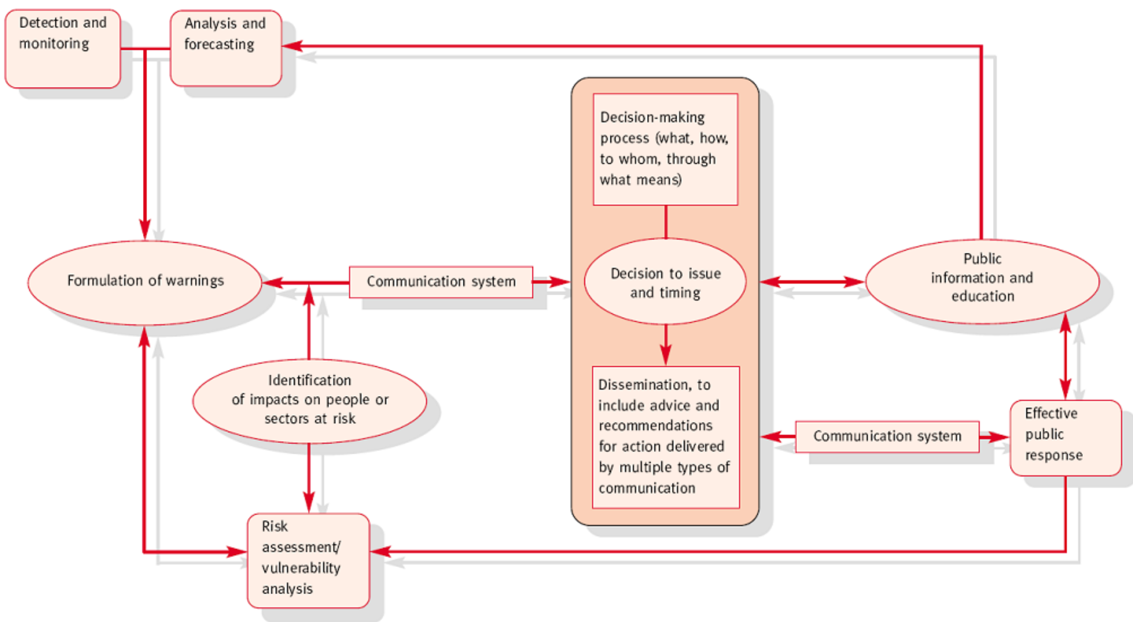

Figure 2.6 Generic model of forecasting / warning systems developed by Schlosser, C. (Twigg, 2004, p.301)

Historically high levels of uncertainty in natural hazard science have resulted in scientists becoming core stakeholders in EWS, due to their expertise and responsibilities, so that EWS became 'hazard-focused, linear, top-down, expert / driven systems, with little or no engagement of end-users or their representatives' (Basher, 2006, p.2712). From this, mistrust of expert and local authorities can develop based on criticism that implementing a EWS is a long-term process where local populations can sustain themselves and thus benefit for generations to come. Twigg (2004, p.306) highlights that:

> The bulk of effort and expense is put into transmitting detailed clearly presented information to decision-makers and government emergency management services. Far less effort and funding go into disseminating this information right down to individual communities or households through accessible messages that will warn them and help them to make sensible decisions about how to respond.

To date there has been little evaluation of the influence of institutional organisation and the flow of information between different actors in a EWS on making decisions. Typically, government institutions that mange potential disasters use simple policy, often prescriptive in manner however, with the recognition that decision-making is more complex, local practitioners and vulnerable populations are increasingly managing disasters relevant to them using community based EWS. These EWS are based upon local capabilities and technologies where communities can have ownership, generating an EWS that adopts a bottom-up approach. The idea of community-based EWS has gained momentum, in line with the radical approach developed by Hewitt (1983), and is suggested as an approach to develop people-centric EWS by the UN ISDR PPEW (2006).

2.2.2 Communicating a warning

Warning effectiveness is not just a function of good hazard knowledge and the generation of a warning message, but needs to be complemented by accurate knowledge of risk and risk management actions (Leonard et al., 2008). However, the effectiveness of an integrated response can be constrained by communication, coordination, training, and organisational constraints (Paton et al., 1998). Once a decision to warn has been made, communication of it, in an understandable format to decision-makers and the public is fundamental. It is imperative that all warning communication must be one consistent message, with no contradiction to generate confusion, to help establish faith between the public and other users that the information is correct, and useful (Mileti and Sorenson, 1990). This creates a problem because often there is scientific controversy.

A number of volcanic crises have highlighted the importance of effective communication between different actors of a VEWS. The first crisis illustrates the need to communicate danger to the public and decision-makers. The 1991 eruption of Mt. Pinatubo in the Philippines demonstrated the success of educating the public and government of volcanic hazards by using a video on 'Reducing Volcanic Risk' filmed by the late Maurice and Katia Kraft. This video enabled scientists to help the government and local populations understand the extent of devastation that Mt. Pinatubo could cause, and generated the political will for the safe evacuation of over 60,000 vulnerable people (Tayag et al., 1996). Second, is the issue of communicating with stakeholders to prepare for volcanic crises. The study by Solana et al (2008) highlighted the importance of stakeholder (e.g. civil agencies, land owners, the public) discussion prior to an emergency to establish plans and to discuss expectations and knowledge limitations at Vesuvius volcano observatory, Italy. Third, miscommunication can often occur between the scientists and the media. A public power struggle between two scientific groups over the interpretation of volcanic activity of Soufriere Hills at Guadeloupe during 1976, resulted in widespread confusion (Fiske, 1984). In another example, when Galeras volcano in Colombia reawakened in 1989, the media publicised the unrest as another potential tragedy like Nevado del Ruiz, scaring local communities. This resulted in the public loss of confidence in the scientists. Banks, businesses and traders, who were seriously affected by the uncertainties of the situation, forced the regional and local authorities to ignore the volcanic activity (Velasco, 2000, Cardona, 1997). It took many years to rebuild relationship at Galeras between the scientists and the local authorities, because of the media's actions. Lastly, interactions and relations between scientists and authorities can strain communication. At Soufriere Hills volcano, Montserrat (1995-ongoing), communicating the level of risk of local populations with the local government became a difficult task. Poor social dynamics within the scientific community at Montserrat led to the introduction of expert elicitation to weight the value of each 'experts' view on the scientific interpretation of the volcano's behaviour (Aspinall et al., 2003). This led to distrust and a lack of credibility of the volcano observatory by the local communities (Haynes et al., 2008a).

Within a volcano observatory, culture can shape the ability to communicate and discuss contentious views at a time of crisis. In the 'USGS: Long Valley Caldera Response Plan 2002' (Hill et al., 2002) a conceptual framework for organisational culture was developed that incorporated elements of society (cultural, social, political and judicial systems), history (the organisation's genesis, history, and transformations) and contingency (technology, economics). Broader cultural and social dynamics are also relevant as vulnerable populations have specific cultural preferences. It is interesting that historically warnings have been tailored to local cultures by using different shapes, colours, and words that the particular users are familiar and comfortable so that warnings can be communicated more effectively (discussed in chapter 4).

2.2.3 The importance of local context

Local context is very important to the success of VEWS. This section outlines four key local contexts: the political context, issues of trust and credibility, resources available to operate the VEWS, and finally the type of volcanic activity.

Several historical volcanic disasters have resulted from political interference. The 1902 eruption of Mt. Pelee that destroyed Saint-Pierre, Martinique was in part the result of politicians who, in the middle of an election placed pressure on inhabitants to vote, effectively 'obliging them to stay in the city and vote', resulting in the death of approximately 30,000 people (Scarth, 2002, p.43). In Montserrat, (1995 to present) the decision to evacuate nearly two thirds of the island took much longer than expected while the government remained uncertain as to the status of the volcano, despite scientific advice (Haynes, 2008). Forecasting volcanic eruptions is made further difficult for monitoring scientists because they are confronted by differing political and economic interests; this is most prominent when developing risk maps and issuing alerts. The possibility of lawsuits and false alarms leading to a loss in credibility and potential inappropriate decisions in the future are consistent concerns (Denis, 1995).

The ability of responsible scientists to maintain trust and credibility during volcanic crises is vital to the safety of vulnerable populations (Peterson et al., 1993). Insights from VEWS case studies demonstrate there is no one formula for transmitting scientific knowledge, so that the credibility of experts is in a sense always being negotiated and evaluated therefore, trust cannot be routinised (Wynne, 1996). The relationship between scientific expertise and the public is therefore far more complex than typically recognised in calls for 'public understanding' that emanate from the scientific establishment. A study in Montserrat discovered the most trusted source for volcanic information is 'friends and relatives' (Haynes et al., 2008b, Haynes et al., 2008a), thus highlighting the need for volcanologists to negotiate acceptable levels of risk and trade-offs with the public.

Ideally, a VEWS would have adequate resources and scientists / staff to maintain full communications with stakeholders, develop land-use plan based on the hazards, and run emergency drills. However, this optimal response on an active volcano rarely coincides with an actual crisis (Peterson et al., 1993). There are too few observatories, many with limited staff, funding and equipment for monitoring, resulting in poor communication with local civil officials, and sometimes scientists are so engrossed in their work that they regard interactions with the press and public as annoyances and distractions.

Vulnerable populations vary around a volcano, from those that live on the volcano and nearby, to those that live 10’s of kilometres away in the river valleys formed by the volcano, to those that live 100’s of kilometres away that can be affected by ash. These vulnerable groups have different needs relating to the different hazards and their knowledge of them. With these factors to consider there is a real problem in making sure that scientific information is communicated, understood and effectively aids decision-making to respond to an imminent crisis. Peterson et al. (1993) identified five key factors that lead to some of the complexities involved in operating a VEWS. The majority of these observations relate to the physical aspects of the volcano that determine the ability for scientists to communicate effective warnings. For example, ‘small, frequent eruptions induce good communications and promote good relations between scientists and the public’, as ‘uncertainty about the outcome of volcanic unrest, especially if major violence is among the possibilities, seems to induce poor inter-relations’, partly the result of high levels of uncertainty (Peterson et al., 1993, p.340). In addition there is recognition that ‘the public often has unrealistic expectations of scientists' forecasting ability’ (Peterson et al., 1993, p.348). Therefore, the volcano’s eruptive style, activity and hazards are integral to making a warning relevant to the affected community.

In summary, many lessons have been learnt from VEWS that operate in practice, and during real crises; including the volcanological community who have subsequently reviewed their professional conduct during volcano crises (Newhall et al., 1999). The few case studies outlined in this section demonstrate the value that a more comprehensive understanding of decision-making, communication, and the relevance of local contexts can make VEWS more effective (Ronan et al., 2000). These examples also demonstrate the need for flexibility in a VEWS for variation in the physical hazard and the social context, both of which are locally dependent. This raises questions about the ability for a standardised VEWS to achieve its objective. Volcano alert level systems (VALS) focus on the process of deciding a warning and communicating it. Since this process has repeatedly failed in numerous examples outlined in this section, this thesis focuses on VALS, the first mile of a VEWS, rather than the broader scope of a VEWS.

2.2.4 The case of volcano alert levels

Volcano alert level systems (VALS) are a key sub-system within a VEWS that focuses on the development and communication processes of warnings both prior to and during an event. Typically within a VALS scientists assess the state of the volcano, anticipate future behaviour and decide the alert level. The USGS defines a VALS as (USGS, 2009b):

> A series of levels that correspond generally to increasing levels of volcanic activity. As a volcano becomes increasingly active or as our monitoring data suggest that a given level of unrest is likely to lead to a significant eruption, we declare a corresponding higher alert level. This alert level ranking thus offers the public and civil authorities a framework they can use to gauge and coordinate their response to a developing volcano emergency.

There are many aspects involved in developing a VALS such as the design of the system, the criteria for different alert levels, and the communication between users of the alert / warning. Users often tie alerts issued by scientists into some level of response; this makes a VALS a 'bridge' between the physical and social issues involved in providing hazard warnings. Whilst theoretically VALS are not a complex system, they interact and aim to manage complexity to provide effective warnings.

In 1985, the United Nations Disaster Relief Organisation (UNDRO) published a report on 'Volcanic Emergency Management' outlining one of the first examples of a VALS, called 'Stages of alert of volcanic eruption' (UNDRO, 1985, p.54). Each progressive alert level reflects increasing indicators that the volcano is about to erupt, providing an approximate period and a recommended response by disaster managers. VALS follow a linear progression whereby alerts rise with perceived increasing levels of danger. The UNDRO report also provides strong guidance in relation to limiting panic in volcanic crises via public announcements, decided prior to any emergency, with the public made aware of the arrangements for information. These details vary in each place, region, country, according to the different 'political and social structure of the community and the technical means available. It is therefore difficult to lay down any detailed guidelines for public information and warning' (UNDRO, 1985, p.55). Possibly, because of the importance of local contingencies, literature on VALS since 1985 has remained limited, with some gray literature written by various volcano observatories, institutions and individuals. It has not been possible to find specific literature that addresses VALS at any depth, and therefore no comparative or analytical work on VALS exists to the authors' knowledge. Although as of 2006 the UN recommends standardisation of EWS, it seems the UN previously recognised the importance of local context and developed an idealised VALS for countries to adopt or adapt if they required.

In recent decades increasing standardisation within national VALS has occurred, to allow national adaptations to fit better with the type of volcanism they encounter and their emergency management protocols. In the U.S., there are two standardised VALS, one for ground hazards using words, and one for aviation hazards using colours. In New Zealand, they also use two standardised VALS, but one is designed for the hazards expected at frequently active cone volcanoes, and the other for reawakening volcanoes; both are based on numbered levels (from 0 to 5) (GNS, 2010). Both the U.S. and New Zealand alert levels are decided by the current activity of a volcano; they do not provide action or advice to users for mitigative action. In contrast, the Japanese VALS states the measures to be taken by specifying areas of danger, indicating extent of evacuation, and outlining the expected volcanic activity (Japan Meteorological Agency, 2010). Providing advice on mitigative action or evacuations to civil authorities or emergency managers is also commonly seen in VALS used in developing countries. These few examples illustrate that there are many factors involved in designing a VALS including: what information is provided, whether actions are recommended, the style of warning (actual or forecast), and the number of VALS used.

The World Organisation of Volcano Observatories (WOVO) states that, although there is often worldwide interest in the status of a volcano, 'with the exception of colour codes for aviation, currently there is no standardised international volcano alert levels system' (WOVO, 2008). This is due to a 'wide variation in the behaviour of individual volcanoes and in monitoring capabilities, and different needs of populations, including different languages and symbolism of colours or alert levels' (WOVO, 2008). The WOVO recognise the importance of local contingency, but also the fact that the aviation sector requires a standardised tool they can understand regardless of which airspace they are flying through (discussed further in chapter 4). Whilst the VALS for aviation is standardised globally by the International Civil Aviation

Organisation (ICAO), VALS used on the ground have significant differences in their design and use.

Despite these variances, and in relation to the discussion focusing on the standardisation of EWS discussed above, there has been consideration over the possibility of developing a globally standardised VALS for ground hazards. Scott (2007) investigated this prospect at volcano conferences in the late 1990s and early 2000s, concluding there cannot be international uniformity in VALS given the wide range in volcanic eruptions and hazards, and the recurrence of activity that requires a wide variety of needs to be catered for. Scott questioned whether the process of standardising VALS actually 'undermines the important function they achieve?' (Scott, 2007, p.90) This thesis will address this question in the empirical chapters (4-7), but it is important to note that the considerations made during Scott's study focused only on the hazard and not on interpretations of the hazard, institutional aspects, or the social contexts in which the hazard occurs. These aspects play a vital role in VALS, as will be shown in case studies outlined below that reviews the operationalisation of VALS.

Given the importance of VALS in providing volcanic information to decision-makers, only two papers have been published that specifically review the implementation of VALS, discussing how they operate and analysing their strengths and weaknesses. The first key study reviews the impact of issuing a 'yellow alert' in Quito, Ecuador, for Guagua Pichincha volcano, during unrest in 1998 (Metzger et al., 1999). The VALS used was devised with the USGS and based on four colours (white, yellow, orange and red). The issuance of the yellow alert level (second stage of alert) was during a politically sensitive time, when national level trade unions were calling for a general strike to protest the economic austerity plan implemented by the new President. Yet, the VALS created enough awareness to demonstrate that natural risks could outweigh political circumstances by challenging responsibility, legitimacy and credibility. A number of factors contributed to the fact that officials responded to the volcanic crisis. First, the Mayor, (president of the ecological Nature foundation), was risk averse enough to get involved. This highlights that personalities and the experiences of decision-makers can influence the management of a disaster. Second, the yellow alert level provided a point of reference for politicians, based on the observed phenomena, generating an atmosphere of trust. Third, the analysis by Metzger et al. of the decision-making process and political implications of announcing a yellow alert exposes the difficulties in managing volcanic risk when there are problems over scientific uncertainty and communication, with not only the local authorities, but also scientific experts. At the end of the study, the authors analyse the impact of the yellow alert level one year on from its issuance, discovering interesting results. The yellow alert was no longer a reference point, as they ‘witnessed a gradual change from a system of alerts based on scientific criteria to one based on the expected consequences’ (Metzger et al., 1999, p.220). This led to differentiated spatial management of the crisis, driven by the areas of higher risk to certain hazards. Unfortunately, the alert level system was not redesigned to reflect these spatial differences in risk, resulting in confusion within local populations. In conclusion, 'the way alerts are managed reflects the difficulty the authorities experience in assimilating the changes in volcanic activity, even though these changes are slow, which in turn reduced political credibility during the volcanic crisis management' (Metzger et al., 1999, p.221). This study demonstrates that VALS become complicated precisely because they have different stages of alert that impact the vulnerable society, and indicate the VALS are constantly changing, and therefore difficult systems to understand.

The second study by De la Cruz-Reyna and Tilling (2008), focuses on the introduction of a ‘Volcano Traffic Light’ alert system for Popocatépetl volcano in Mexico that was also assisted by the USGS. This VALS has seven levels of alerts for emergency-management authorities, but only three levels for the public (green-yellow-red). The authors state that ‘the problem of attaining a perception of risk as uniform as possible in a population measured in millions during an evolving eruption requires searching for communication tools that can describe – as simply as possible – the relations between the level of threat posed by the volcano, and the level of response of the authorities and the public’ (De la Cruz-Reyna and Tilling, 2008, p121). The traffic light design aimed to make the system proactive, efficient, unambiguous and culturally adequate, which it appears to have achieved. This paper highlights the fact that there is a further disparity within national VALS, as some countries, such as Mexico, have different VALS for the decision-makers and for the public.

Both papers highlight the need for VALS to be locally adapted, and demonstrate the difficulties of using a linear VALS when volcanic crises can occur for long periods, causing warning information requirements to change as seen in the Metzger et al. study (1999). By studying operationalised VALS, this thesis can provide further insight into how they work in practice.

2.2.5 Summary

This chapter, so far, has demonstrated that for EWS to be effective, a better understanding of the role of social issues, and of the communication and decision-making processes in EWS needs to be developed. There are two key objectives to warnings; to be noticed and encoded, and to provide understandable information for recipients to make informed decisions regarding compliance (Laughery, 2006). Whether warnings achieve these objectives is dependent on the design of the warning, as well as the characteristics of the users and the situation.

Over the last forty years, volcanic crises have supported the argument that EWS are not linear, but have to negotiate numerous complex systems. This requires a bottom-up approach that considers local context (contingency) that needs to respond to changes over time, and are socially constructed and adapted by the relevant society's requirements. This contradicts increasing levels of standardisation in EWS that do not facilitate local flexibility or recognise the complexities involved, and how to best govern them. However, examples outside of disaster management have shown that although standardisation is reductive, it helps establish responsibilities and cooperation between the different groups involved. Currently there are two key challenges to standardising volcanic warnings: first, the variability of the hazard and location; and second, the social context of users of the warning, who have fundamentally different requirements (i.e. between aviation and ground users). Therefore, a key question is how can a warning be standardised to consider local context and appeal to a diverse range of users?

All too often the standardisation of systems has led them to be 'black boxed'; this has happened to VEWS and VALS despite numerous attempts over decades to represent them and address the processes that occur within them. This thesis seeks to open the VALS black box. Part three of the literature review investigates the processes that occur within a VALS by examining how scientists understand and manage the complexity of volcanic hazards and the issues that arise during the process and how social science approaches to these issues can provide insights into the black box of VALS.

2.3 Volcanology, uncertainty and risk

The ability for a VALS to provide accurate and timely warnings is limited by the level of scientific knowledge about volcanoes their behaviours'. This section first addresses how scientists who study volcanoes view and manage these limitations using various tools, and how the complex behaviour of volcanoes leads to scientific uncertainty. Scientists build models to develop forecasts, and conduct quantitative risk assessments to address scientific uncertainties (e.g. probabilistic risk models), but due to a lack of data and high levels of uncertainty these processes are socially constructed. The scientific community commonly define risk as a mathematical process however; social scientists view risk, particularly where uncertainty is high, as a far more complex and abstract concept. The philosophy and sociology of scientific knowledge can provide insights into the management of uncertainty within scientific knowledge; therefore, this section goes on to reflect how social scientists view risk both conceptually and practically. This raises issues concerning who is the expert in determining the risks and in decision-making, and how this affects developing policy, such as the standardisation of VALS.

2.3.1 The complex science of volcanology

Volcanoes are complex natural phenomena because whilst volcanic behaviour tends to follow some underlying principles, it is not linear nor chaotic in nature (Sornette et al., 1991). To date the volcanological community has been unable to generate accurate and reliable predictive models for use on a single volcano, let alone for the many types of volcano and styles of eruption that occur, although improvements in forecasting volcanic behaviour is being developed via a number of models (Kilburn, 2003). Volcanoes tend to occur at tectonic plate boundaries, where plates are either converging (as around the Pacific Ring of Fire which hosts approximately 80 percent of currently active volcanoes) (Clapperton, 1977), or diverging (in Iceland and along the Mid Atlantic Ridge). A number of volcanoes, however, occur above mantle plumes in intra-plate settings. These occur on either continental crust (Yellowstone, Wyoming) or oceanic crust (Hawaiian Islands). The key to differences in relation to volcanic types is the chemistry, which characterises magma composition and its interaction with the environment (Francis and Oppenheimer, 2004). Since magma can only be analysed to very shallow depths the only indicators of magma composition are the deposits produced by volcanic activity such as lava flows. Different magma geochemistry generates a range of igneous rocks typically classified by their silica content, ranging from silicic (granite, dominantly continental crust) to mafic (basalt, dominantly oceanic crust). Depending on the tectonic location of the volcano, the geochemistry of the magma will vary given the interaction of different crust types, and the host rock through which the magma travels through, which may be metamorphic or sedimentary rocks. Different magma compositions lead to different styles of eruptions. However, it is not just magma composition that is important in controlling hazards, but also the potential for magma and water interaction, the stability of the volcano, and interactions with the physical environment. There are further types of volcanic styles resulting from the interaction of volcanic activity with water causing phreatomagmatic eruptions and structural failures such as lateral blasts. Italian geologist Giuseppe Mercalli developed a system of volcanic terminology in the early twentieth century based on the observations of the violence and characteristics of some well-known eruptions: Hawaiian, Strombolian, Vulcanian, Pelean, Sub-Plinian, Plinian and Ultra-Plinian (Scarth, 1994). This system is still widely used today despite more quantitative measures of determining eruption styles such as the ‘violence’ of eruption using the Volcano Explosivity Index (VEI) ranging from 0-8, or a number of other parameters that may be based on tephra (fragmented rock) fall out and intensity. Different styles of volcanic eruptions produce a number of different hazards as outlined in the introduction. Duration of a volcanic eruption can range from minutes to decades, and volcanoes can erupt frequently, or remain dormant for thousands to hundreds of thousands of years resulting in explosive resurgence (as seen at Chaiten volcano in Chile, 2008). Volcanoes can change style during or between eruptions without any warning. All these factors contribute to the complexity of volcanoes; they each have individual characteristics, although these can change. Consequently, understanding and managing volcanic hazards is difficult, but three main methods are adopted; reviewing a volcano's history, monitoring it, and developing engineered structures that can mitigate against volcanic hazards.

To understand past activity of a volcano, detailed mapping and field work is used to collect and analyse samples to review the magma composition, date the rocks using radiocarbon and a number of other techniques (Chester et al., 2005), and to establish the geological history. Drawing a hazard map indicates historical hazards and the scale of their impact on the land surrounding the volcano. Hazard maps aid emergency planners review emergency plans by identifying areas of danger, the hazards that a volcano may produce, and to prevent them evacuating people to dangerous areas. Although mapping is valuable, it requires time, money and skilled geologists, something not all volcano observatories can afford.

Monitoring techniques are used to detect and quantify expressions of magma migration at depth, and to monitor other related hazards. By monitoring current volcanic activity, it is possible to detect changes in activity and develop forecasts of potential volcanic activity or hazards. Monitoring traditionally developed from geophysical techniques such as seismicity (McNutt, 2000), monitoring ground deformation (Dzurisin, 2007), and gravity modelling (Battaglia and Segall, 2004). In addition, geochemical measurements of volcanic gases (typically sulphur dioxide and carbon dioxide) and geothermal liquids help develop a picture of what is occurring underground (Edmonds, 2008). The ability to use monitoring data to develop forecasts is improving significantly as new technologies such as computer, satellite and telemetry technology improve data transmission, analysis and modelling techniques. New state-of-the-art monitoring methods include remote sensing techniques (Galle et al., 2003) and infrasonic pressure sensors (Johnson et al., 2008). The USGS states that volcano monitoring occurs in two modes: a forecasting mode before and between eruptions, and an alerting mode when the volcano is erupting, changing the focus of the monitoring methods used.

The development of scientific understanding and technology is rapidly expanding scientist's ability to monitor volcanoes and interpret data. There is still a need, however, to synthesize monitoring and historical data relating to volcanic behaviour into an integrated model. This development has meant that scientists felt that 'until recently, the science of volcano monitoring has largely been in the observation itself, with the interpretation of observations best described as an art' (Francis and Oppenheimer, 2004, p.446). Although improved monitoring has enabled forecasting to evolve from empirical pattern recognition, to modelling some of the underlying dynamics, there are still many uncertainties therefore it could be implied that volcano monitoring still remains an art, despite monitoring developments. This is discussed further in section 2.3.3.

Engineering large-scale structures to mitigate against the impact of volcanic hazards has been used in a number of countries including Japan and Italy. Engineering methods are typically employed for effusive volcanic activity because the consequences of this type of activity can be manipulated such as at Mt. Etna in 1992 (Barberi et al., 1993), and 1973 at Heimaey Island, Iceland (Williams and Moore, 1983). Engineering around volcanoes has developed significantly via Sabo structures, built to cope with secondary erosional hazards such as debris flows and mudflows by filtering different sizes of boulders and sediment (Takahashi, 2007). The use of engineering in managing volcanic crises remains limited, partly due to high costs and the ability to contain only specific hazards. However, in some cases they have enabled populations to live safely on and around volcanoes, as seen at Unzen in Japan (Ikeya, 2008).

2.3.2 Modelling and quantifying uncertainty

Once a volcano erupts there is often no time to evacuate effected regions, therefore a precautionary approach is adopted. Consequently forecasting the nature, scale and extent of volcanic hazards is essential despite the difficulties in generating an accurate forecast. Scientists (typically geochemists, geophysicists, geologists, volcanologists and mathematicians) have exploited a range of quantitative theoretical and statistical models of volcanic monitoring data to develop better prognosis of a volcano's behaviour, and deal with the high levels of uncertainty involved. Many volcanic systems are inherently unpredictable, complex and sometimes chaotic, however some systems can be constrained, particularly for volcanoes showing regular periodic behaviour (Sparks, 2003, Marzocchi et al., 2007, Marzocchi et al., 2006). Therefore, volcanoes are not considered chaotic systems, but complex ones.

Scientists and mathematicians attempt to understand underlying dynamic volcanic processes by developing theoretical models. Often only one component of many processes occurring can be modelled, thus removing consideration as to how processes may interact with one another. In addition, obtaining measurements to test models can be extremely difficult (often due to high temperatures and pressures) so that observations are fed into models without fully understanding the dynamics involved. A number of theoretical models have been developed that have been successfully used for many years including the Mogi point source model used to model ground deformation (Mogi, 1958), models to forecast lava flow velocities and distances for 'Aa' and 'Pahoehoe' flows (Kilburn, 2003, Kilburn, 2004), and forecasting eruptions using multi-scale fracturing (Kilburn, 2003, Kilburn and Sammonds, 2005). Whilst these and other models have been useful, the physical properties of magmas are highly complex, non-linear, time-dependent processes that are typically coupled making it difficult to isolate any one process (Melnick and Sparks, 1999). The non-linear and time-dependent characteristics of volcanic systems are fundamental disadvantages in the ability to develop forecasts, given the complexities and subsequent uncertainties involved.

Due to the intrinsic uncertainties within the complex volcanic system Sparks (2003) argues that 'forecasts of eruptions and hazards need to be expressed in probabilistic terms that take account of uncertainties' (p.1). It is thought by scientists that statistical analysis of complex volcanological data can improve forecasting by developing rigorous methods for quantifying the likelihood of outcomes given a set of observations, both present and past (Mader, 2006). There are a number of ways in which statistical tools are used to forecast volcanic activity: forecasting methods and application (Varley et al. 2006), volcanological time series (Young et al., 2006), methods that link numerical simulations of volcanism and probabilistic modelling including sensitivity analyses and inversion techniques (Neuberg et al., 2006), and forecasting activity based on geostatistical concepts (Jaquet et al., 2006). Frequently decision-support models combine these statistical estimations to provide what scientists regard as 'objective' analyses of eruptive state in probabilistic terms.

Many volcanologists believe the future of forecasting lies in statistical modelling. In practice, however, the statistical modelling of volcanic behaviour and processes inevitably has high levels of uncertainty, making decisions based on the interpretation of raw data difficult. To solve this issue decision-support models are commonly applied in forecasting models, based on Bayesian Belief Networks (BBN)[2], that provide a general framework to combine uncertain evidence (soft or hard data, beliefs, probability distributions) on the basis of evidential likelihood of each element (Aspinall et al., 2003). An example commonly used is that of event trees, used as a framework to discuss probabilities of possible outcomes of volcanic unrest and convey hazard information to non-scientists (Newhall and Hoblitt, 2002). Additionally, combining an evidence-based approach with other formalised procedures such as the elicitation of expert opinions provides an auditable trail for the way scientific information has been used (Aspinall et al., 2002, Aspinall et al., 2003, Aspinall et al., 2006b). Quantifying the value of an expert is difficult, so expert elicitation generated controversy when applied at the Montserrat crisis in 1996-7. Rather than rely on the opinions of experts, Marzocchi facilitated a quantitative volcano risk metric to base decisions for eruption forecasting using a Bayesian Event Tree[3] (BET_EF) (Marzocchi et al., 2006, Marzocchi et al., 2007), and a probabilistic scheme for

[2] Bayesian Belief Networks (BBN) use models for reasoning about uncertainty.

[3] Bayesian Event Tree (BET) translates volcanological input into probability of any possible volcano-related event. 'Volcanological input' is every type of information relevant for the event under study. It ranges from models (i.e., ash fall model), to historical / volcanological information (i.e., eruptive catalogues), to monitoring measures (i.e., detecting magma movement). Taken from: Probabilistic Volcanic Hazard Assessment and Eruption Forecasting: The Bayesian Event Tree approach. Open File Report, Marzocchi, W., Selva, J., and Sandri, L. INGV, Bologna, Italy, p.81.

eruption forecasting and cost-benefit analysis (Marzocchi and Woo, 2007). However, when these schemes were applied in Italy during the 2007 Stromboli response, they demonstrated only a small cost-benefit in their application (Bertolaso et al., 2009) demonstrating limited value in practice.

Of particular interest to this study is the quantitative approach adopted to change an alert level (Aspinall et al., 2003, Baxter et al., 2008). 'Volcanic crises may be represented as a staged progression of states of unrest' and 'if the state conditions can be interpreted physically, e.g., in terms of advancing materials failure, this knowledge could be used directly to inform a decision on alert level setting' (Aspinall et al., 2006a, p.112). Since civil authorities often respond directly to alert level changes Aspinall and Cooke (1998, p.4) state that:

> Setting the level always becomes especially critical or contentious when a decision may be needed to switch from one level to another. It is at these times that the formalized elicitation approach comes into its own and, at the MVO [Montserrat Volcano Observatory], a semi-quantitative weighted voting scheme was devised and used to good effect in 64 separate reappraisals.

By using the expert elicitation system Aspinall et al. developed, they provided the decision-makers with an 'optimal' value from the expert elicitation and the measure of the spread of views so they could make their own judgement in accepting recommendations, see Fig. 2.7.

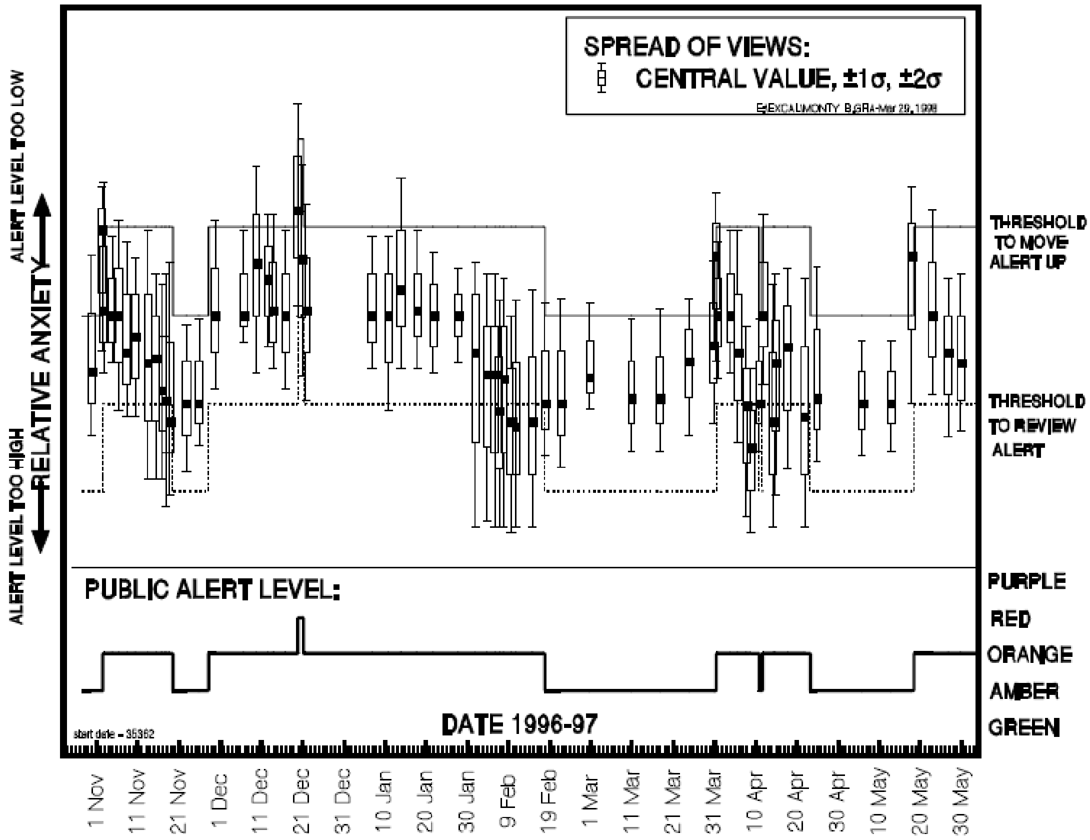

Figure 2.7 Repeat appraisals of volcanic alert level using expert judgement elicitations (Aspinall and Cooke, 1998, p.4)

Although Aspinall et al. recognise the difficulty in identifying the 'state' conditions of the volcano, they suggest that by using a decision-support tool ‘the assessed probability of an event to any number of such varying and variable factors can be resolved *objectively* in terms of an evidence-based decision’ (Aspinall et al., 2003, p.284) (author’s emphasis). Insights provided by the sociology of scientific knowledge (discussed in the next section) indicate that no such decision-support tool, or any statistical model, is objective because the parameters put in place to run the model are inherently subjective. In fact, Aspinall et al. go on to state that in practice there will ‘often be a multitude of observations, theories, models and expert opinions to consider, most of which can address only partially the issue of a volcano’s state and its possible progress to eruption, and some of which will be contradictory’ (Aspinall et al., 2006a, p.113), implying there are no objective interpretations . This point will be expanded in section 2.3.4 that reviews the role of risk assessment to manage the scientific uncertainties in volcanic crises commonly employed by scientists.

Obtaining and modelling data play a role in understanding and managing phenomena that result from volcanic processes, yet actual understanding of these processes remains incomplete. The interpretation of monitoring data by scientists is critical, as there are no right or wrong answers; rather there are theories of what they may indicate. It is therefore imperative to understand what factors affect this process of interpretation and theory development, and to question how knowledge is constructed and what it means. What to do when there are large uncertainties? How can decisions be accountable? Over the last 50 years the philosophy and sociology of science has surveyed, criticised and transformed our knowledge practices. The next section explores some of these discoveries within the context of how people have thought about coping with scientific uncertainty in different contexts.

2.3.3 Theorising the philosophy and sociology of uncertainty

The problems of scientific uncertainty and lack of consensus in data and interpretation are not unique to volcanology. Questions regarding the assumptions, foundations, and implications of scientific knowledge have long been a feature of the philosophy of science and highlight the difficulties involved in establishing both 'science' and 'scientific knowledge' (Curd, 1998). The philosophy of science has developed from repeatedly asking questions concerning the nature of truth, how to form theories, and proving them. Scientists investigate the world using experiments, observations, and theory-structure that generate and validate scientific ideas, but there are problems with these methods. This section will review some of these issues and their implications for the methods adopted by scientists to understand volcanic behaviour and form warnings.

Philosophers typically adopt one of four methods to understand how scientific knowledge is constructed and how its special character can be defined: inductivism (Chalmers, 1999), falsification (Popper, 1968), scientific values in paradigms (Kuhn, 1962, Kuhn, 1977), and scientific conduct (Merton and Storer, 1973). Historically arguments were commonly constructed using induction, ascribing properties or relations based on a number of observations or experiences, or to formulate laws based on limited observations of recurring phenomenal patterns, much like volcano scientists do with monitoring data. Yet to borrow Karl Popper’s example, the assumption that all swans are white is invalidated when one black swan is observed. Since inductive conclusions cannot yield certainty, Karl Popper a critic, replaced it with falsification. His argument states that logically no number of positive outcomes at the level of experimental testing can confirm a scientific theory however; a single counterexample is logically decisive as it shows the theory to be false. Therefore, he argued that a theory or hypothesis should be considered scientific if, and only if, it is falsifiable.

Falsification has its limits; when evidence conflicts with prediction of a law or theory, it could be the evidence at fault, not the theory. This is known as the Duheim / Quine thesis, i.e. the claim that a theory can never be conclusively tested in isolation, what is tested is an entire framework of beliefs (Gillies, 1998). Kuhn tried to solve the problem by determining that historically scientific revolutions are characteristic of scientific progress, where a revolution involves the abandonment of one theoretical structure and its replacement by another incompatible one. He stated that the disorganised and diverse activity that precedes the formation of an area of science becomes structured and directed when a scientific community adheres to a single paradigm. A paradigm sets the standards for legitimate work within the science it governs, and comprises general theoretical assumptions, laws, and techniques for their application that members of a particular scientific community adopt. Therefore, rival paradigms are ‘incommensurable’. Kuhn took a ‘relativist’ view whereby the account of progress is determined by the values of the individual, group or culture rather than a definitive, neutral factor. Although Kuhn was not comfortable with portraying a relativist position, he indicated that the way we discover nature is ‘intrinsically sociological’.

Kuhn’s Structure of Scientific Revolutions in the 1960s opened the door to the study of the sociology of scientific knowledge (SSK). SSK is based on the assumptions that natural reasoning capacity and sense perceptions are not sufficient conditions for the production of scientific knowledge. Sociologists began to look at contents, style, methods, conventions and institutions, in other words knowledge itself as being socially and materially constituted. This research initially focused on historical studies of changing paradigms in science, exploring how scientific understanding changed not only because of internal scientific debate, but also due to external context. Bloor’s ‘Strong Programme’ was right at the heart of the new SSK by denying the exceptionality of scientific methodology. He stated that the sociology of knowledge examines the interaction between whatever counts as knowledge in a particular culture and the social characteristics of that culture (Collins, 1981). Bloor offers a characterisation of scientific method by stating that science proceeds by arranging experiments so that social, psychological and other variables are as balanced as possible. The key finding of the Strong Programme is of ‘finitism’, where the drawing of implications is always a cultural accomplishment. Finitism was a significant turning point in science studies establishing that people collectively determine what knowledge is, even if they experience that knowledge as compelling and external to themselves. What the Strong Programme demonstrated is that scientists are not objective, and their capabilities to interpret and analyse hazard data will depend on 'finitism' i.e. cultural aspects, both within for example the volcano observatory and organisation, and the country and regional cultures. As discussed in the above section it is clear that some scientists do not think of their science as subjective, socially constructed, or recognise and the importance of culture in their beliefs. The Strong Program has since been supplemented by other schools: the empirical program of relativism EPOR (Collins, 1981, Collins, 1990), Actor-network theory (Latour, 1987, Latour, 2005), Constructivism (Knorr-Cetina, 1981, Knorr-Cetina, 1999), Social construction of technology (SCOT) (Bijker et al., 1987), Symbolic interactionism (Blumer, 1969), Ethnomethodology (Lynch, 1993), and the Normative Structure of Science (Merton and Storer, 1973).

Developments in the philosophy and sociology of science demonstrate that observational data is not an infallible tool in developing models as it excludes the unknown. Testing and verifying theories on volcanological processes are difficult for a number of reasons: a volcano needs to be well monitored and erupt frequently to provide the best hope of developing a good scientific understanding, and scientists need to be able to measure processes like pyroclastic flows using robust technology (which is still not possible). Scientists employ computer models to simulate volcano's behaviour, but the interpretation depends on the analyst as much as the interpretation of science, and their assumptions when inputting parameters of a model. This raises questions about the validity of developing models and forecasts for volcanic hazards and the reliance that scientists can develop on models, forgetting that the underlying science remains indefinite.

In addition to the social construction of knowledge by scientists, the cognitive 'product' of the work of science is shaped by scientists' choice of work organisation (Yearley, 2005) and its cultural approach to complexity. Merton and Storer (1973) outlined that if the exceptional quality of science cannot be located in a method, then it could be located in the social norms that govern conduct within the scientific community. The way organisations are structured and how and why they behave in such a way is important in the context of VALS since there are a number of stakeholders and organisations involved, each with a key role in knowledge production. Vaughan (1999) drew on organisational theories to demonstrate 'the ironic fact that organisations, necessary to produce, coordinate and maintain complex techno-scientific systems also have irreducible and emergent effects of the way complex information is transmitted, communicated, processed and stored' (p.913). Failed organisations (Vaughan, 1996, Eden, 2004, Knorr-Cetina, 1999) have highlighted the problems involved in large government related scientific institutions that have to make decisions (such as the issuance of volcano alert levels). Eden (2004) investigated how organisations frame the problem they try to solve, defining frames as 'problem representation and solution requirements within which are embedded organisational goals, assumptions and knowledge about the world and traces of previous definitions of problems and solutions' (p.224). Her model demonstrates that problem-solving and sense-making are more intimately related than has been acknowledged in the existing literature. However, volcanic crises not only deal with laboratory sciences, but with hazards that are both situated and idiographic. Consequently, there are difficulties in using risk frameworks to manage volcanic crises that suggest that they are better considered through frameworks of uncertainty.

2.3.4 Risk and uncertainty in the science of volcanology

Scientists commonly regard risk as the interaction between the hazard and society; 'the magnitude of a potential loss – of life, property, or productive capacity – within the area subject to hazard(s)' (Wright and Pierson, 1992, p.28). Historically risk has been reviewed using risk assessments that are quantitative, despite often being based on qualitative measurements (Stirling, 2003, p.36). Scientific methods of understanding risk include a range of 'quantitative and / or expert-based risk assessment techniques, involving varying forms of scientific experimentation and modelling, probability and statistical theory, cost-benefit and decision analysis, and Bayesian and Monte-Carlo[4] methods' (Stirling, 2007, p.309), as demonstrated in the section 2.3.2. They are intrinsically reductive processes from complex and contested realities (i.e. what a volcano's activity is) into a discrete set of ordered categories (such as alert levels) amongst other simplifications. Assumptions in volcanic risk are based on past behaviours but there are situations where the unknown or unexpected (i.e. ignorance) have occurred (as seen at Mt. St. Helens in 1980, and Mt. Unzen in 1991).

Within mathematical and scientific disciplines, risk assessment is usually conducted on the basis illustrated in Fig. 2.8, which demonstrates 'the unifying approach to risk and risk analysis is based on the idea that risk is a way of expressing uncertainty related to future observable quantities' (Aven, 2003, p.47). Models in risk analysis, such as Fig. 2.8, first require observable quantities used to develop a deterministic model that link the systems performance with these

[4] Monte Carlo methods (or Monte Carlo experiments) are a class of computational algorithms that rely on repeated random sampling to compute their results.

observations. Ultimately, it is possible to calculate the uncertainty distribution of the performance measures and determine a suitable prediction.

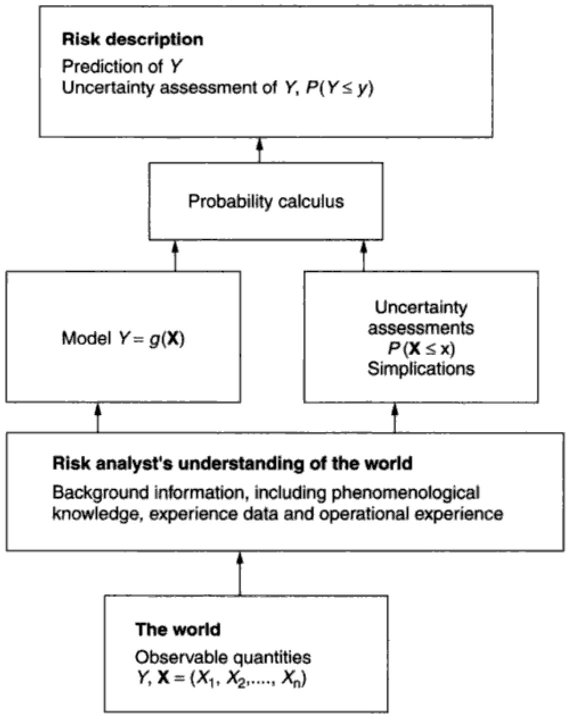

Figure 2.8 Basic elements of risk analysis (Aven, 2003, p.49)

These models are useful when there are observable quantities, but as discussed, there are few such quantities in volcanic processes. Without such quantities, it is not possible to conduct a risk analysis, as there is no basis on which to calculate probabilities. In addition, the risk analyst's understanding of the world would be dependent on, or influenced by their own experiences or the behaviour of a particular volcano. Because of this there would be different levels of ambiguity arising from different framing assumptions (i.e. the views of the different users), and ignorance in assessing the uncertainties involved because it is not possible to fully quantify the likelihoods or characterise all the possible outcome factors i.e. our uncertainty about our uncertainty (Cyranski, 1986). This means that when it comes to volcanic hazards, a mathematical approach to risk assessment is not yet possible to any meaningful degree. In the context of high uncertainty, Stirling states that 'reductive quantitative risk fails to recognise the intrinsic limitations and contradictions in the rational choice foundations that underlie risk assessment' (Stirling, 2003, p.52). This suggests that models, such as Bayesian event trees and expert elicitation, are less useful because they do not consider ambiguity and ignorance when attempting to quantify risk.

It is difficult when there is no scientific certainty to say that whatever evidence there is, it is enough ‘to determine that the potential harm is significant and irreversible’ (von Krauss et al., 2005, p.4). However, there is a need to address these uncertainties and risks, despite the complexities involved. Complexity impinges upon scientific enquiry in three key ways: ‘i) physical reality where the properties of self-organization, irreducible uncertainty, emergent, and others come into play; ii) the need to consider different epistemologies (a plurality of perceptions or viewpoints must be acknowledged and respected, even if not accepted as equally valid); iii) the need to consider different “intentionalities” (differing goals)’ (Gallopin et al., 2001, p.226). Complex volcanic behaviour generates scientific uncertainties, making it difficult for decision-makers responsible for public safety to establish what the risks are. Therefore, these risks are multiple as there are many stakeholders involved in any one-volcano crisis.

Risk is a concept that is often perceived to have a potentially negative impact on an asset or some characteristic of value that may arise from some present process or future events. Commonly risks are presented as a probability of a known loss or gain. In his seminal work ‘Risk, Uncertainty, and Profit’, Frank Knight established the distinction between risk and uncertainty: ‘a measurable uncertainty, or ‘risk’ proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We [...] accordingly restrict the term ‘uncertainty’ to cases of the non-quantitative type’ (Knight, 1921, p I.I 26). This implies that unless risk is quantified, it is not a risk but what we call uncertainty.

A traditional risk assessment uses a powerful set of methods when looking at risk, but as shown in this section they are not applicable under conditions of high uncertainties. Although nearly every aspect of a VALS is uncertain, understanding uncertainty alone does not capture ‘incertitude’; a concept that combines uncertainty, ignorance, ambiguity and risk to provide a more holistic view of knowledge, or lack of (Stirling, 2007)[5]. This has practical implications for the robustness of conventional reductive risk assessment in decision-making, and Stirling believes that persistence in using these reductive methods under conditions other than a strict state of risk (as defined by Knight 1921), are irrational, unscientific and potentially misleading. Uncertainty indicates that a single aggregated picture of risk is neither rational nor ‘science-based’; ambiguity highlights that it is not rigorous or rational to provide a single ‘sound scientific’ picture of risk; and ignorance demonstrates that parameters are not only contestable but also, at least in part, unknown (Stirling, 2007, p.310). Ignorance can also be classed as ‘the black swan’, reflecting our reliance on inductive knowledge (Taleb, 2007). These four elements

[5] Stirling's concept of incertitude emerged from his work on science and technology policy.

of incomplete knowledge are presented in Fig. 2.9 providing schematic examples and showing the relationship between knowledge of probabilities (risk, uncertainty) and the outcomes (ambiguity and ignorance).

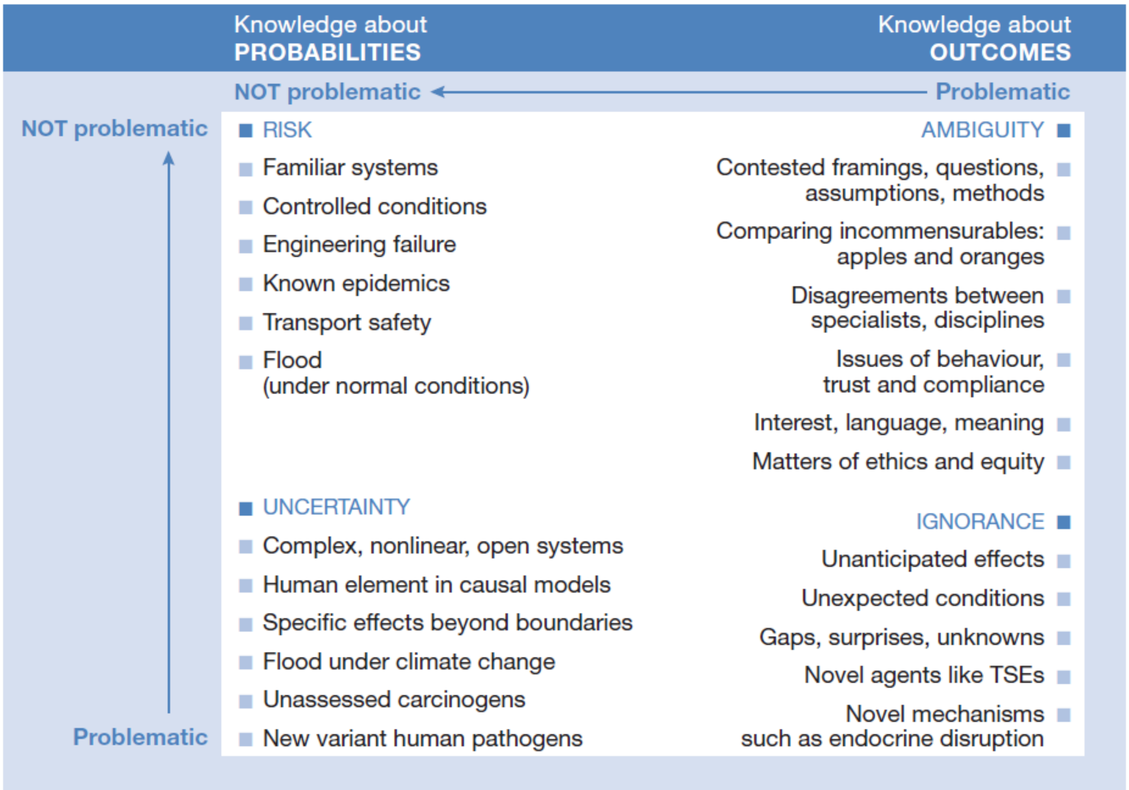

Figure 2.9 Contrasting states of incomplete knowledge, with schematic examples (Stirling, 2007, p.312)

The concept of 'incertitude' provides a tool to evaluate the risks covered by existing forms of assessment in volcanology, as shown in Table 2.1. The sub-table on risk in Table 2.1 reviews the volcanological literature that evaluates methods of assessing risk, which are usually adopted under conditions when systems are familiar and conditions controlled. Given our knowledge of volcanoes remains incomplete, as discussed in section 2.3.1, it is unsurprising that many of the methods applied to understand risk are based around probabilistic models. The sub-table on uncertainty reviews the methods used to analyse the complex, non –linear system of volcanoes and typically uses historical data to understand the volcano's past behaviour as a method of indicating future behaviour, and reviewing possible outcomes via event trees. Ambiguity relates to the contested framings, assumptions and disagreements between experts, and relates to the impact of behaviour, trust, compliance, ethics and equality when assessing risk and uncertainty and making sense of data. Volcanological approaches to ambiguity have predominantly revolved around the work conducted on expert elicitation and guidelines developed for scientists during a crisis. Approaches to ignorance are broad and motivate most research on volcanic processes and behaviour. The quest to understand incomplete knowledge and unanticipated events is driven by experimental research, monitoring volcanoes so that it possible to determine volcanic activity, and by developing databases to share knowledge globally to prevent ignorance about events already experienced.

Table 2.1 demonstrates that within volcanic risk literature, assessments have considered different aspects of incertitude, but not under Stirling's' categories of risk, ambiguity, uncertainty or ignorance. Studying the interrelationships between these four aspects may provide beneficial insights. This supports the view that taking a more holistic approach to the decision-making processes involved in VALS may be advantageous; recognising the limitations of science and the incertitude involved. In natural hazards, risk is regarded as the likelihood of occurrence of a hazard which is determinable through the formula 'risk = likelihood of occurrence x seriousness' or 'risk = hazard x vulnerability' (Wisner, 2004). For either definition, quantifying risk is difficult given the inability to quantify social concepts such as 'seriousness' and 'vulnerability', and excludes issues relating to incertitude. Uncertainty about when a volcano is going to be active, what type of hazard it is going to produce, and how this is going to affect vulnerable populations affects how effective a VEWS or VALS can be. Scientific uncertainties result in passing on uncertain information in a warning, placing the vulnerable populations at risk. Risk assessments by scientists aim to overcome this issue by evaluating the risk of them getting their forecast right or wrong. The next section explores a social scientific approach to understanding risk rather than using reductive risk assessments.

<u>Risk:</u> State of incomplete knowledge: familiar systems, controlled conditions, engineering failure

Methodological Responses	Related Volcano Literature	References
Risk assessment	Mapping and historical evidence	(Pareschi et al., 2000)
Multi-attribute utility theory	Statistical models – predictive and hazard specific	(Varley et al., 2006)
Cost-benefit, decision analysis	Decision analysis with cost benefit models	(Marzocchi and Woo, 2007)
Monte Carlo modelling	n.a	(Jaquet et al., 2006)
Bayesian methods	BET modelling	(Marzocchi et al., 2007)
Statistical errors, levels of proof	**n.a**	

<u>Uncertainty</u>: State of incomplete knowledge: complex, non-linear, open systems

Methodological Responses	Related Volcano Literature	References
Burden of evidence	Geological reports looking at eruption styles	(Tilling, 2002)
Onus of persuasion	Research further to understand volcano behaviour	(Dzurisin, 2007)
Uncertainty factors	Use event trees and databases	(Newhall and Hoblitt, 2002)
Decision heuristics	n.a	
Interval Analysis	Volcano interval analysis	(Pyle, 1998)
Sensitivity analysis	**n.a**	

<u>Ambiguity:</u> State of incomplete knowledge: contested framings, questions, assumptions, methods, comparing incommensurables, disagreements between specialists, disciplines; issues of behaviour, trust and compliance; interest, language; matters of ethics and equity

Methodological Responses	Related Volcano Literature	References
Participatory deliberation	Expert solicitation, stakeholder negotiation	(Aspinall et al., 2006b)
Stakeholder negotiation	IAVCEI crises guidelines	(Newhall et al., 1999)
Q-method, repertory grid	n.a	
Scenario workshops	n.a	
Multi-criteria mapping	n.a	
Interactive modelling	**n.a**	

<u>Ignorance</u>: State of incomplete knowledge: unanticipated effects, conditions; surprises, unknowns

Methodological Responses	Related Volcano Literature	References
Targeted research and horizon scanning	Monitoring volcanoes	(McGuire et al., 1995)
Transdisciplinary and institutional learning	Experimental research	(Johnson et al., 2008)
Open-ended surveillance and monitoring	Overseas assistance	USGS VDAP team
Evidentiary presumptions	Databases	WOVOdat
Adaptive management	**n.a**	

Table 2.1 Studies within the volcanological community that address the methodological responses to risk decision-making, and 'uninvestigated' responses framed by Stirling's model of incertitude (Stirling, 2007, Stirling, 2003)

2.3.5 Social dimensions to understanding risk

Risk remains an elusive, contested and inherently controversial concept with a number of specialist definitions and classifications to define its meaning. There are different facets of risk such as how do we know risk, how is it perceived, and how do people and institutions embody this knowledge? Risk has two key schools of thought. First, the mathematicians, scientists and economists who want to define risk using a quantitative value as explored above. Second, social scientists who view risk as a social construct that is difficult to reduce to a number given the complexities involved in perceiving risk, the irreducibility of contingency, and the effect of societies on actions. This section reviews social scientists approaches to risk to explore how they can help understand volcanic risk in uncertain contexts with particular emphasis on what is at stake for publics.

So far, this chapter has focused on how scientists understand risk to formulate a warning and reviewed the social context in which they make these decisions. However, there is a process of communication involved to relay the identified risks to non-scientists, who have their own social contexts that shape their understanding of the risks involved. In communicating risk Fischoff, an experienced emergency manager, suggested that: ‘to get the content of a communication right requires a significant analytical and empirical effort. It means summarising the relevant science, analysing recipients’ decisions, assessing their current beliefs, drafting messages, evaluating their impact, and iterating the process as needed. Accomplishing these tasks can significantly reduce the chances of producing messages that patently violate the norms of communication’ (Fischhoff, 1995, p.142). Therefore to communicate risk in the 'right' way is a complex process, because there are different concepts of what the risk actually is between the scientists and the decision-makers.

The sociological concept of risk is broad and fuzzy which, although is often regarded as a weakness, reflects a key sociological insight that ‘risk involves more than simply an objectively given probability’ (Arnoldi, 2009, p.5). Sociologists are cautious of how risks are calculated, but are interested in the objectifications of risk i.e. how they are made and what they are used for. A majority of sociologists adopt a social constructivist approach to risk, but there is a wide spectrum of risk analysed in sociological analysis as this quote highlights:

> Risk is a calculation. Risk is a commodity. Risk is a capital. Risk is a technique of government, Risk is objective and scientifically knowable. Risk is subjective and socially constructed. Risk is a problem, a threat, a source of insecurity. Risk is a pleasure, a thrill, a source of profit and freedom. Risk society is our late modern world spinning out of control (Garland, 2003, p.49).

For social scientists risks are potential dangers that have social and political consequences, are understood within a social and cultural context, and influence the practices and knowledge's with which society is governed. These three key aspects are derived from three of the most important sociological theoretical approaches to risk developed by Ulrich Beck, Mary Douglas and Michael Foucault. Douglas focused on the cultural logic behind differences in what people fear and what risks they take. Her work stems from an anthropological approach to risk and highlights the role that different beliefs play when defining risk, and the cultural and social rationales behind these approaches (Douglas, 1984, Douglas and Wildavsky, 1983). Slovic builds on this approach by reviewing the psychometric response to risk, risk perception, but instead focuses on individual approaches to risk (Slovic, 2000, Slovic, 1999, Slovic et al., 2007). The influence of culture however extends from local risk perception to the cultural influence of scientific institutions, the public understanding of science, and use of scientific expertise for political purposes (Jasanoff, 1987, Lynch and Jasanoff, 1998, Jasanoff and Martello, 2004).

Given these insights into the complexity of risk and risk perception, communicating risk becomes a challenging process. In the 1970s Stuart Hall, who worked within communication studies, focused on the process of message exchange rather than the complex structure of relations involved in a message. Hall (1980) stated that not only are frameworks of knowledge, relations of productions, and technical infrastructure important to understand when encoding a message (or warning), but also when decoding it. Hall's work on encoding and decoding challenged prior mass communication models by arguing that '(i) meaning is not simply fixed or determined by the sender; (ii) the message is never transparent; and (iii) the audience is not a passive recipient of meaning' (Procter, 2004, p.59). Consequently, there is a lack of fit between the two sides of communication where encoding and decoding are the points of entrance and exit to different systems of discourse. This is illustrated in Fig. 2.10, which illustrates Hall's model to show information production (encoding), and readings (decoding). Consequently, it is not possible to predict how others will interpret a message, such as a warning.

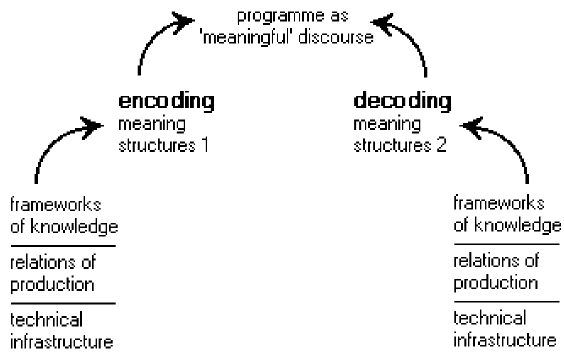

Figure 2.10 Encoding / decoding (Hall, 1980, p.130)

The concept of encoding / decoding demonstrates that social and cultural contexts are critical to generating an effective warning. It is therefore difficult to see how standardising messages (i.e. the USGS VALS) can capture these different important contexts. After twenty years experience of communicating risk, Fischhoff concludes that 'a complex network of mutually respectful relationships may offer the best hope of reaching agreements, when they are there to be had (Fischhoff, 1995, p.144). This suggests adopting an approach of post-normal science (discussed in the next section).

Beck coined the phrase 'relations of definitions' to encapsulate his view that risks are socially constructed; 'relations of definitions include the rules, institutions and capacities that structure the identification and assessment of risks; they are the legal, epistemological and cultural matrix in which risk politics is conducted' (Beck, 1997, in abstract). Beck's key work (Adam et al., 2000, Beck, 1992, Beck et al., 1994) stems from investigating the dangers presented by new technologies (i.e. the 1986 nuclear disaster at Chernobyl) and the difficultly that humans have in coming to terms with these risks because they are complex and overspill conventional modern forms of managing risks in society, given the significant uncertainties involved. The problems that arise in contexts of uncertainty develop from a lack of trust, and the need to make accountable decisions, both politically and in terms of responsibility. Beck famously argued that modern society has become a 'risk society' driven by new risks (such as climate change) that are the unintended side effects of technological developments originally designed to solve, not create problems. Beck distinguishes between 'dangers' as caused by nature, and 'risks' as caused by humans. Risks are therefore manufactured or fabricated uncertainties (Beck, 1992, p.19). Volcanic hazards sit at an uncomfortable boundary between danger and risk since it is the presence of humans on and around volcanoes that creates a risk, in addition to the dangers created by hazards. In a 'risk society', individuals are ever more conscious of self-produced or manufactured risk. This new type of risk tends to be intangible; detected only by scientific tests and are often latent in that their damage will only manifest over time. This means that traditional risk assessment and management are no longer relevant as not only are public views influenced by ideologies and values, so are the scientists, particularly when working within the confines of their own expertise (Beck, 1992). In the risk society, science is both problematic and paradoxical, mostly because science produces as much uncertainty as certainty. Beck describes a new condition of science, where it is science that has made risk knowable, but when faced with risk, more science is called for. With increasing levels of politicisation, science is losing its autonomy and ‘science becomes more and more necessary, but at the same time, less and less sufficient for the socially binding definition of truth’ (Beck, 1992, p.156).

Beck's theory of risk is part of his larger theory of ‘reflexive modernisation’ or ‘second modernity’. The change from an industrial society to a risk society means ‘that doubt and uncertainty are replacing trust and belief in progress though science and technology' (Arnoldi, 2009, p.50). The main criticism of Beck's theory is his focus on uncertainty rather than risk, but Beck, like Knight, believes risks are calculable therefore they would be defined as uncertainties if incalculable. Funtowicz and Ravetz (1994) argue that contrary to Beck's views, there is no longer a distinction between ‘natural’ and ‘man-made’ disasters because ‘all disasters are in some sense man-made’ (p.576). They state that even with disasters caused by natural phenomenon ‘the systems or containment, planning, warning, protection, amelioration and recovery are of the same emergent complex character as in the case of industrial disasters’ (p.576). Another German sociologist, Niklas Luhmann, defines danger and risk differently; dangers as random events, while risks are attributable to decisions where individuals or society has narrowed their frames of expectation. Therefore for Luhmann, a risk society is a society that does not know what to expect any more, yet is forced to make decisions (Luhmann, 1993, Luhmann, 1998).

These approaches to risk suggest that VALS (as framed in the USGS standardisation process) work to exclude risk by describing only the volcanic activity. Consequently, VALS become a closed system focusing solely on science, without the need to engage with users about which alert level to issue. By doing this, VALS do not suggest any form of mitigative action, and consequently reduces accountability when changing alert level (Haag and Kaupenjohann, 2001). Therefore, VALS ignore issues of risk by focusing only on observations or inductive knowledge, which also have attached uncertainties and risks. Scientists consider the decisions and actions taken by the authorities and public in response to a VALS as risk-related because they involve ‘complex inter-plays between public perceptions, societal demands and infrastructure capacities' (Aspinall et al., 2003, p.113). This creates a paradox because the scientists tend to ignore risk, yet, as part one explored, a VALS cannot exclude risk in practice because it is dependent on local context and perception.

2.3.6 New approaches to risk management

Sociological studies on risk reconceptualise not only what risk is, but also how to best measure it and for whom is this measurement best? This section first reviews the role of experts in developing knowledge and a warning; second conceptual and theoretical approaches to risk management by integrating different experts using a post-normal science approach; and finally how these approaches can aid the development of policy such as adopting a precautionary approach.

In recent decades, debate has developed about just whom the experts are in relation to scientific topics that relate to complex issues, notably in the context of the Chernobyl fallout and its effect on sheep farming in Cumbria (Wynne, 1996, Irwin and Wynne, 1996, Wynne, 1982). In recent decades crude deficit models of the public understanding of science have been replaced by more contextual models of the communication of science that views publics as having different knowledge's and making use of scientific knowledge in different ways (Lash et al., 1996, Irwin and Wynne, 1996). Today, the public are the focus of many scientific-institutional concerns, despite ever increasing levels of scientific complexity and uncertainty (Wynne, 2005). Wynne demonstrates that the role of the expert can no longer be confined to the scientists.

In the last twenty years there has been a growing recognition by philosophers and sociologists of science that when there are extensive scientific uncertainties, science can no longer be treated as 'normal' where there is universal, objective and context-free knowledge (Gibbons, 1994). Science, it is argued, is post-normal in that it has entered the polity, and is no-longer viable as 'normal' puzzle-solving conducted in abstraction from the issues of who pays and why. Consequently, this suggests complex science (such as volcanic behaviour) is more akin to post-normal science (PNS). This is where 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1993, p.744). Mode 2 is a mid-20th century theory of knowledge production that is context-driven, problem-focused and interdisciplinary. It involves bringing together multidisciplinary teams for short periods of time to work on specific problems in the real world (Gibbons, 1994). Labelling this knowledge as Mode 2 knowledge production distinguishes this new theory from traditional research based on academic, investigator-initiated and discipline-based knowledge production, labelled Mode 1. PNS expanded on Mode 2 theory to create a new way of thinking about science that complements the diverse expertise in complex contexts. Since 'we can no longer separate 'nature', 'science' and 'society' (Ravetz, 2004, p.348), decisions of risk have to consider various sorts of uncertainty and value-commitments, and therefore scientific aspects in these situations should be complemented by other considerations (De Marchi and Ravetz, 1999). PNS helps provide a basis to understand complexity so that 'we may successfully anticipate, when possible, and adapt, when appropriate or necessary, to changes in the self-organising systems of which we are an integrated and dependent part' (Kay et al., 1999, p.737). All these modes help recharacterise the role of science in society theoretically. They illustrate that the division of volcanic hazards, science and the society in which the hazard affects cannot be separated within a VALS, but require greater integration.

Like Mode 2 knowledge, PNS brings together an extended peer community to enter into a dialogue about the uncertainty, ignorance, perspectives and values of each stakeholder, using their expertise. Values of relevant policy stakeholders therefore replace the scientific method. In recent years, the principles and practices of PNS have been widely adopted under the title 'participation'. PNS can be represented by Fig. 2.11 that reviews increasing levels of uncertainty and decision-making stakes that indicate that a complex situation is within a PNS state.

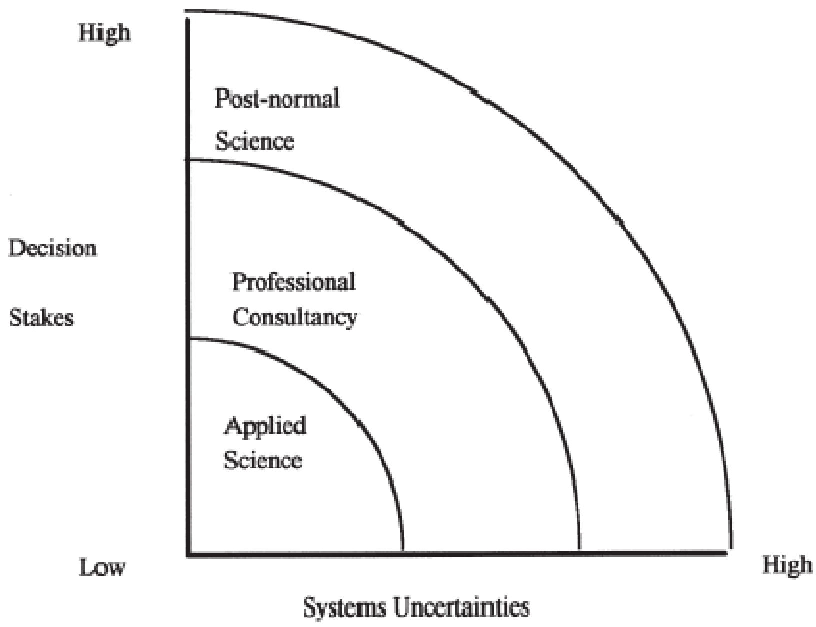

Figure 2.11 Post-normal science (Ravetz, 2004, p.354)

There is a growing paradigm of placing uncertainty at the heart of the science-policy and science-society interface, but this assumes there is consensus of what uncertainty is within the science community. Sluijs highlights that although PNS and other reflexive sciences aim to assimilate uncertainty by placing it in a deliberative environment, there is a major pitfall to this process. By changing the categories by which one judges the problem, it is likely to generate new problems, 'as every categorisation is an imperfect reduction of complexity' (van der Sluijs, 2005). Therefore, even if adopting a PNS method to discuss assigning an alert level in a VALS, it is likely to encounter new problems; however, the value that this approach provides is that it integrates different levels of expertise that helps develop policy that is more robust.

Growing recognition that the public and other stakeholders have a role to play in policy development implies that top-down policy making is no longer viable. Effective risk reduction requires that all actors are involved in the social learning process; adopting a bottom-up approach promotes local stakeholders to create a more resilient community (O'Brien, 2008, O'Brien and Read, 2005). However, there is a distinction between risk perceived by experts and laypersons. Jasanoff and Lynch (1998) suggest that less hierarchical and more inclusive styles of decision-making may be more favourable when developing policy. The relationship between science and politicians should therefore be viewed as a process of 'hybrid management' through bounding and demarcating their relevant domains of authority; neither science or politics has a monopoly on truth or power, especially when there is a complex mix of facts and values (Miller, 2001). Often there are controversies during decision-making, but the process can end or be resolved by 'closure' (Martin et al., 1995a). Closure can be achieved via four different social approaches: positivist where scientists (both physical and social) provide the expert knowledge; group politics where scientific expertise is heard via a democratic panel and reviewed within the context of political, economic and social resources; via the sociology of scientific knowledge where scientific knowledge is reviewed in context of wider society dynamics; and finally, social structure (Martin et al., 1995a). Whilst most controversies do not fit neatly into these four approaches, there is a need to recognise that they engage both the 'inside' scientific technological knowledge, and 'outside' politics of competing interest groups and thereby integrate the investigation of both science and politics.

In many countries VALS are a form of policy used to determine a risk assessment on volcanic hazards. This policy is designed to 'close down' social appraisal, whereby the design of the VALS has been developed to 'cut through messy, intractable, and conflict prone diversities of interests and perspectives to develop clear, authoritative, prescriptive recommendations informing decisions' (Stirling, 2008, p.278). During a volcanic crisis, there is little time to be deliberating actions; although deliberation can occur in establishing the VALS and for planning purposes (Mitchell, 2006). Many argue that adopting a 'closing-down' approach is the only way to achieve effective management of policy, in this case by providing an alert level that excludes local contingencies, assumptions or sensitivities in its framing. This approach is common within scientific advisory processes in many countries despite different jurisdictions and institutional-cultures (Jasanoff, 2005). It could be interpreted that VALS aims to 'close down' or reduce complex and uncertain science into a simplified linear process; an approach often used in conditions where science is more certain i.e. normal science. In contrast an approach of 'opening-up' is focused on 'plural and conditional' policy advice that involves systematically reviewing different courses of actions under different framing conditions that relate to the 'real world of divergent contexts, public values, disciplinary perspectives, and stakeholders interests' (Stirling, 2008, p.280). This opening-up process provides robust information for policy development, accountability and transparency without the need for justification. Some studies have reviewed methodological approaches to hazard crises highlighting need to move away from traditional techniques (Ronan et al., 2000).

The PNS based approaches of precaution; deliberation and participation, are opening up transparent, localised processes that are non-compliant with the concept of standardisation that restricts flexibility both in practice and on a policy level. Precaution can be viewed as a process, focusing on responding to a problem by providing 'adoption of more long-term, holistic, integrated and inclusive social processes for the governance of risk than are typically embodied in conventional risk assessment' (Stirling, 2003, p.52). The precaution process advocates shifting attention to system properties, moving development of risk-inducing technologies and activities to earlier in the process, and reviewing benefits as well as adverse affects. This process is often compared with 'sound scientific' methods of risk assessment that do not offer 'unqualified rational, rigorous or robust basis for decision-making under uncertainty, ambiguity or ignorance' (Stirling, 2007, p.314). The precautionary approach provides a tool to fulfil these requirements, making it more robust than current scientific risk management techniques. This approach offers open policy discourse and democratic accountability through open and continuing criticism, debate and concern (Stirling, 2007). In addition, it encourages greater humility that can restore the credibility of risk science, reveal the importance of divergent values, and uphold the central role of democratic accountability and public consent, which could be beneficial within disaster management contexts. Fig. 2.12 below outlines a general framework for effectively articulating conventional risk assessment with other broader qualities and associated methods of the precautionary principle by using 'a criteria-based screening process to identify crucial attributes of scientific uncertainty, or social or political ambiguity. When none of these criteria is triggered, then the case in question is subject to conventional risk assessment. Only when there is uncertainty or ambiguity does the process initiate a more elaborate precautionary appraisal or deliberative process' (Stirling, 2007, p.313-314).

Unfortunately, there is a common perception that the precautionary principle must be used cautiously because it does not 'lead us anywhere' when developing policy, and tax payers money can be wasted on something of high uncertainty that may not happen. Many could argue this is what happened during the Eyjafjallajökull eruption in 2010, which closed UK and European airspace due to volcanic ash.

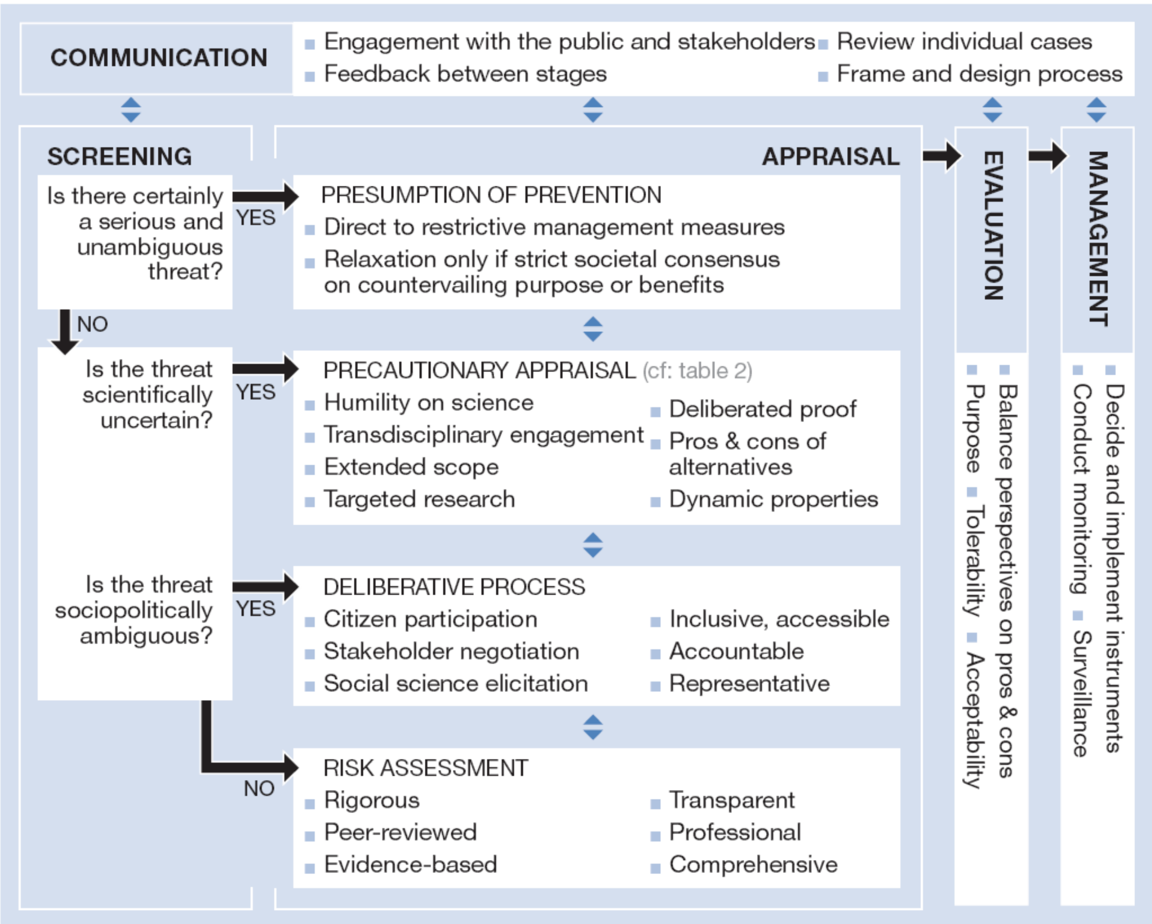

Figure 2.12 A framework for articulating precaution and risk assessment (Stirling, 2007, p.313)

Focusing on policy is important because the pressure to develop VALS often comes from government, partly to provide security, but also from other civil authorities to provide information enabling them to fulfil their responsibilities (reviewed in more detail in chapter 4). Policy makers ‘set the agendas that determine the questions asked of scientists; scientists formulate hypothesis in ways limited by their tools and their imaginations; thus, the information they provide to policy makers is limited and to a degree socially determined’ (Kriebel et al., 2001, p.875) therefore, there will always be value judgements in policy development.

2.3.7 Summary

Social science theory and practices can help provide insights into improving VALS, for example by using more interactive processes suggested by adopting a PNS approach in the planning and development stages. In addition, the growing recognition that VALS are difficult to use during long volcanic crises, indicates that the design, operation and meaning of them may be critical for its success. Therefore, stakeholder participation can ensure that VALS are relevant for users. With contention over who the expert is and a growing number of people and businesses impacted by a diverse range of volcanic hazards, the issue of policy development is further exacerbated by increasing levels of globalisation as the number of stakeholders rises. The need to balance the needs of local static populations (usually most vulnerable) with those of mobile non-local populations (i.e. aircraft) makes the job of VALS very difficult. At the root of these problems are the many different and complex systems involved (the volcano, social context, institutional environment, location of users of the VALS, communication etc.). Part four aims to understand complex systems in order to reconceptualise how VALS operate.

2.4 Reconceptualising volcano alert level systems

There is a growing recognition that VALS interface with complex systems and that VALS have to negotiate many issues, in addition to globalisation, pluralisation, and an erosion of expertise. Linear models of VALS are also unable to represent the relationships and feedback within these complex systems because of their constraints in design. If society wants to be prepared for volcano crises then it needs a ‘truly complex-systemic approach to both the practice and method of science’ (Gallopin et al., 2001, p.223). There is a need to understand the connectedness, relationships and contexts of volcanic warnings and their dynamics in order to investigate ‘how the different components and processes interact functionally to generate system responses and emergent properties, how the system adapts and transforms itself' (Gallopin et al., 2001, p.223). Therefore, this section first aims to review complexity theory and its use in practice, particularly within disaster management studies; and second reconceptualising VALS by viewing them as a tool that interfaces complex systems and applying the methods to best manage that interface.

2.4.1 The contributions of complexity theory

Complexity is remarkably difficult to define, yet is present in and around us every day. Whether it is the way that insect colonies function, how the brain works, or how the world wide web and national economies operate, there are a number of common properties that complex systems have (Mitchell, 2009, p.13). The first is complex adaptive behaviour; the collective action of vast number of components that give rise to complex hard-to predict, and changing patterns of behaviour. The second is signalling and information processes that result from the components producing and using information and signals from both their internal and external environments. Third is adaption, because complex systems adapt, or change their behaviour to improve their chances of survival or success through learning or evolutionary processes (Mitchell, 2009, p.13). A complex system can be defined as 'a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing and adaptation via learning or evolution' (Mitchell, 2009, p.13). In addition, complex systems 'exhibit nontrivial emergent and self-organising behaviours' (Mitchell, 2009, p.13).

Complexity theory is different to chaos theory which is deterministic therefore, with knowledge of the initial conditions and of the context of an action (which is often not possible), the course of this action can be predicted (Gleick, 1987). Complexity theory, although rooted in chaos theory, is non-deterministic and therefore it is not possible to predict the future. The emergence of complexity theory shows a domain between deterministic order and randomness which is complex (Cilliers, 1998), also referred to as the 'edge of chaos' (Bak, 1996). Since it is not possible to know the initial conditions of a disaster or the context of action, emergences fall under the classification of complexity, rather than chaos.

The popularisation of the chaos theory demonstrated that 'experts' did not know as much as they thought resulting in closing the gap between the governors and the governed in developing policy. Complexity theory has been applied to core topics of sociology, spurring a diverse range of studies (Urry, 2005b, Nowotny, 2005), but this application has not been without contention

(Hemaspaandra and Ogihara, 2001). Pragmatists suggest that complexity provides a lens that helps us to look at our world and shape our actions, but it should not be seen as the only way to look and do things, Chambers questions whether 'we have a deep a paradigmatic insight, an interesting parallel, or an insignificant coincidence' (1997, p.200). Critics dismiss the relevance of complexity science beyond the natural sciences, due to a lack of specific application (Sokal and Bricmont, 1998). Since there are many examples of application (including technology and mathematics) this argument has become less of a criticism. However, many still have concerns with the reliance of complexity thinking as a method of solving all apparent woes. The most robust critique is that key concepts of complexity are often poorly understood, with issues of their relevance and applicability often ignored or glossed over (Piepers, 2006). Whether or not critics believe that complexity can show anything new in the social sciences, it is becoming a popular method to view an ever increasingly interconnected and uncertain world, that is unable to be viewed or understood using reductionist methods. There will however, always be concern that the theory that tries to explain everything, may in fact explain nothing at all.

A core element of complexity is that traditional 'boundaries' no longer exist, although they may be in place institutionally. Drawing boundaries is an eminently social process and boundaries are routinely drawn between science and non-science, experts and lay persons, science and politics and the social and the natural (Gieryn, 1983) with consequences for what is taken into account when understanding and managing risk. Complexity appeals most to those who feel that top-down and reductionist approaches are inappropriate in real world situations because complexity approaches 'use rules which promote and permit complex, diverse, and locally fitting behaviour; decentralise, minimise controls and enable local appraisal, analysis, planning and adaption for local fit in different ways' (Chambers, 1997, p.221).

2.4.2 Managing complexity in practice

Using VALS to communicate hazard information has identified the need to manage and interact with a number of complex systems, including the volcano, environment, and society. But how are these complexities negotiated? Historically cost-benefit models and producing policy that tends to revert to a 'reductionist' nature have been adopted, but today it is expected to know better, but how exactly this can be done, remains a challenge.

Complexity literature offers little resolution as to how to model and use complexity to help manage knowledge and make decisions. There is one such model, Cyneform (Snowden, 2005, Kurtz and Snowden, 2003), that addresses differing levels of complexity, not by narrowing opportunities through compartmentalising them into frameworks, but moving from different stages of known, knowable, complex and chaotic systems (Fig. 2.13). Cyneform is a model or approach to policy formation and operational decision-making that recognises the value of uncertainties and risk, by reducing pattern entrainment. Although the model originates within knowledge management research, it is a sense-making framework which means its value is not in logical arguments of empirical verification, but in decision-making and facilitating shared understandings to emerge though the many discourses of the decision-makers (Ravetz, 1999). This model enables people to make sense of complexity by relaxing three basic assumptions prevalent in organisational decision-making: assumptions of order, rational choice, and of intent.

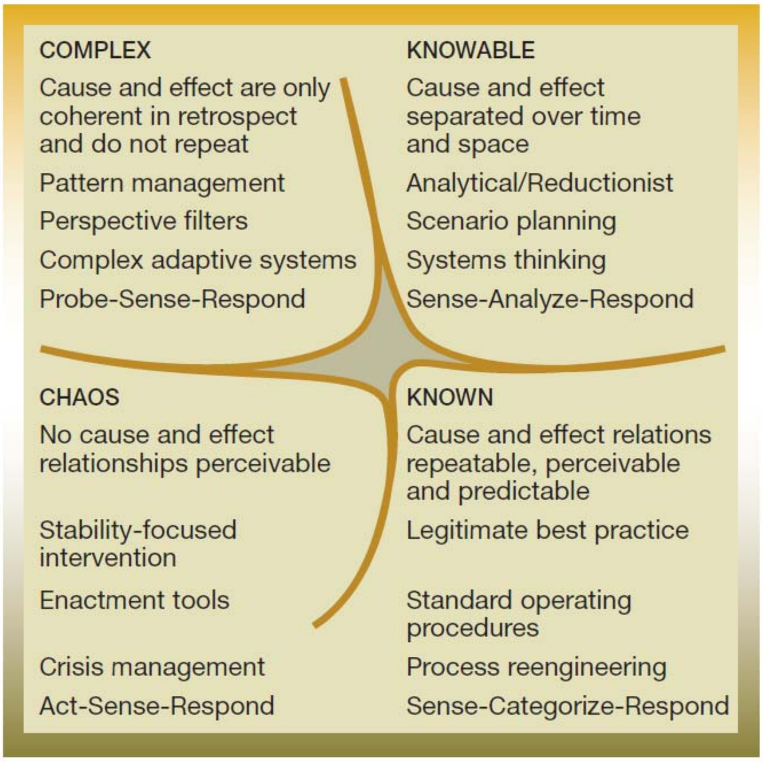

Figure 2.13 Cyneform model (Kurtz and Snowden, 2003, p.468)

The four different domains in the model represent the dynamics of situations, decisions, perspectives and conflicts when making a decision under uncertain conditions. The boundaries shown are more like phase changes than physical boundaries, so it is possible to consider the problem as it moves between different phases, such as 'knowable' to 'complex'. This model helps understanding and the interpretation of problems by indicating they are not always static, which is an interesting concept because in volcanic crises order, complexity and chaos are all involved at different stages and within different systems.

Recently a number of studies (Paraskevas, 2006, Ramalingam et al., 2008) have looked at how complexity theory can be used to model and understand a variety of crises, providing insights into how VALS may be reconceptualised. During the 1980s and 1990s theories on complexity, chaos, and complex adaptive systems began to emerge within disaster management literature. By the 2000s numerous papers highlighted the need for holistic systemic approaches that accommodate the complexities involved, and provide integrated approaches to disaster management (McEntire and Fuller, 2002, Geis, 2000). To date no single overarching theory has been ascribed, suggesting that no one theory captures every variable and issue associated with disasters (McEntire, 2004). For this reason, complexity and chaos theories have gained recognition with the growing understanding that disaster responses should be flexible and adaptive (Koehler, 1995, Mileti, 1999). Likewise, climate change debates have generated a wealth of literature relating to uncertainty, risk and the plural values of society built on the theory of systems through the concept of complexity and chaos.

Studies of organisational crises that adopt a complex science approach demonstrate that a complexity-informed framework can aid the design of response to a crisis by developing a co-evolving system that essentially self-organises, learns and adapts to their dynamically changing environment; a complex adaptive system (CAS) (Paraskevas, 2006, Zhong and Low, 2009). A CAS is defined as ‘a number of components of agents, that interact with each other according to sets of rules that require them to examine and respond to each other’s behaviour in order to improve their behaviour’ (Stacey, 1996, p.10), and evolve (Axelrod and Cohen, 1999). Interactions within the system can produce unexpected patterns or behaviours that can have unexpected effects on other parts of the system creating non-linear feedback networks. During a crisis, feedback is required to monitor the progress of the crisis response, and this feedback enables a system to self-correct or modify behaviour, learning from experience. Crisis response communication systems, such as VALS, can be viewed as CAS where agents self-organise and restructure at a local scale.

In 2008, the Overseas Development Institute (ODI) reviewed the applicability of complexity approaches within real world crises (Ramalingam et al., 2008). The report highlights that complexity science can generate useful insights into managing complex problems, with a more realistic and holistic approach, supporting useful intuitions, actions, and policy. The idea of self-organisation indicates that ‘actors at all levels of a given system need to be empowered to find solutions to problems, challenging the existing dichotomies of ‘top-down’ versus ‘bottom-up’ so often discussed in disaster practice and international aid agencies' (Ramalingam et al., 2008, p.62). The concepts of complexity challenge the very method in which current governance conducts its work, as outlined in the following quote (Telford and Cosgrove, 2006, p.119):

> International agencies need to pay as much attention to how they do things, and their capacities to do them, as they do to the content of their policies and programmes [...] sensitivity to context and the flexibility to adapt to evolving realities are essential, instead of applying predetermined strategies and one-size-fits-all solutions.

Complexity theory and models can provide a tool for practitioners, policy makers, managers and researchers to reflect collectively on how they are trying to solve problems, by providing better awareness of why disaster or development and humanitarian work is so problematic.

2.4.3 Summary, research themes and questions

This section has demonstrated that complex systems are difficult to manage because they are un-deterministic and are constantly changing and adapting. VALS attempt to manage the many complex systems within a volcanic crisis, many locally focused. Standardisation provides a ‘one size fits all’ approach that is reductive in nature and potentially unable to accommodate local flexibility required to effectively prevent loss of life and minimise economic impact. If VALS are going to be standardised nationally or globally then it is unlikely they will be able to integrate local needs and available resources so that they are relevant to the vulnerable population. Instead, standardisation appears to be a tool that helps simplify the organisational elements of VALS for policy-makers and large-scale decision-makers, such as government institutions. Currently there is no literature reviewing the impacts of the standardisation of VEWS or VALS from either a national or a local perspective, therefore it remains unknown as to how standardisation can compromise the need to accommodate users both local and global, and effectively manage complexity. This is an important issue that warrants further research, and if left answered could generate a number of problems that could lead to further disasters, rather than reducing them.

This literature review has identified a number of empirical themes. By understanding how these operate in practice within a VALS, in the context of the USGS case study, it is possible to address these issues:

1. **Standardisation:** There many diverse users of VALS, given the diversity of volcanic hazards and spatial distribution of the users, so how can a VALS accommodate all these separate and diverse needs, whilst maintaining an effective level of understanding. The process of standardisation is generally perceived as a top-down approach adopted by policy makers, so does a VALS only address their needs, or does it consider the local and vulnerable populations' needs?

2. **Decision-making:** Decision-making occurs at every stage of the VALS, from designing the VALS, the scientist interpretation of the science (SSK) (via monitoring, modelling and forecasting), deciding an alert level (managing the uncertainties and risks), and then providing guidance on possible implications using a complex scientific approach (PNS, Cyneform techniques). The complexities and uncertainties make decision-making an iterative process that requires effective communication between the actors of a VALS.

3. **Uncertainty:** The numerous complex systems involved in VALS means there are high levels of uncertainty in many aspects of VALS, including the physical hazard and social contexts. This makes decision-making and risk management extremely challenging. Understanding that a VALS operates within a complex adaptive system that will change and adapt over time, means that uncertainty also includes ambiguities, ignorance and risk; collectively referred to as 'incertitude'.

4. **Communication:** Communication is critical to the success of a VALS, but how best can alerts be developed and understood. Communication consistently fails during volcanic crises, whether it is the warning, communication between scientists, or scientists and decision-makers, the media, public, or government officials. Consideration of the encoding and decoding of messages can provide insights into how to communicate warnings and how complexity (including uncertainty) is understood between different actors in the VALS.

These four themes are dependent and influence one another. Uncertainty makes decision-making difficult. This in turn makes communication less focused; consequently, this affects the many users of the VALS and their needs.

To recap, using the USGS VALS as a case study, the aim of the research is to answer the following research questions, and secondary queries, through reviewing the use of a newly emplaced standardised VALS at five volcano observatories, three of which previously had a locally developed VALS. Through the lens of standardisation, it is possible to look into the VALS black box to understand better, how they function, and to determine whether standardisation is an effective method of managing complexities.

To what extent is a linear, standardised VALS an effective warning tool for volcanic hazards in different contexts of complexity, uncertainty and risk?

1. Why and with what implications did a linear VALS emerge as a tool for managing complex volcanic hazards?
   1.1. How did the standardised VALS emerge?
   1.2. What are the complexities that VALS aim to manage?
   1.3. How capable is a linear system in managing these complexities?

2. How are decisions made using the standardised VALS given contexts of complexity, uncertainty and risk?
   2.1. How is scientific knowledge constructed?
   2.2. How is risk considered when scientists make decisions?
   2.3. How are decision made between scientists and users with different needs and expertise?

3. Does the standardisation of VALS function in communicating volcanic hazards between different users?
   3.1. How does the communication process function?
   3.2. Can a standardised VALS accommodate the needs of different users?

Chapter 3. Methods

This chapter introduces and explains the methodological approach adopted in the thesis. To reiterate, the aim of this research is to open up the volcano alert level system (VALS) black box, in order to explore how this linear tool operates in practice to communicate volcanic hazards, and to review the extent to which standardisation is an effective method of managing volcanic hazards. To address these research questions qualitative social science methods are adopted. A multi-sited ethnographic study was conducted at all five volcano observatories of the United States Geological Survey (USGS) (outlined below). Semi-structured interviews were completed with a number of actors involved in the VALS: scientists within the USGS Volcano Hazard Program (VHP), including volcanologists, seismologists, glaciologists and chemists; with users of the VALS at other federal agencies, such as the National Weather Service, U.S Forest and National Park managers; and with collaborative partners, such as Universities and State officials. The interviews provide insights into the personal perspectives of the variety of scientists and users involved in the design and implementation of the VALS. This is complemented by ethnographic observational data on the interactions between these different perspectives in practice, and document analysis on the historical emergence and stabilisation of these policies. Developing this research approach to VALS raises a series of issues including the conceptual challenge of building a rigorous, yet open-ended and exploratory research methodology alongside the practical question of obtaining access to the USGS volcano observatories.

This chapter opens with an exploration of the conceptual basis for the methodology, reviewing related social science and disaster management studies to develop a multi-sited ethnographic approach to studying knowledge's in practice. Second, the chapter outlines the research approach and methods used in this study, outlining the rationale behind their selection. Third, the methods of describing, interpreting, and analysing the data collected are reviewed, including a new method developed during the research to cope with the many interviews conducted, based on the adaptation of mind mapping. In addition, the organisation of the data collected into empirical chapters is reflected in this section.

This study seeks to open up and understand a new area of research within disaster management, focusing on the 'first mile' of a VEWS through understanding the processes by which scientists understand scientific information, make decisions and communicate them as part of a VALS. To understand these processes, the use of social science theory and practices that emerge in the literature review provide frameworks and models to conceptualise the complexities within a VALS. It follows that social science methodologies present the best opportunity to investigate these issues and provide the type of information required to address the exploratory research questions. My background is within geological sciences, using standard scientific research methodologies, so this is also personal exploration into the social science research methodologies required to achieve the interdisciplinary goals of this thesis.

3.1 Methodological contexts and choices

All research is underpinned by underlying assumptions about what constitutes 'valid' research and data. The philosophical assumptions within research relates to the underlying epistemology guiding the research, which Orlikowski and Baroudi (1991) categorise as being either positivist, interpretative or critical. The methodologies used within this study do not adopt a simple positivist approach; rather, the research methodology is designed to be sensitive to the subjective elements of decision-making which influence the performance of the VALS in practice. Such interpretative research does not seek to enumerate the measurable properties of social characteristics and contexts, but instead aims to explore the constitution of shared meanings or contested moments through attention to language and practice. This form of research does not predefine dependent and independent variables, but focuses on the complexity of human sense-making as the situation emerges (Kurtz and Snowden, 2003). Critical research focuses on social critique such as the oppositions, conflicts and contradictions within contemporary society and aims to be emancipatory. This too has a role within the methodologies used in this study. The underlying epistemology and methodological choices in this thesis are derived from related studies in the sociology of science and disaster management, which are reviewed below.

3.1.1 Qualitative research methods in disaster management

Qualitative research methods have been commonly used within natural disaster studies for many years. Barton's work on disaster classification (1969) helped to trigger a move from descriptive disaster studies into more analytical ones, consequently both qualitative and quantitative tools have been adopted as recommended (Gillespie and Perry, 1976). The gradual shift from a dominant to radical perspective, follow the publication of Hewitt's 'Interpretation of Calamity' (1983), which brought into focus the role of location and socio-economic and cultural conditions of the affected society. This shift is reflected by the adoption of qualitative studies; ‘human behaviour is significantly influenced by the setting in which it occurs; thus one must study that behaviour in situations’ (Marshall and Rossman, 2006, p.53). Qualitative research aims to develop in-depth understanding of human behaviour and the rationale behind this behaviour by investigating the *why* and *how* of decision-making, not just *what*, *where*, and *when*. Qualitative methods provide tools to review contextualisation, conduct interpretation, and understand actor’s perspectives within this research, but there are limitations. The key criticism of qualitative methods are the axiological issues concerned with the personal values, morality, and the ethics of the researcher who will impose their values on the inquiry and its analysis. As discussed in chapter 2, all research methods have subjective elements, but social science methods tend to be more explicit about this.

The growing interdisciplinary character of natural disaster studies means it is unsurprising that qualitative methods have been commonly adopted in studies focusing on VEWS. As Velasco (2000) describes, studies in VEWS or VALS tend to focus on context, offering valuable empirical detail on lessons learned. The study of the Nevado del Ruiz tragedy by Hall (1990) adopt social science research methods, using interview techniques and historical document archives to develop a picture of the actions that led to the disaster in 1985. Some studies have become focused on the role of socio-economic and political conditions and their influence on VEWS, for example by Tobin and Whiteford (2002) who addressed the evacuation of the populations living on the foot of Tungurahua volcano in Ecuador following its eruption. Using a mixed methodology over 12 months of fieldwork, including observational studies, interviews, a qualitative study using small focus groups, and a quantitative survey using formal structure questionnaires, they provided a thorough qualitative methodology and analysis to review the decision-making processes in response to the eruptive activity by local officials and populations.

During the 1990s and 2000s the UN's Early Warning System conferences I, II and III held in Germany, many papers that focus exclusively on case studies and on decision-making by responders were published (UN ISDR, 2006a, Kuppers and Zschau, 2002). Many studies focused on case study areas or specific crises, discussing the context in which decisions were made in the 'last mile'. For example, a study by Sinha and Avrani (1984), reported on the disaster of the 1981 Gujarat cyclone by examining the channels through which warning of the impending October-November cyclones were received and disseminated by investigating three different villages within Northwest India. They conducted in-depth interviews and group discussions with a range of villagers and officials to examine the EWS. Unlike the aforementioned research, this thesis focuses on the contexts that are internal to the scientists and civil authorities who make decisions that generate warnings. The aim is to demonstrate that context is not just important in responding to VEWS in an external sense, but that internal context is relevant to the decision-making of scientists and civil authorities in developing the warning, in the 'first mile' of the EWS.

Studies within VEWS, as presented thus far, frequently focus on one crisis as a case study, focusing on the related contexts of this incident. From this we learn the importance of context in EWS and this raises further questions relating to how different crises or contexts compare, and the importance of contexts that are internal to developing a warning. Are there trends that can be identified in natural hazard crises that occur despite the context, or is the context a unique aspect of EWS? How do internal contexts affect the effectiveness of a warning? This study aims to expand on VEWS literature by comparing different contexts so as to begin to address the need to conduct more comparative studies, particularly relevant given the growing levels of standardisation within VEWS, and develop guidance on how to develop a framework for future use.

3.1.2 Laboratory studies and the sociology of scientific knowledge

As discussed in the literature review, studies on EWS focus on decision-making outside the scientific 'laboratory' where scientists make decisions about scientific knowledge and warnings. Within the sociology of scientific knowledge (SSK) the method for observing where and how knowledge is produced via ethnographic studies and discourse analyses is referred to as ‘laboratory studies’ (Knorr-Cetina et al., 1995). Laboratory studies became a methodological focus of the SSK, which examined how internal scientific standards and experimental evidence fail to provide for scientists' beliefs, and how the beliefs and knowledge claims of scientists are influenced by their social context. This focus provides a guide to the methodological development in this study to develop an understanding of the decision-making processes within volcanic behaviour interpretation, analysis and forecasting. The use of SSK research methods such as laboratory studies have shown that, through the use of qualitative methods, it is possible to delineate issues that this research aims to investigate, including how scientific knowledge is constructed and the different values of scientists.

This study takes from the SSK an interest in the located context and nature of knowledge production, the institutional and organisational cultures that shape knowledge practices and the social, as well as epistemological, factors which lead to decisions around risk. Together these represent an interpretative and critical approach to studying knowledge production and communication, drawing inspiration from a large body of work which has emerged since the 1960s. As described in the literature review (section 2.3.3), the SSK movement demonstrated that scientific knowledge is not objective but depends on 'finitism', or cultural contexts. This development caused a historical shift in how research methods were used to understand scientific knowledge. Thomas Kuhn's intensive documental analysis of how changes in scientific paradigms occurred throughout history enabled him to publish 'The Structure of Scientific Revolutions' providing the foundation for SSK in 1962. Historical documents played a vital role in providing an account of the processes of how scientific knowledge was developed and the changing roles of values and expertise over time, enabling a comprehensive insight in the mechanics of how decision-making processes evolve over time. It is through documents that this study is able to review effectively the process of standardisation of the USGS VALS, and review the decision-making processes involved.

Ethnographic studies have been used in many SSK studies. In 1979, Latour and Woolgar studied the constitution of laboratory science through ethnographic research, reviewing the daily lives of scientists. The study observed that the settlement of objective, factual scientific outcomes were more complex, contingent and unclear than expected, and largely dependent on the local and national context of the UK at the time. This study of the mundane and daily habits of scientists triggered a large number of studies of laboratory and other knowledge practices, which revealed the range of material and social practices that underpinned accepted knowledge's. As David Glover and Sheelagh Strawbridge illustrate:

> What is eventually agreed upon as knowledge will have involved choices concerning such things as which raw materials to use, which measuring instruments and how to set up experiments as well as negotiated decisions about the interpretations of results. Moreover, the personalities, relative statuses and particular relationships of scientists involved will all affect these decisions' (Glover and Strawbridge, 1985, p.65).

From the late 1970s, attention has focused on studying the complex negotiations, contingencies and skills that are involved in creating a 'fact' (Knorr-Cetina et al., 1995, Latour and Woolgar, 1979).

A key method for understanding the decision-making processes of scientists and understanding the interrelationships between the scientists and civil authorities that use this information, is thus ethnographic observations. In this study, the scientists are located over five different volcano observatories or 'laboratories' across a wide range of locations, consequently this study is multi-sited with multiple contexts. The next section reviews the value of ethnographic studies, in particular methods for reviewing multi-sited research, to provide a framework in which to conduct a 'laboratory study' at each observatory.

3.1.3 Multi-sited methods

Traditional ethnographic research involves ‘the study of groups and people as they go about their everyday lives’ (Emerson et al., 1995, p.1), involving an immersive study where the researcher must live with the group studied and become part of the group, either actively or as acknowledged background (Hammersley, 1991). Through this immersion, participation enables understanding of the cultures and processes involved, whilst at the same time keeping a certain observational distance. Ethnographic conventions claim that ‘a detailed, in-depth picture of a group, organisation and its members can be developed', so that the 'social, cultural and political issues which other methods find intangible are at the centre of analysis' and that 'ethnography is strongly participative, allowing for members of groups to comment on the data and data gathering as it occurs’ (Neyland, 2008, p.160). Adopting this approach is valuable to this research in understanding the role of conventions at each observatory, and across different observatories. In this research, interviews are used as an ethnographic tool to gain insights into how VALS operate, supported by ethnographic observations and documental analysis of the standardisation process of the VALS at the USGS. These methods used will be reviewed in section 3.2.

In recent decades, ethnography has moved beyond a technique used within anthropology and sociology, emerging as a key method in a number of disciplines, including laboratory studies and organisational studies (Weeks, 2004). Ethnography has evolved significantly from its association with studying singular and, often non-western cultures, to explore late-modern cultures in ways that give attention to their poly-vocal, reflexive, and ‘multi-sited’ nature (Marcus, 1995). In multi-sited ethnography, the study moves from a single-site location to ‘multiple sites of observation and participation that cross-cut dichotomies such as the "local" and the "global", the "lifeworld" and the "system" ' (Marcus, 1995, p.95). At the core of multi-sited ethnographic research is the tracing of a cultural formation across and within multiple sites of activity, which involves following connections, associations and putative relations. This provides a framework to conduct this multi-sited study, providing a 'way to engage with scientific and technical practice in complex allegiances that go beyond description and critique' (Hine, 2007, p.668). Multi-sited ethnographies define their objects of study through different modes or techniques, for example they can follow people (i.e. migration studies), or follow a thing (i.e. the circulation of material objects such as money); in this thesis, VALS are the object being followed. As already outlined, this research aims to define its study through understanding the role of local and social contexts in the decision-making of scientists in their laboratory (internal), rather than those outside the laboratory (external). Ultimately, as Marcus believes, adopting multi-sited approaches makes it possible 'map a terrain, which may not be a holistic representation, but one that cannot be understood by analyzing just one site' (Marcus, 1995, p.112).

There are a number of concerns with using multi-sited ethnography. First, the connection between different sites in a local-global contrast can be questioned as to whether this is a strictly ethnographic technique. Second, due to the nature of multi-sited ethnographies, the knowledge base developed will vary in intensity and quality. Despite these issues, the focus of multi-sited ethnographic studies has been to shift the focus to 'stimulate accounts of cultures composed in a landscape for which there is as yet no developed theoretical conception or descriptive model' (Marcus, 1995, p.102). Therefore, adopting this methodology provides a new framing of VALS and a method to analyse the impact of standardisation across the decision-making process of five different volcano observatories.

In summary, this section has reviewed the rationale behind using qualitative research methods that historically have been adopted to review social contexts of decision-making outside of volcano observatories. Laboratory studies, developed within SSK to review the decision-making processes in laboratories, are adopted in this study and include ethnographic observations, predominantly via interviews, and documental analysis. These methodological approaches value the role of the local context, and by using a multi-sited framework it is possible to provide a comparative framework for understanding decision-making processes that occur within a VALS, and the impact of standardisation of the VALS in each observatory. The next section outlines the methods used to conduct the study using the methodologies outlined.

3.2 Materials and methods

This study comprises a single case study, the USGS VALS, studied across multiple sites. This section outlines the research methods used to collect data, first, outlining how the USGS were accessed, and understanding them as an organisation; second, how interviews were conducted to obtain most of the empirical data; third, how additional ethnographic observations were made during the research; and finally how documents were analysed to reconstruct valuable historical and contextual knowledge.

3.2.1 Accessing and understanding the USGS

Volcano observatories are the environments within which scientists operate VEWS and VALS. Therefore to understand the context of their environment and decision-making processes within the VALS (i.e. monitoring, decision making, communication of the warning) it was imperative to spend time within the observatories using ethnographic methods. Conducting research at the volcano observatories also provided access to documents, contact details for the key users of the VALS to conduct interviews, and attend meetings, workshops, open days, educational events and meet collaborating universities and agencies. Using established contacts via my supervisor, I applied to conduct research with USGS, and following internal discussions within the USGS, I was accepted. The study took part in two phases, a pilot fieldtrip and then the main research phase.

The exploratory nature of this research meant that a pilot study was essential. This was conducted in 2007 during year one of the research, to establish the key issues of using VEWS. During the pilot research six weeks (two weeks at each location) were spent at the Cascades (CVO), Long Valley (LVO) and Alaska Volcano Observatories (AVO). Open-ended informal interviews were conducted and ethnographic observations were made to understand how each observatory operates including the institutional structures, and to establish the different processes of the VEWS in place. From this research it emerged that there were concerns relating to VALS and its recent standardisation that led to the implementation of new systems at the observatories. This focus formed the basis of a more formalised research plan and semi-structured interview schedule to be taken into the next phase of research. Pilot fieldwork also provided the opportunities to explore the feasibility of the research methods.

The main research phase was undertaken during 2008 at all five of the USGS' volcano observatories, including Yellowstone (YVO) and Hawaii Volcano Observatories (HVO) following additional approval from the USGS. The five observatories are located in: Anchorage and Fairbanks (AVO), Vancouver, Washington State (CVO); Big Island, Hawaii (HVO), and Menlo Park, California (LVO & YVO). A total of twelve weeks was spent with the USGS, three weeks at each location to gather data using three key research techniques: semi-structured interviews, a multi-sited ethnographic study, and investigation of document and archival collections.

During the fieldwork, I was generously provided with an office, internet connection, photocopying and all the other facilities I required to conduct research by the USGS. In addition, documents that were made public under the Freedom of Information Act, that review the communication between scientists during the standardisation process of the VALS, were photocopied from USGS Headquarters in Reston, Virginia, and sent to Menlo Park where I was able to review the documents and ship them back to the UK. The VHP team chief scientist organised this for me, which reflects the generosity of the USGS shown throughout the whole research project. This material provided the basis for documental analysis.

In the first few days at each observatory, I met the scientist in charge (SIC) to discuss the research and ask for suggested recommendations about who would be most suitable to interview within the observatory (mainly those that interact with the VALS), and the most relevant users of the VALS and their contact details. Although many of the recommendations by the SIC were accepted, staff and users not recommended but seen by myself to be of relevance to interview, were part of the study, to make it more representative and remove bias. I was free to interview whom I chose, dependent on their consent and availability. The scientists in the observatories, who formed the bulk of the interviewees, were wide ranging from junior to senior positions, to the management, and those actively engaged in the standardisation of the VALS. Three weeks of fieldwork in each location provided enough time to arrange meetings with all the potential interviewees both internal and external to the observatory. Occasionally interviews were conducted by phone; this was particularly the case with staff working out of the USGS headquarters in Reston, Virginia, and also two members of Yellowstone Volcano Observatory located in Utah. Face-to-face interviews were the preferred method, so often I travelled distances to conduct interviews, sometimes in people's homes. At AVO, scientists were visited both in Anchorage (USGS) and Fairbanks (Geophysical Institute of the University of Alaska Fairbanks (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS). In the Cascades, a brief excursion in Washington State enabled me to interview county emergency mangers, National Weather Service staff, and collaborative partners at the University of Washington. Finally, I also attended two excursions to Mammoth Lakes town to attend the quarterly Unified Command Meeting with the staff and scientist in charge of Long Valley Observatory. Regrettably on both occasions the meeting was cancelled at the last minute, however, this did provide an opportunity to interview local users of the VALS, meet the USGS employee based there, visit the caldera, and develop understanding about the volcano and the town’s relationship with it. In Hawaii, users of the VALS in Hilo, including emergency managers and land owners were interviewed and I visited the National Weather Service office in Honolulu, Hawaii. Table 3.1 below summarises the full range of interviews conducted and the meetings and events I participated in that formed the ethnographic observations.

Observatory	AVO	CVO	HVO	LVO	YVO
USGS VHP Scientists interviewed	• 12 at AVO in Anchorage	• 17 at CVO • 1 ex-employee via phone	• 13 at HVO	• 6 at LVO • 4 at via phone • 1 at Mammoth Mountain	• 1 at YVO
No. of staff at each observatory	• Approximately 22 full-time staff	• Approximately 45	• Approximately 20	• Approximately 10 VHP scientists at Menlo Park	• 1
Federal Agencies interviews	• Meteorologist, NOAA / National Weather Service (NWS) Center Weather Service Unit (CWSU) • Traffic Management Officer, Federal Aviation Administration (FAA), Traffic Management Unit (TMU) • Emergency Management Specialist, Alaska State Department of Homeland Security and Emergency Management (DHSEM) • Meteorologist, NOAA / National Weather Service (NWS) Anchorage Weather Forecast Office (AFO) Alaska • Meteorologist in Charge, National Weather Service (NWS) Alaska Aviation Weather Unit (AAWU), Anchorage VAAC	• Meteorologist, NOAA / National Weather Service (NWS) • 2 U.S Forest Service Specialist at Mount St Helens Monument • 2 Emergency Management Specialist at Pierce County Department of Emergency Management • 1 Emergency Management Specialist in the Mount Baker / Glacier Peak Coordination Plan • Clackamas County Emergency Management • 2 Journalists: from the Columbian Newspaper and Oregon State Newspaper	• 2 at Kilauea National Park Service • 1 at State of Hawaii DLNR - Natural Area Reserve • 2 at Hawaii County Civil Defense / Mayor's Office • 1 at Hawaii Tribune Journalist • 1 at Washington VAAC (via phone) • 1 at Hawaii National Weather Service, Honolulu, Hawaii	• 1 at Mono County Sheriff • 1 at Mammoth Lakes Town Management • 1 at Mammoth Lakes Police Department • 1 at Mammoth Lakes Fire Service • 1 at U.S Forest Service • 1 at Mammoth Mountain Ski Area Office	• N/A

Collaborating partners interviewed	• 3 at University Alaska Fairbanks • 2 at Alaska Division of Geological & Geophysical Survey	• 1 at University of Washington • 1 Oregon State Geologist	• 1 at University of Hawaii, Hilo • 1 at Center for the Study of Active Volcanoes, Hilo	• N/A	• 1 at National Park Service, Yellowstone • 1 at University of Utah
Total Interviews	• 22 Interviews	• 29 Interviews	• 23 Interviews	• 17 Interviews	• 3 Interviews
Meetings attended	• Weekly science meetings at both Anchorage and Fairbanks	• Weekly science meetings • Search And Rescue Workshop, Mount Rainier • Mt. St. Helens Coordination Meeting • Alert Level Discussion Meeting	• Weekly science meetings • Kilauea National Park Emergency Coordination Meeting • Kilauea National Park outreach meeting	• 2 Visit to Mammoth lakes to at the Unified Command meeting at Mammoth Lakes, which was cancelled both times • Interviews with other USGS staff involved in tsunami, earthquake and debris flow warning systems	• N/A
Other Events	• Small event to mark the 30th anniversary of AVO in Anchorage	• USGS Open Day (helped in kids room) • Educational events at school in Washington State • Visit to Mt. Hood telemetry sites • Visit to Orting to see lahar EWS	• Attended fieldwork on the lava fields and to measure volcanic gases • Visited Hawaii Civil Defense Emergency Operation Centre	• Access to Menlo Park Library • Attended USGS lectures and events at Menlo Park • Partook in a teaching event at Stanford University	• N/A

Table 3.1 Summary of interviews conducted and ethnographic observations via meetings and other events attended.

3.2.2 Conducting interviews

Interviews are used in this study as in-depth ethnographic tools to discuss the use of VALS and the relationships between the actors involved, providing a method to gain personal perspectives on the decision-making process involved in a way that exceeds the constraints of a survey (McCracken, 1988, Baxter and Eyles, 1999). They also provide a narrative opportunity to examine the opinions and views of individuals relating to the standardised VALS established in 2006. Interviews are particularly useful in circumstances where information is mainly found in grey literature or accepted knowledge within an organisation, which has not yet been written down.

A research interview is more than just an 'informal chat'; it has the specific purpose to generate the information required to address research questions. Interviews provide the opportunity to obtain large amounts of contextual data quickly, but to do so the questions need to be well designed. Within this study, semi-structured interviews were used to facilitate the flexibility required to obtain specific information, whilst also exploring the meaning and understanding behind the answers. In the preliminary fieldwork, open-ended interviews were conducted to gain insights into the role of the scientists and the function of the volcano observatory from the interviewee’s experience. These initial enquiries then formed the basis for the development of a more systematic interview schedule (see appendix A).

The semi-structured interview schedule used during the main research phase was centred around a set of core questions or themes, repeated with different respondents to explore the issues raised by the standardisation of the VALS in more detail, and to follow up questions around meaning, understanding and context. Semi-structured interviews are an intensive form of research, that enable researchers to fill gaps in knowledge, to investigate complex behaviour and motivations, and collect a diversity of opinions and experience (Baxter and Eyles, 1997). A disadvantage is that they provide information on the range of views, rather than seeking to provide a statistically representative picture. They are also subject to researcher biases. In this study, the majority of interviewees were interviewed twice, during the pilot research and main study, thus adding insights into the stability and diversity of views, as well as building rapport and trust.

At the start of the interview, each interviewee was given an introduction to the research, consent was requested by the interviewee to digitally record the interview and for me to use the data in this study by signing an ethics form (see appendix B), discussed later in this chapter. By making the study anonymous it not only protects the employees but also provides more comfort in speaking the truth. Following this, the interview commenced, structured around six key themes. The first section aimed to understand contextual information about the interviewee such as what their job is, in what way they are involved in VALS and VEWS, and what they consider as the purpose of VALS and how they define it. In the second section, questions focus on their understanding and involvement in the standardisation process, reviewing questions relating to why, what, when, and who. Third, the implications of the application of the standardised VALS were reviewed by discussing what protocols were in place, how the new VALS was implemented and whether any issues for them or the users of the VALS have arisen thus far. In the fourth section, questions revolved around how the interviewees dealt with uncertainty and how they created meaning within the VALS. This included questions about how alert levels are decided, what the decision-making process is, and how uncertainty and risk are considered. In the fifth section, I asked interviewees if they could provide examples from their experiences that illustrate how VALS worked before and after standardisation, in the attempt to prompt contextualisation to the elements of knowledge, uncertainty, risk, and communication involved. In the final section, the interview opened out to review the changes the standardised VALS has brought, what the future challenges are, and whether in their opinion it is feasible to globally standardise VALS. At the end, interviewees were asked if they had any other contributions or questions, or feedback to me. This structure was not always suitable for interviews with the users of the VALS; consequently, these interviews tended to be more flexible, providing the opportunity to learn more about their role and their interactions with the USGS and the VALS, and how they are used to fulfil their corresponding responsibilities.

Although interviews were on average one hour long, they varied from fifteen minutes to three hours, depending on the availability of the interviewees and their levels of involvement with the standardisation of the VALS. All interviews were one-to-one to encourage in-depth discussion of complex issues, remove potential bias due to organisational hierarchies that may be apparent in group interviews, and enable interviewees to express personal opinions. The same interview schedule was repeated with each scientist, returning to the issues from different angles and perspectives. A group interview was not seen as suitable for this study. These can be difficult to organise and facilitate within organisational settings where there are existing group dynamics, which are not known to the researcher and may inhibit certain viewpoints.

In total, 93 interviews were conducted with scientists at the volcano observatories, with the users of VALS in other US Federal Agencies, such as the US Forest Service (USFS), Federal Aviation Authority (FAA), the National Weather Service (NWS), Volcanic Ash Advisory Centre (VAAC), and with staff of collaborating universities, and regional and state emergency management agencies. These further interviews provided additional perspectives on the effectiveness of VALS from the users themselves. Six interviews were conducted on the telephone, and one at a conference in Iceland two months after the fieldwork. Table 3.1 provides a detailed review of the interviews conducted at each observatory. All interviews were recorded on a digital Dictaphone with the participants permission, and field notes were taken during the interviews enabling the opportunity to review the interview if focus waned, which fortunately was not the case. The process of interviewing is exhausting, and so on most days only two interviews were conducted, but in some cases up to four were conducted in one day. All interviews were anonymised using a coding system attributing them to the relevant observatory or Federal Agency. Given the number of interviews completed, interviews were not fully transcribed, rather a different 'mind-mapping' methodology was used, discussed further in section 3.3.

A number of limitations are recognised in using interviews as a method of collecting data. In all interviews the researcher is the research instrument 'through which data are collected' (Sorrell and Redmond, 1995, p.118). In addition, the presence of the researcher can also bias participant accounts. To account for these two forms of bias, steps were taken to make the interviewee as comfortable as possible with me; they were given the option to ask questions before the interview began and many knew me from the pilot research or had encountered me during my time in the observatory whilst conducting the ethnographic aspects of the study. To reduce my own bias and assumptions, I sought clarification where needed. Discrepancies in the data may also come from the interviewee who may recount a story with errors, either intentionally or not, possibly due to memory inaccuracies. Although this can reveal priorities and challenges in thought, by interviewing many different people it was possible to create as consistent a narrative as possible, and when possible correlate the information with documents and papers.

3.2.3 Additional ethnographic observations

As part of the ethnographic observations I attended a number of meetings and events at each observatory (listed in Table 3.1). Through these additional activities, I was able to access documents, conduct a more rigorous ethnographic study and become more 'immersed' in the institution and the observatory culture. At many of the observatories I registered as a USGS volunteer and attended weekly meetings to discuss the week's news and volcanic activity from the different monitoring divisions within the observatory, review various administrative features such as new IT tools and products, and new equipment, and attend visitor meetings or lectures. Of particular note was a meeting I attended at CVO to review the alert level of Mt. St. Helens, providing enormous insight into how the decision-making processes work when assigning VALS. During and following meetings, events and fieldwork or trips, notes were made to reflect my observations that formed part of the analysis.

Whilst ethnography is a widely used technique, a number of critiques exist in relation to ethnography and participation observation (Denzin, 1997). The predominant critique is that ethnography is ethnocentric and therefore ultimately relays the view / voice of the researcher. Other criticisms are that it is based in on overly holistic notions of culture where the boundaries of groups are fuzzy and social mores are contested and mutable. In practice there are a number of constraints in using the technique. Significant time in the field is required, and as a result trust, credibility and integrity are required by both the researcher and the people they are working with to get as accurate a perspective as possible as there is a need for honesty, and often employees do not want to say something completely honest in case it should be used as evidence or data. Whilst a number of critiques with the methodologies are valid, it is important to note that multi-sited ethnographic studies can provide fresh insights to the broader picture, which may provide a very different perspective than individual studies of the same picture, whilst also highlighting the issues concerned. Biases are kept to a minimum by trying to not pass judgement or go 'native' but maintain an isolated perspective of the environment.

3.2.4 Analysing documents

Whilst there are records of the standardisation process and the decisions made public under the Freedom of Information Act in the U.S. (FOIA), there is little documentation about the USGS VALS, the standardisation process and their use. Written and graphical documents, including USGS publications, photographs and meeting minutes (available at the individual observatories) can provide information about what people said and did during the standardisation process, whilst reflecting the values of the different individuals and groups. Since documents are often written at the time of the event or shortly after they tend to preserve knowledge and views at the time of writing while information is 'fresh' in people's minds. Therefore, the documents available under the FOIA provide another dataset to compliment the interviews and provide a more accurate account of the standardisation process as recorded at the time of discussion. They are referred to as FOIA archives within the empirical chapters.

In 2007, correspondences between the USGS staff relating to the standardisation of VALS were released under the FOIA. Originally, this request was made by a journalist who was looking for a controversial story relating to the change in VALS. The journalist never published an article on the information made available, presumably as there was nothing controversial in the process, however, this request did lead to the collation of email correspondence and other documents that chart the standardisation discussions. Although not all the information was visible since some had been redacted under certain exemption laws[6], I was able to access many of the details from other USGS interviewees and develop a better understanding about the framing of the issues involved, not just for facts, but also the respective values.

The USGS has published numerous hazard reports, books, bulletins and circulars relating to significant events and crises, geological and hazard maps, information pamphlets for the public, educational materials and videos, and newspaper articles. Literature, both old and new, can be found on the internet, in the volcano observatories and within the institutions' libraries: Menlo Park Western USGS Headquarters library, and most of the volcano observatories had a library room. Both public and 'grey' literature was given to me, bought or photocopied with permission for the purpose of this research. These additional documents provide an important source of historical and contextual information about the volcanic crises the USGS have dealt with, the development of the volcano observatories, and the evolution of the USGS and VHP; all reviewed in chapter 4.

There is some critique in the over-reliance of documents since they may portray biased perspectives (Yin, 2003). Therefore, it is critical to be aware of these issues to correctly interpret the content and contexts of the evidence. With archival data it is particularly important to check the conditions under which it was produced as well as its accuracy. Archival data in this research available under the FOIA consisted of: emails, white papers, and other documents generated during the time of standardisation of the VALS, all clearly labelled with dates to help understand the conditions at the time of writing. Using documentation and archives, complimentary values of the different data sets can be identified, strengthening the data used within this study.

[6] Information redacted largely included the names of the personnel in documents and correspondence, as well as personal information not relevant to the standardisation of the VALS.

3.2.5 Summary of research and data

The techniques involved in this research are summarised in Table 3.2 below which outlines the methods used and summarises their strengths and weaknesses.

Source of evidence	Details	Strengths	Weaknesses
Interviews	• Semi-structured interviews	• Targeted – focuses directly on case study design • Insightful – provides perceived causal inferences	• Bias due to poorly constructed questions • Response bias • Inaccuracies due to poor recall • Reflexivity – interviews give what the interviewers wants to hear
Ethnography (Direct observations)	• Multi-sited ethnographic study with field notes	• Reality – covers events in real time • Contextual – covers context of events	• Time-consuming • Selectivity – unless broad coverage • Reflexivity – event may proceed differently because it is being observed • Cost-hours needed by human observers
Documentation	• USGS Public Docs / booklets • Internal USGS docs • Emails • External doc's and books	• Can be reviewed repeatedly • Unobtrusive • Exact details • Broad coverage – over time, events and settings	• Retrievability • Biased selectivity if collection incomplete • Reporting bias • Access may be deliberately blocked
Archival Records	• Freedom of information docs on standardisation	• Same as for documentations • Precise and quantitative	• Same as for documentations • Accessibility to privacy reasons

Table 3.2 Summary of research methods adopted during the study (adapted from Yin, 2003, p.86)

Together these research techniques complement one another to provide a robust mix of methods to obtain the data needed to address the research questions, reducing bias, reflectivity and selectivity as much as possible. Using these methods it was possible to conduct flexible, open exploratory research to address the specific areas of interest, obtaining data from different sources to provide a form of corroboration, yet also represent the different values and viewpoints of the actors involved in the VALS.

3.3 Analysis and reflections

Here I review the tools and methods adopted to analyse the qualitative data and ultimately address the research questions. The methods adopted were based on qualitative data analysis (QDA), although the process developed to interpret interview data was modified to reflect the multi-sited nature of this research and to cope with the large number of interviews conducted within the timeframe available and a limited financial budget (I was unable to afford transcription by external parties). QDA methods are frequently used in qualitative research, and are adapted and applied in this study to manage the large data sets collected.

3.3.1 Qualitative data analysis

QDA involves a range of processes and procedures that transform the qualitative data collected into an explanation, understanding or interpretation identifying a person’s point of view, how they relate to this view, their context, and how they convey their view. This process typically involves writing and the identification of themes that help interpret and organise the data. McCracken (1988, p.29) outlines a 'four-step method of inquiry' for use when conducting long interviews that divides the qualitative methods into four different processes: i) the review of analytic categories and interview design; ii) review of cultural categories (cultural factors relating to the interviewee) and interview design; iii) interview procedure and the discovery of cultural categories; and iv) interview analysis and the discovery of analytical categories. McCracken's method accurately describes the process of analysis undertaken during this research. Since this research is exploratory, it produced an exceptionally large data set making analysis a long and iterative process.

Documental analysis of the USGS archives involved using quotations and memos to develop interpretation of their historical content, factual information, and the representation of different values. This information was corroborated with interview data, and other documental information published by the USGS. Inferences were made from the documents reviewed, to review the discussions in the development of the standardised VALS.

To organise the data sets, all recorded interviews were uploaded into the QDA software package, Atlas-Ti. The interviews were played back via freeware called Express Scribe v.4.2.3, written by NCH Software, which enabled the interview to be played back at different speeds, to aid transcription, so enabling the simultaneous construction of a mind map (see below). During play back, a mind map was drawn, important and relevant quote times noted, and the maps then scanned into the Atlas-Ti database. Research memos and original field notes for each interview were also uploaded into Atlas-Ti so that all files, audio, visual and written materials relating to a single interview were stored together. In Atlas-Ti different Hermeneutic Units were used for each observatory, so keeping all the related information for an observatory case study together. This method enabled the data to be organised in a manageable form.

3.3.2 Describing, interpreting and analysing the data

In this section, I will discuss the use of mind mapping as a descriptive and analytical tool and the development of the analysis method used, providing a rationale and justification for the analysis methodology. The analysis in this study consisted of two stands; the more open-ended pilot study and the main research phase of the study which was targeted towards specific concepts.

Traditional qualitative studies typically use description, classification, and connection processes using coding of transcribed interviews (Kitchin and Tate, 2000). Since it was felt that the normal process of description, which is transcription for all 93 interviews, would have been too time consuming and made the data unmanageable. Therefore, a different method was developed to address this problem. Based on the interview schedule, a mind map was produced for each interview (see appendix C for sample). The ‘mapped’ interview was represented by seven branches representing the different questions in the interview schedule: background and involvement of interviewee with VALS, process of VALS, use of VALS, implications of standardisation of VALS, case study examples, future of VALS, and an additional branch for other information. The mind map thus reflects the interview schedule, while also providing a detailed view of the interview content. In addition, producing the mind map helped develop the initial descriptive process into a classificatory and connective one, providing an immediate visual comparison between interviews and observatories. The mind maps were cross-referenced to the recording, noting the times of significant statements, which were later fully transcribed to form quotes for more detailed analysis, thereby following more closely the typology that Kitchen and Tate (2000) outline. The quotes were selected on the merit of articulating or representing key points that emerged from the interviews, many of which were already established following the fieldwork from notes and ethnographic observations. The quotes were then reclassified under more specific classification codes (by hand, not using Atlas-Ti) that addressed specific aspects of the themes emerging from the data, and are presented in the empirical chapters under the research questions they address directly.

Mind maps are diagrammatic representations of words, ideas or tasks, arranged around a central theme (Buzan and Buzan, 2006), as opposed to mental maps which are used to refer to a person's individual perception of their world or environment (Gould and White, 1986). They are used to generate structure and classify ideas as an aid in study, organisation, problem-solving, decision-making and many other purposes. Mind maps are a useful guide to the intuitive arrangement of concepts into branches, using key words to make connections between portions of information and are often hierarchical. In this respect they bear many similarities to the use of nested hierarchies of codes used in QDA. However, there is little published on the use of mind maps as a tool in qualitative research. In studies of nursing it has been suggested that 'mind mapping can allow researchers to make rapid and valid transcriptions of qualitative interviews without the need for interviews to be transcribed verbatim' (Tattersall et al., 2007, p.32). In that particular case, maps were generated during the interview, rather than from recorded data. This PhD research builds on the research by Tattersall et al. to use the technique to transcribe recorded interviews as mind maps. In so doing, the boundary between transcribing and analysis becomes blurred. Using a new untested technique provides some concern as it has not been ratified, but it is important to note that all forms of analysis are ultimately interpretative, requiring a workable combination of researcher creativity and accountability to the data. The mind map records less textual detail than a full transcription, and may only make sense to the researcher; it would be difficult for someone to read a mind map and make the connections between the branches without actually knowing the information, or to replicate the study.

Using mind maps to transcribe has a significant number of benefits. Using an interview recording it is always possible to sense and record verbal emphasis or hesitation, which a written transcript does not provide. Listening to the interview again and producing a mind map provides instant 'closeness' and familiarisation of the data that facilitates an understanding of the context of the comments, rather than just using text. The process of transcribing using a mind map allows creative thinking between the themes and aids in identifying common themes that emerge. There is little literature from the academic community on the benefits or use of mind maps despite their potential application. This method of research is likely to be something that will be addressed more during multi-sited ethnographic studies where the researcher is doing exploratory work relating to one research area, but in many locations and thereby must conduct a significant amount of interviews to develop a 'fuller', more holistic picture. Concise methods of description and analysis such as the mind map offer a tool to get the data into a form that is usable for analysis quickly.

3.3.3 Considering research ethics

Due to ethical considerations and the requirement to comply with UCL and ESRC research ethics frameworks, the identities of interviewees remain anonymous in this study. The volcano observatory from which the interviewee is located is recorded and a classification system is used to identify whether the interviewee is a volcano hazard program (VHP) manager, senior scientist, or scientist; or a user of the VALS where the federal agency or institution will be listed. For example, following a quote, the reference may be '*HVO senior scientist 1'*, or '*LVO user - emergency manager 1'*. Anonymity has a number of benefits; first, it protects the identity of individuals in the observatories, and second, it serves to provide a more honest representation of the social dynamics investigated. By presenting the results as anonymous the analysis will aid comparison without prejudicial bias relating to the employees. Every interviewee was requested to sign an ethics brochure that outlined my research, explained the degree of anonymity and requested their consent (see appendix B for the ethics brochure).

3.3.4 Introducing the research findings

To analyse the data, extensive writing of ideas, themes and issues led to establishing the overarching themes that emerged from the data, which go on to form the empirical chapters. The findings are presented in the next four chapters to outline the constituent research questions and the themes that emerged from the research and explore some of the issues identified, before addressing the research question in the conclusion chapter. The first empirical chapter, the case study, is based largely on document and archival analysis, but also includes interview data. This chapter aims to provide the contextual information behind the research by reviewing the history and development of the USGS, the VHP and the five different volcano observatories. Through a number of significant volcanic crises in the U.S., it is possible to review the evolution of the VALS and explore some of the difficulties raised in designing and implementing a standardised VALS. The chapter also addresses the processes involved in the standardisation of the VALS and the factors that triggered the need to standardise.

The three empirical chapters that follow are based on three principal issues that emerged during the data analysis: managing complex systems using a linear VALS, decision-making within a VALS, and accommodating and communicating with different users, which form the three constituent research questions outlined in the literature review. In these chapters the key findings of the thesis research are presented in a narrative form, supported by quotes from the interviews, again rooted in the data collected. Each chapter will present the issues discovered from the research and explore them in further depth, representing the different perspectives between the volcano observatories, the different levels of scientists that work in that observatory, in addition to the views of the users and collaborative partners of the VALS. The contexts from which the issues arise will be explored and each chapter will address key literature that supports the observations, providing corroborating theoretical models from the literature review. Following the presentation of the empirical data, it is possible to address the research questions directly within each chapter, drawing from the empirical data presented and the literature presented in the literature review. In the discussions and conclusions the materials presented in the empirical chapters are evaluated to address the key research question of this thesis, to what extent are linear, standardised VALS an effective warning tool for volcanic hazards in different contexts of complexity, uncertainty and risk?

Chapter 4. The USGS and Volcano Hazard Program: a local and national perspective

This chapter discusses the case study of this research, the United States Geological Survey (USGS), with the aim of providing contextual information for the following three empirical chapters. First, the chapter provides an overview of the USGS, the Volcano Hazard Program (VHP) within the USGS, and their respective warning systems and legal mandates. Second, it reviews the history and local perspectives behind the formation of the five observatories of the VHP. Last, it views the USGS and VHP as an institution from a national perspective providing a summary of the centralisation factors that influenced the USGS. Reviewing the USGS from these different perspectives provides insight into the pressures placed on the volcano observatories at a local level, and the USGS at a governmental level, which led to the development of volcano alert level systems (VALS) and their subsequent standardisation in 2006. The design of the standardised VALS emerged from previously developed VALS and the lessons learnt from crises experienced by the observatories during the previous thirty years, along with U.S. federal policy development. The catalysts behind the standardisation are discussed in this chapter to provide the context from which the analysis of the remainder of this thesis is conducted.

4.1 The USGS: background and responsibilities

This section provides a brief overview of the USGS, the VHP, and the legal mandates for the USGS to provide volcanic hazard warnings. A majority of the material discussed is from documentary sources, including USGS publications, published papers and grey literature. Additional insights are provided by interviews conducted with the VHP scientists during fieldwork conducted in 2008.

4.1.1 The formation of the USGS

During the 1830s, growing awareness of the importance of science in Federal Government led to the establishment of the Corps of Topographical Engineers in 1839, to explore and map the continent. By 1848, the discovery of gold in California became the focus of the Corps, and by

1867, Congress had authorised four major western explorations under the General Land Office that focused on geology. Conducted by both military and civilian parties, conflicts occurred between the four surveys, resulting in their merging as the Geological and Geographical Survey of the Territories, which went on to become the USGS (Rabbitt, 1989). Established in 1879, the USGS was originally charged with duties for the 'classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain' (U.S. Congress, 1879).

Early USGS activities focused on geological surveys of agriculture and water, metal resources and geological mapping, but by 1901 oil and other fossil fuels became the top priority (Rabbitt, 1989). Following the world wars, where mining resources were the primary focus to aid the war efforts, the USGS shifted once more towards scientific research and the provision of scientific information to understand and describe the earth, becoming a world leading research institute in the natural sciences. In 1979, an earthquake in the Imperial Valley, Mexico-California Border, caused US$30 million in damage (Rabbitt, 1989), and in 1980, Mt. St. Helens volcano erupted explosively. These events, amongst many others, led to a shift in focus of the Survey from natural resources to natural hazards, partly the result of the growing realisation of the costs of hazards in terms of the value tied up in critical infrastructure. In 1996, the Biological Resources Discipline was established within the USGS, so that the USGS now has five key science divisions: Biology, Geography, Geology, Geospatial and Water (USGS, 2009c). This thesis focuses on the Geology division, specifically the Volcano Hazard Program (VHP).

Today, the mission of the USGS is to 'serve the Nation by providing reliable scientific information to describe and understand the Earth; minimise loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life' (USGS, 2009a). The USGS is a bureau of the Department of Interior (DoI) of the U.S. Federal Executive Department of the U.S. Government, and is the DoI's only scientific agency with no regulatory responsibility. Employing over 10,000 people the USGS has its headquarters in Reston, Virginia, with major offices in Lakewood (Eastern Region), Colorado (Central Region), and Menlo Park in California (Western Region).

4.1.2 The Volcano Hazard Program

The Volcano Hazard Program (VHP) is one of three hazard programs within the USGS's Geology Division; the others being earthquake and landslide. The USGS has been involved in volcanic hazards since its formation in 1879 (pers. comm. at Menlo Park), but became a key area of interest when in 1912, Thomas A. Jaguar founded the Hawaiian Volcano Observatory (HVO) (Heliker et al., 1968). HVO was administered between 1919 and 1948 by various Federal agencies (National Weather Service, USGS, and National Park Service), but from 1948 was operated continuously by the USGS (Tilling et al., 1987). It was not until the late 1960s that the VHP became a separate budget within the USGS (pers. comm. at Menlo Park). Following the 1980 eruption of Mt. St. Helens in Washington State, volcanic hazards received increased attention from government authorities, the media and public (Wright and Pierson, 1992). The U.S. Government expanded the VHP in mid-1980 (Bailey and USGS, 1983), and it continued to evolve rapidly following three further periods of volcanic unrest in the 1980s from Long Valley Caldera (California), Mt. Redoubt (Alaska) and Mauna Loa and Kilauea (Hawaii). Prior to the Mt. St. Helens eruption, the VHP was an interdivisional activity involving the cooperative efforts of the Geology, Water Resources, and National Mapping Divisions. After this eruption, the VHP worked with the Water Resources Division for 18 months on related projects before separating. Today the Geology division frequently collaborates with other USGS departments to conduct volcanic research.

The VHP was formed with the aims of: 'preventing loss of life and property resulting from volcanic eruptions and volcano related hydrologic events, and minimising economic hardship and social disruption that commonly occur when volcanoes threaten to erupt' (Wright and Pierson, 1992, p.6). To fulfil these aims it focuses on four activities: volcanic hazards assessment, volcano monitoring, research, and emergency-response planning / public education (Wright and Pierson, 1992). These activities aim to accumulate as much information as possible on volcanic processes, and provide the means for public officials to respond to volcanic crises rapidly and effectively. In addition to the five volcano observatories (AVO, CVO, HVO, LVO, and YVO), the VHP assists the Commonwealth of the Northern Mariana Islands. In 2002, the five U.S. volcano observatories and their federal, state, and academic representatives became part of the Consortium of U.S. Volcano Observatories (CUSVO), established as a scientific working group to strengthen interaction and communication[7]. The VHP has a team chief scientist that resides at the volcano observatories, and a VHP coordinator, who is based at the

[7] See www.cusvo.org

USGS headquarters in Reston, Virginia. In addition, each observatory has a scientist in charge (SIC), which is a rotating position.

The VHP provides information on potential and current hazards to federal, state, and local government officials; the media, and other concerned groups, as well as local populations. This creates a 'boundary' between the USGS who provide information, and those who use it to take action. It is important to note that the USGS itself sees a boundary between the scientific advice it provides and the action that must be taken in response to this information:

> The USGS does not dictate or even recommend specific mitigation measures, because such measures must be balanced by social and economic considerations beyond USGS mandate or expertise. Rather, the program provides information about volcanic hazards that will help people to choose and manage the risks associated with living near a volcano (Wright and Pierson, 1992, p.6).

The USGS monitors 169 active volcanoes characterised by a wide range of eruptive styles and located in six different tectonic settings: Aleutian subduction zone (Alaskan volcanoes), Juan de Fuca plate remnant of a subduction zone (Cascade volcanoes), three different basin ridge spreading centres (including Long Valley volcano), intercontinental hotspot (Yellowstone volcano), oceanic hotspot (Hawaiian volcanoes), and Marianas subduction system (Anatahan volcano) (VHP manager 1). The VHP has gained experience of volcanic crises all around the world via the Volcano Disaster Assistance Program (VDAP) (Ewert et al., 2007) and also continues to work closely with the Kamchatka Volcanic Eruption Response Team (KVERT), making the USGS one of the most diverse volcano monitoring institutions in the world (Kirianov et al., 2002). Observatories located in other countries with many volcanoes such as Indonesia, Philippines, New Zealand and Italy do not have such diversity in tectonic locations, styles of volcanic activity and experience in crises.

4.1.3 Role, legal responsibilities and mandates

The aims and activities of the VHP have been shaped by the need to provide warnings about potential hazards from volcanic activity. On November 23, 1988, the Robert T. Stafford Disaster Relief and Emergency Assistance Act[8] was signed into law; amending the Disaster Relief Act of 1974[9]. The Stafford Act was designed to bring an orderly and systemic means of

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[8] Public Law 100-707

[9] Public Law 93-288 (88 Stat. 143)

federal natural disaster assistance for state and local governments in carrying out their responsibilities to aid citizens. Through this act and subsequent Executive Orders, the USGS was assigned responsibility for providing technical assistance on volcanic hazards and as the authority to issue volcanic warnings. The President delegated responsibility to the Secretary of the Department of the Interior to empower the Director of the USGS 'to exercise the authority, functions, and powers granted by Section 202 of the Disaster Relief Act of 1974 with respect to disaster warnings for an earthquake, volcanic eruption, landslide, mudslide, or other geological catastrophe' (USGS, 2004, p.9)[10]. In response to this directive, the VHP's mission was to enhance public safety and reduce losses from volcanic events through effective forecasts and warnings of volcanic hazards based on the best possible scientific information. The definition of a warning is not clearly stated in the Acts, so it is not possible to establish whether it is just to provide scientific information or to provide information on the risks. However, a 'major disaster' combines these issues in its definition as:

> Any natural catastrophe […] in any part of the United States, which in the determination of the President causes damage of sufficient severity and magnitude to warrant major disaster assistance under this Act to supplement the efforts and available resources of States, local governments, and disaster relief organizations in alleviating the damage, loss, hardship, or suffering caused thereby (FEMA, 2007, p.2).

Whilst the USGS is the lead agency for VHP activities, it is just one organisation of many involved to comply with the Stafford Act. The USGS works on broader public, interstate and regional issues involving other agencies, referred to as 'users' in this study, such as federal and state land and mineral agencies, FEMA, Emergency Services, other Federal Agencies (U.S. Forest Service (USFS), National Weather Service (NWS), National Park Service (NPS), National Aeronautics and Space Administration (NASA)), state and private universities, and clients of emergency-response planning (Federal Aviation Authority (FAA), Army, etc.). The need for such diverse federal involvement in the VHP is largely a result of interstate, regional and national implications of volcanic disasters, including economic disruption and effect on federal lands. In addition, there is a public need for information about impending volcanic hazards to aid mitigation and develop integrated research programs to provide sufficient warnings. In 2009, the USGS received approximately US$140 million as part of the American Recovery and Reinvestment Act to help upgrade and improve some of its laboratories and

[10] Executive Order 11795 entitled 'Delegating Disaster Relief Functions Pursuant to the Disaster Relief Act of 1974' (30 FR 25939, July 11, 1974) and subsequent actions (as reported in 40 FR 52927, November 13, 1975, and 49 FR 213938, 1984)

research capabilities (USGS Newsroom, 2010). US$15.2 million will be used to modernise equipment as part of the National Volcano Early Warning System (NVEWS) at all USGS volcano observatories, including many of the universities and institutes with which the VHP collaborates (USGS Newsroom, 2010).

4.1.4 The initial early warning system

In 1977, the USGS developed procedures for providing warnings for all the hazards for which it had been given responsibility by the Stafford Act. It drew on the research and experience of other government agencies in meteorology and hydrology to establish a three-tiered system. Depending on the perceived magnitude of risk of the geological phenomena, a notification was issued as a notice, watch, or warning; increasing in severity. Table 4.1 below provides detailed definitions of each warning level. It is important to note that first, this system separates risk and science by only focusing on scientific information; second, a hazard warning assumes that it will be possible to provide a prediction (i.e. time and magnitude) which is extremely hard to do for volcanic hazards; third, the time scale for each level varies depending on the accuracy of the prediction rather than the anticipated time until event; and last, the most severe warning is shown at the bottom of the Table. Only the Director of the USGS could issue this warning.

Notice of Potential Hazard	Information on the location and possible magnitude of a potentially hazardous geological event, process, or condition. However, available evidence is insufficient to suggest that a hazardous event is imminent or evidence has not been developed to determine the time of occurrence.
Hazard Watch	Information, as it develops from a monitoring program or from observed precursors, that a potentially catastrophic event of generally predictable magnitude may occur within an indefinite time (possibly months to years).
Hazard Warning	Information (prediction) as to the time, location, and magnitude of a potentially disastrous geologic event.

Table 4.1 The 1977 USGS Warning System from the Federal Register (v.42. no.70) (Hill et al., 2002, p.33)

In 1979 the USGS commissioned a report to analyse and evaluate the warning system for a potential landslide in Kodiak, Alaska (Saarinen and McPherson, 1981). The conclusions showed that while the USGS had developed a warning system that provided scientific and technical information, ‘it is not enough to deliver technical information and then leave, for local officials may not understand the full implications, and hence may not have the tools to prevent a disorder and grave danger without inducing undue fear’ (p.77). The report highlighted the need for education and communication between the USGS and local authorities and populations, so they can understand the full implications of the hazard, and make educated decisions on the basis of technical information. Saarinen and McPherson recommended the USGS become more sensitive to the views and needs of the affected community, as hazard notification has social, economic and political impacts. However, to do this, the report states that the USGS would have to go ‘beyond the letter of the law to include empathy for the communities involved’, and by doing so the USGS would ‘stand a better chance of having a positive impact on the performance of its sometimes unpleasant duty’ (Saarinen and McPherson, 1981, p.80). These recommendations were not heeded, most likely because the USGS regards itself as an organisation that provides scientific and technical information however, volcanic crises in the 1980s eventually illustrated the report authors' point. During these crises, explored in the accounts of individual observatories below, a number of social, economic and political factors had extraordinary impact on VHP scientists’ ability to do their job and fulfil their legal mandate. To ignore the local contexts and not recommend specific mitigation measures may make providing warnings easier for the USGS, but it does not necessarily make them effective.

The Congressional mandate under the Stafford Act for the USGS to issue ‘timely warnings’ (FEMA, 2007, p.5) of potential volcanic hazards to responsible emergency-management authorities and to the populace affected, is extremely difficult to achieve. As discussed in the literature review, scientists can rarely make accurate forecasts of volcanic activity given significant scientific uncertainties. Prior to the Stafford Act scientists focused on understanding volcanic processes, hazards and whether they can be modelled. Suddenly scientists had to start thinking about the broader implications of their research, and the context of a volcano and its activity. This realisation was described during an interview at CVO with a senior member of staff:

> We would not have been having this conversation when my career began. There was no perceived need to think about, talk about issues like this. Volcano scientists were monitoring volcanoes and learning about them, and not as engaged in the forecasting or prediction business, and probably not as aware of their responsibility

> to the public. I mean we were trained as scientists and we were learning about volcanoes and that was our job. Now, I think, especially after a series of disasters that included Nevada del Ruiz, which really was a watershed, when we realised as scientists, the potential for that lahar was very clear and yet more than 20,000 people died, we realised there was a disconnect. Something had to change and the onus was partly on us and so now we're having these kinds of discussions; what's the best alert system, what's the most effective, how do we deal with our customers? I don't know I ever used the word customer until the last decade or two. Now, we recognize that and I think that's a positive development. I think there has to be give and take […]. Discussions like this are evidence of that it matters whether this is a good alert system or not. That is a step forward. (CVO Senior Scientist 1).

This comment highlights the growing awareness of VEWS and VALS over the last few decades from non-existence, to playing an important role in the VHP and the daily life at a volcano observatory. In addition, it highlights the reorientation of the professional identity of the USGS and expertise of the volcanologists, which is discussed further in chapter 6. It is not only the contingencies of the hazard that make warnings complex, but the trajectory and tracing of researchers that leads them to think about risk in certain ways. The warning systems developed and lessons learnt by the VHP have been heavily shaped by local volcanic crises that led to the establishment of the five different volcano observatories and three different VALS, which are discussed in the next section.

4.2 Local perspective: the observatories

During the 1980s, three serious volcanic crises shaped the evolution of the VHP and the early use and development of VEWS and VALS. The 1980 eruption of Mt. St. Helens woke the nation to the realisation that explosive eruptions can occur on the mainland, near large populations. The volcanic unrest during the 1980s at Long Valley Caldera, California, highlighted the need for good communication and trust during a crisis, and the influence of politics on the official warning system. Finally, the eruptions of Augustine and Redoubt volcanoes, Alaska, created the awareness that ash poses serious risks to the aviation sector. This created a demand to develop ash specific warning systems, and the realisation that the users of warnings have different needs.

This section aims to provide a summary of these key volcanic events and their influence on the development of different observatories and warning systems, reflecting each observatory's interpretation of a warning. The lessons learnt by the VHP can be understood by referring to the idea of the social construction of technology (SCOT) (Bijker et al., 1987) where, understanding what is defined as the best technological solution to a particular contextual problem, means reviewing how the groups and stakeholders that participate in it define it. By reviewing the individual volcano observatories it is possible to understand the local context and practical application of providing warnings, along with the difficulties involved, both scientifically and socially. The observatories are reviewed individually, in a chronological order of their establishment, to aid the reader in developing a historical context of the issues raised by each location, and ultimately the implications this had on the warning system and VALS developed. The locations of the observatories and their collaborative partners are shown in Figure 4.1.

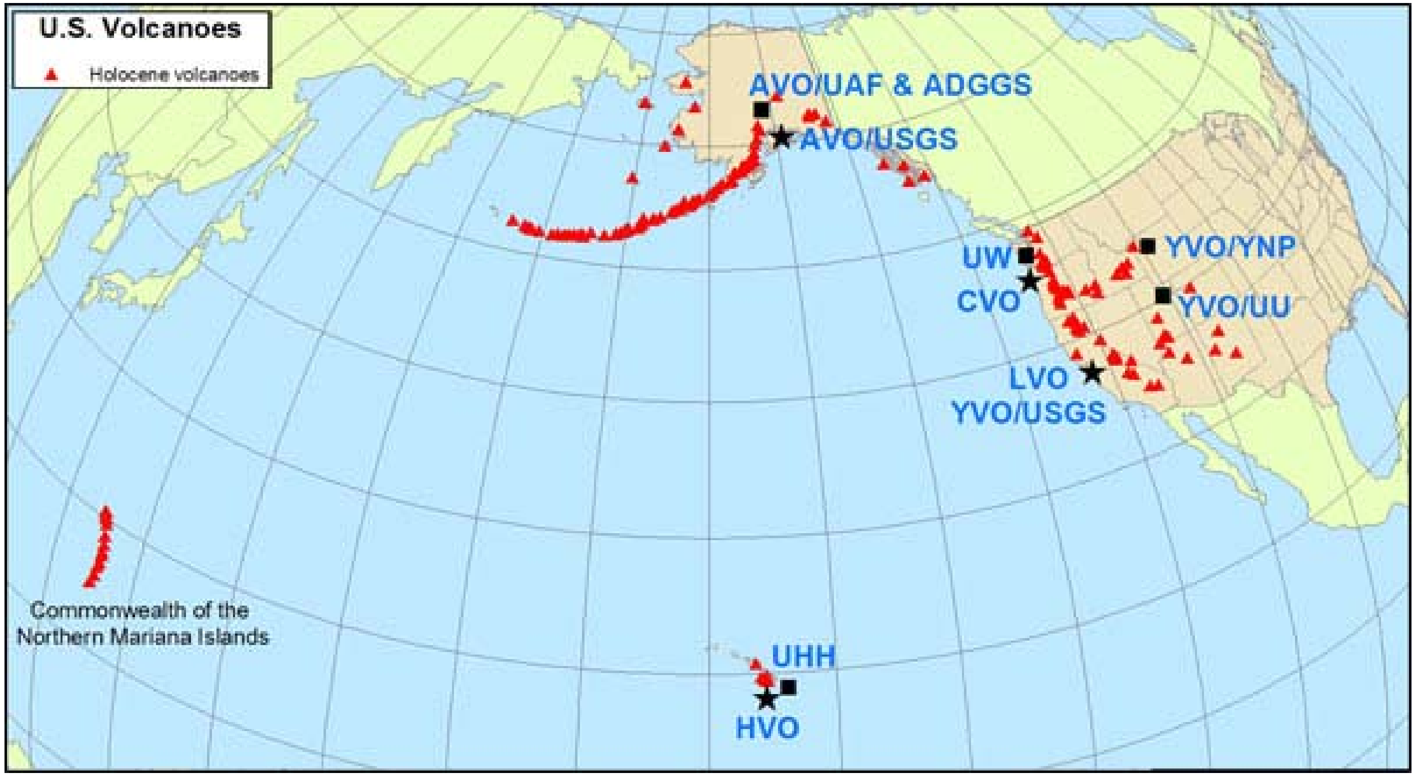

Figure 4.1 Map of the USGS VHP observatories and their collaborative partners (USGS VHP Website, 2008). The observatories are: the Alaska Volcano Observatory (AVO), Cascades Volcano Observatory (CVO), Hawaiian Volcano Observatory, the Long Valley Observatory, and the Yellowstone Volcano Observatory (YVO). The collaborative partners are: University of Alaska, Fairbanks (UAF), Alaska Division of Geological and Geophysical Surveys (ADGGS), University of Washington (UW), University of Hawaii, Hilo (UHH), University of Utah (UU), Yellowstone National Park (YNP).

4.2.1 Hawaii Volcano Observatory (HVO)

HVO is the oldest USGS volcano observatory, established in 1912, following frequent eruptions of Kilauea volcano. High levels of activity at Kilauea, including its constant eruption from 1983 to the present, have facilitated the development and testing of volcano monitoring techniques providing a fertile training location for volcanologists. Historically, USGS staff trained at HVO went on to work in the other observatories as they were established in the 1980s (Wright and Pierson, 1992). HVO remains unusual within the USGS, predominantly because it is the only volcano observatory in a small island community setting, isolated from the U.S. mainland. Another distinguishing factor is the near constant eruption of Kilauea and another highly active volcano, Mauna Loa, resulting in HVO and the local agencies fostering close relationships (Tilling et al., 1987). Islanders have experienced numerous volcanic crises and emergency responders have developed sophisticated communication and responsive procedures (HVO user – emergency manager 1). The small size of Hawaii Island enables the County of Hawaii Civil Defense to bring together all departments and agencies responsible for developing and maintaining supporting disaster response plans, using a multi-hazard 'Integrated Emergency Operations Plan' (HVO user – emergency manager 1). These agencies are coordinated to plan development and respond to crises by identifying the roles required at the Emergency Operation Centre, but the final decision is made by the State Governor and Mayor of Hawaii County, who was also the State Deputy Director of Civil Defense. Email correspondence between senior staff at HVO to the VALS standardisation team in April 2003 (FOIA archive) highlight that the constant eruption, experienced and educated public, and single emergency management agency imply using a VALS, standardised or not, would be redundant or 'pointless' in the Hawaiian context:

> When asked for his opinion of the proposed alert-level system, the director of Hawaii County Civil Defense said he had no strong feelings about it one way or the other. He noted that it seemed pointless to use it for the ongoing eruption of Kilauea, but said that it might be useful during the build up to a Mauna Loa eruption. On the other hand, he said that it might be just one more thing that he would need to explain to the public.

The fact that HVO has operated for over 80 years without a VALS indicates they may be redundant for continuous eruptive activity. Additionally, the simple but effective organisation of the Hawaiian Civil Defense provides an ideal environment for communication, decision-making and coordination, particularly given Hawaii's small size and community that lends itself to this particular organisational set up. HVO serves as an example that with good communication, warnings can be expressed quickly, accurately and obtain the required response without the use of VALS.

4.2.2 Cascades Volcano Observatory (CVO)

The 1980 eruption of Mt. St. Helens was the deadliest and most economically destructive volcanic event in the history of the U.S., yet the VHP successfully managed the crisis (Swanson et al., 1983, Swanson et al., 1985, Lipman and Mullineaux, 1982, Saarinen and Sell, 1985). The eruption gained unprecedented media attention following the growth of media news channels, providing a new context in which scientists were expected to engage with the media, both local and national. The wide media coverage generated problems because stakeholders interpreted scientific data differently and expressed their opinions via the international, twenty-four hour broadcasting media (Saarinen and Sell, 1985). Consequently, knowledge about the event became pluralistic. This crisis was the first to use the newly established USGS warning system by issuing a 'Notice of Potential Hazard' in 1977 (Crandell and Mullineaux, 1978). The eruption led to the expansion of the VHP and increased financial investment into volcano related research.

A number of lessons were learnt by the VHP during this eruption, relating to scientific understanding, the management of the crisis, and significant media interest, which are summarised below. Despite a number of complex issues encountered during the crisis, the assumptions by the scientists were that with further scientific knowledge of volcanic behaviour, volcanic crises could be managed better.

The eruption of Mt. St. Helens generated a lateral blast causing devastation over a greater distance than the scientists had forecast. Since none of the VHP scientists had seen a lateral blast before, the eruption made volcanologists aware of the danger inherent in their ignorance of some volcanic processes and limitations in their knowledge (Crandell and Mullineaux, 1978). Many of the scientists working on Mt. St. Helens were from HVO, working on Kilauea which has a very different style of volcanism. Therefore monitoring, decision making and scientific understanding was heavily influenced by the experience of the HVO scientists, which created some tension between groups of volcanologists in the VHP (Thompson, 2000). In addition, there were a number of conflicting reports on the likelihood and magnitude of eruption issued by non-USGS scientists that produced inconsistent advice and warnings for federal officials.

The USGS did not want to lose its credibility to other scientists, so it attempted to resolve any differences prior to any statement issuance to officials or the media (Foxworthy and Hill, 1982).

The majority of the 57 deaths occurred because tourists ignored designated risk zones established by the USGS (Crandell and Mullineaux, 1978). This highlighted a misunderstanding in the public's perception of volcanic risk, and of the rationale behind the volcanic hazard risk zones developed. It was fortuitous that the volcano erupted on a Sunday as many loggers that work around the volcano were away. Whilst the logging companies had been strongly advised to evacuate the area, the commercial demands to keep logging meant that during the day loggers were permitted into the established hazard zones (Foxworthy and Hill, 1982). This raised the issue of how seriously do the local officials need to take warnings from the scientists even if it leads to economic loss?

The growing interest of the media, the public and other federal agencies meant that demand for information from the scientists was highest at critical periods when they were immersed in evaluating the hazards and their potential consequences. This caused problems for the scientists who had to learn to balance their need to understand the volcano with making time to provide information about the crisis (Thompson, 2000, Peterson, 1988).

At the time volcanic unrest began in March 1980, the VHP was operating out of Menlo Park in California and Hawaii. With no onsite office, the USGS collaborated with a number of federal agencies and the University of Washington (who were seismically monitoring the volcano, and still do today with the USGS) to manage the crisis. An Emergency Coordination Centre (ECC) was set up by the U.S. Forest Service at its administrative headquarters providing work spaces, communication facilities and other logistical support for the USGS, enabling the VHP to receive and evaluate all monitoring information and then disseminate it, including rapid warnings (Foxworthy and Hill, 1982) (CVO scientist 5). The initial lack of resources and facilities made the basic tasks of the USGS difficult and time was wasted in setting up appropriate working areas and resources, which would have been better spent on analysing the crisis and educating the local agencies and public. This is likely to have been one of the key drivers behind why volcano observatories were later established in different regions.

For these reasons, including the lessons learnt, the U.S. Congress provided additional funds for a larger VHP and further research to understand volcanoes. Consequently, the USGS established a permanent regional office at Vancouver, Washington, on May 18, 1982. It was designated the David A. Johnston Cascades Volcano Observatory (CVO), in memory of the VHP volcanologist killed 2 years earlier, and was the first volcano observatory founded since HVO in 1912. CVO was established to continue long-term monitoring and hazard assessment of all the Cascades volcanoes, and to focus on the recurring eruptive activity at Mt. St. Helens, in partnership with the University of Washington Geophysics Program. It also became a centre for studying the interaction of volcanic activity with glaciers, rivers and lakes that can lead to landslides (CVO scientist 16).

Between June 1980, and October 1986, Mt. St. Helens continued to erupt in the form of a dome-building phase punctuated frequently by dome explosions. Due to the cyclic nature of this activity, CVO was able to develop accurate warnings as far as three weeks in advance for nineteen of twenty-one explosions (Bailey and USGS, 1983). This gave many scientists confidence in their ability to provide precise predictions, and gave the impetus to develop a VALS for use at CVO (HVO senior scientist 5).

There are 20 volcanoes within the Cascade Mountain range, so when CVO scientists developed a VALS specifically for use in the there during the 1990s, it had to encompass a wide range of volcanic styles (from calderas to basaltic cones) and hazards, across three different states (Washington, Oregon, and California). The VALS developed reflected alert-level terminology used at Mt. St. Helens during the dome-building years based on two types of event 'notifications' to accompany the alert level issued (HVO senior scientist 5). First, information statements for unexpected short-lived events (i.e. steam bursts, minor lahars) often with no opportunity to provide warning or evacuation information; and second, advisory or alert statements where additional information is provided with an alert level change, along with updates of volcanic unrest and imminence of hazardous volcanic activity. The alert levels issued increase in severity from an information statement, to an extended outlook advisory, volcano advisory, and volcano alert, labelled from one to four for increasing severity (see Table 4.2). Emergency Managers throughout the Cascade Mountain range correlated suitable responses for each level, and although the public were aware of the VALS, it was primarily targeted at Federal Agencies. Unlike the USGS warning system of 1977, based on a notice of potential hazard, watch, warning (Table 4.1), this VALS has criteria based on 'threat', incorporating the risk aspect of volcanic hazards that the report by Saarinen and McPherson (1981) argued was needed in order to generate more effective warnings. The CVO VALS was flexible because the use of statements enabled scientists to provide information in the accompanying reports.

Alert Level	Description Summary
Information Statement (Hazard Level One)	Usually a short-lived, isolated event
Extended Outlook Advisory (Hazard Level Two)	First confirmation of changes that may lead to an eruption or hydrologic event
Volcano Advisory (Hazard Level Three)	Hazards are elevated but do not pose an imminent threat
Volcano Alert (Hazard Level Four)	Hazards are elevated; imminent threat to life and property

Table 4.2 Volcano hazard level at CVO (US Forest Service, 1992, pp.20-22)

The VALS developed at CVO specifically focused on eruptive behaviour and hazards that can be reasonably determined; however, the events that occurred at Long Valley Caldera generated a situation where the VALS had to relay more uncertainty and encompass hazards not necessarily related to volcanic eruptions.

4.2.3 Long Valley Volcano Observatory (LVO)

On May 25th 1980, just one week after the climatic Mt. St. Helens eruption, four magnitude 6 earthquakes occurred at Long Valley Caldera, generating serious concern amongst USGS scientists that volcanic activity might be about to occur. Long Valley volcano is a 15km by 30km caldera in eastern-central California, located in Inyo and Mono Counties. The eruptive characteristics of calderas were, and still are, poorly understood (Newhall and Dzurisin, 1988, Troise et al., 2006). Past unrest and activity at calderas such as Rabaul in Papua New Guinea, 1983 and 1994, and Campi Flegrei in Italy, 1982-4, generated no indicators that could provide warnings for imminent caldera activity or eruption. The lack of understanding of restless calderas generated widespread concern when Long Valley, a large and potentially dangerous caldera, started to show signs of activity (LVO senior scientist 1). This was further exacerbated by the Mt. St. Helens crisis that was already stretching limited VHP staff and resources. Initially Long Valley caldera was monitored as an observatory-like project operated from the USGS Western Region headquarters in Menlo Park, California. Increased monitoring of the caldera by the USGS and university community led to the formal organisation of Long Valley Observatory (LVO) in the late 1990s (VHP manager 4).

On the rim of Long Valley caldera, the town of Mammoth Lakes has a permanent population of more than 5,000, and a temporary population that swells to over 40,000 during peak weekends in the ski season (Hill, 1998). The local ski area on Mammoth Mountain is a popular ski resort with Californians and at the time was developing into a major international ski resort. Many businesses and investors felt the negative attention of a volcano could ruin this growth potential in the 1980s. This made the entire management of the volcanic crisis very difficult. The damage caused by poorly managed communication of volcanic hazard warnings made it almost impossible for the USGS to fulfil its warning mandate, resulting in a change from the 1977 USGS warning system. A number of events contributed to this failure.

The first contributing factor was the lack of effective communication from the scientists to emergency managers and local populations, resulting in the relationship between them deteriorating and setting an example of ‘how to start out on the wrong foot’ (Hill, 1998, p.401). Two days after the magnitude 6 earthquakes shook Mammoth Lakes in 1980, the USGS Director announced a ‘Hazard Watch for potentially damaging earthquakes’ in the Long Valley area (Hill, 1998). Discussions began between the USGS, the California Division of Mines and Geology (CDMG), and the University of Nevada, Reno, resulting in a consensus that they had the obligation to inform local civil authorities about the potential volcanic nature of Long Valley Caldera. A draft report was sent to the USGS director's office recommending a ‘Notice of Potential Volcanic Hazards’ (Mader et al., 1987). During discussions between the USGS Director and the Governor’s Office in Sacramento about the precise wording of the announcement, officials for the Inyo and Mono Counties remained unaware of any potential volcano hazard. George Alexander, science writer at the *Los Angeles Times*, unofficially discovered these discussions and wrote an article announcing that the USGS were to release a warning 'Notice' for the area in due course (Alexander, 1982). The local civil authorities and the citizens of Mammoth Lakes were completely taken by surprise, since they had received no correspondence from the USGS about the potential for volcanic hazards, only earthquake hazards. The very next day the USGS Director issued a ‘Notice of Potential Volcanic Hazards’ but the lack of communication between the county officials and the USGS generated responses of outrage, anger and disbelief about the volcano (Hill, 1998, Mader et al., 1987).

The second key social factor leading to the warning system failure was the threat of volcanic activity on the economy of Mammoth Lakes town, which led to poor communication between the stakeholders involved. Keen to expand their ski resort, which already had significant local investment, many officials and local populations denied there was a volcano, especially as there was no perceptible change in the environment, only some ground deformation picked up by sensitive scientific equipment (LVO senior scientist 1). During 1982-1985, Mammoth Lakes town media hardly reported on any volcano or earthquake crises around the world, and USGS geologists were not welcomed in the area, they were '*personae non gratae*' (Hill, 1998, p.401). This denial generated significant problems in convincing Mammoth Lakes to take mitigative actions. In January 1983, an intense earthquake swarm caused nearly constant shaking for a couple of weeks. Large quantities of snow from the El Niño winter blocked roads, including the only paved road connecting the town to the highway out of the caldera. This raised concerns about maintaining access to the town. The Chairman of the Mono County Board of Supervisors ordered a second dirt road to be ploughed and eventually paved, to provide an alternative route out of town called 'Mammoth Scenic Loop'. This was not a popular decision with the local population since it in part 'carried an implicit knowledge that there might actually be a volcanic hazard' (Hill, 1998, p.401). The Chairman was recalled in a special election over the summer, such was the level of bad feelings.

In October 11, 1983, the official 1977 USGS 3-tiered warning system was dropped to only one tier. It was rumoured that friends of the U.S. President living at Mammoth Lakes used their contacts to combat the problem of the original 'Notice of Potential Volcanic Unrest' (LVO senior scientist 1). The new warning system comprised of 'a formal statement by the director of the USGS that discusses a specific geologic condition, process, or potential event that poses a significant *threat* to the public, and for which some timely response would be expected', Federal Register (v.48, n197), (Hill et al., 2002, p.33) (author's emphasis). The use of the word 'threat' here is important, because a warning became no longer just about the hazard; a level of risk needed to be determined. Independent social researchers suggested this new warning system would eliminate 'unwarranted public concern over potential hazards that present a low risk to the public' and clarify situations where the 'potential hazard may deserve either a near-term or immediate response to save lives or property' (Mader et al., 1987, p.31). The change in warning system indicated the USGS had become more sensitive to the public response from Mammoth Lakes, and political pressures had forced the USGS to reinterpret their federal mandate.

Still in effect, the official (bureau-level) USGS hazard notifications system can only issue a formal hazard warning. No warnings have been officially issued since the 1984 eruption of Mauna Loa, Hawaii on March 29th (email correspondence from Menlo Park scientist to standardisation committee in March 2003, FOIA archives). Although the eruption began on

March 25th, delay in getting the Hazard Warning signed off by the USGS Director illustrated that the bureaucratic process took too long to make the warning useful (LVO senior scientist 1 / VHP manager 6). This resulted in individual observatories developing warning systems to cater their own needs, rather than using the universal USGS warning system of 1977.

In 1989, following persistent earthquake swarms at Mammoth Mountain, significant levels of carbon dioxide gas were released destroying more than 100 acres of forest over two years (Sorey et al., 1996). The newly incorporated Mammoth Lakes town (in 1984) created a new group of civil authorities who were keen to discuss relevant hazards at Long Valley Caldera. The LVO scientist in charge (SIC) became exasperated by constant requests from the city manager about the evolving activity, so when the state geologist of California asked if there could be written criteria for how seriously he should regard the varying level of activity, it led to the development of the ‘Response Plan for Volcanic Hazards in Long Valley Caldera and the Mono Craters Area, California’ (Hill, 1991). This plan included a VALS based on the recent USGS Parkfield earthquake prediction experiment which, used an alphabetic scheme of five alert levels from E to A in ascending order of concern, so that 'A' reflects a warning, 'E' reflects weak unrest (Bakun, 1988, Bakun, 1987). This system was adapted for volcanic hazards at LVO because it was the only formal alert level system the USGS used in California. The VALS in Table 4.3 consists of the status, the USGS required response, the activity level of the volcano and the likely recurrence of this activity. Within each 'status' were a number of 'sub-statuses', used by LVO scientists as criteria (seismic, continuous strain, geodetic strain, and magnetic field status) assigned ‘a-e’ levels, used to assign the alert level using a sophisticated matrix of values (Hill, 1991, pp.39-46). This VALS, unlike the one used at CVO, was immensely complex, and this may be a reflection of the uncertainties relating to the behaviour of calderas The VALS also had stand-down criteria with fixed periods of time required to lower each level, and template messages for different levels to aid the communication process (pp.32-33). The decision to change alert level was no longer the responsibility of the USGS Director, but that of the SIC of the volcano observatory, reflecting a decentralisation of power within the USGS and recognition of the role of local scientific experts in making judgement on different alert levels.

Status	USGS Response	Activity Level	Recurrence Intervals
A Alert	Issue Geologic Hazard Warning	Eruption likely within hours to days	Decades to centuries
B Alert	Alert Director, trigger Event Response	Intense unrest	Years to decades
C Status	Notify Office Chief, OES Headquarters State Geologist	Strong unrest	Months to years
D Status	Notify team leaders, Branch Chiefs, OES comm., USFS CDMG, & UNR	Moderate unrest	Weeks to months
E Status	Notify Chief Scientist's personnel. Information call to OES communications and local authorities as appropriate (i.e. a locally felt earthquake).	Weak unrest or possible instrument problems	Weeks
N	Normal monitoring activities	Background activity	-

Table 4.3 Status Ranking and Activity Levels at LVO (Hill, 1991, p.4)

High levels of volcanic unrest during the 1990s provided extensive opportunity to exercise the lower status levels. However, it became clear, via the media, that most people had no idea what a 'D-level' alert meant, other than it seemed serious. This led to exaggerated concern by the public, renewing frustration in the business community over negative 'volcano' publicity. Discussions began between the different stakeholders on how to improve this VALS by making it less susceptible to misinterpretation by the media and public. In June 1997, the alphabetic code was converted to a four level colour code (Green, Yellow, Orange, Red) (see Table 4.4), expressed with normal conditions at the top of the alert level table, in contrast to being at the bottom of the table as designed in the 1991 VALS (Table 4.3). Like the previous VALS there are complex sub-levels and stand down criteria (see appendix D), but it also preserved the useful aspects of the 1977 USGS system such as the terms 'notice of potential hazard', and 'hazard watch'. In addition, distinctive shapes were used for the colour codes that could be identified when using black and white print, and faxing. So far, the lack of technology to relay colours meant colours were absent within most warning and alert level systems. The shapes used were designed to fall in line with the increasing difficulty of ski slopes, so that skiers could intuitively identify the severity of a warning (LVO senior scientist 1 / VHP manager 4). Finally, the red alert level was divided into four sublevels to express eruption intensity from minor, to moderate, strong to massive, all of which occur within calderas. Therefore, the LVO VALS was specifically designed around the requirements of local users of the VALS and to incorporate the characteristics of restless calderas.

CONDITION	USGS RESPONSE[1]	ACTIVITY LEVEL	RECURRENCE INTERVALS[2]
GREEN – No immediate risk	Normal operations plus information calls to local and other authorities for weak through strong unrest as appropriate	Background or quiescence	Most of the time
		Weak Unrest	Days to weeks
		Minor Unrest	Weeks to months
		Moderate-to-Strong Unrest	Months to years
YELLOW (WATCH)	Full call-down and EVENT RESPONSE	Intense Unrest	Years to decades
ORANGE (WARNING)	Full call-down and EVENT RESPONSE (if not already in place under YELLOW)	Accelerating intense unrest: Eruption likely within hours to days	Decades to centuries
RED (EUPTION IN PROGRESS)	Full call-down and EVENT RESPONSE (if not already in place under YELLOW or ORANGE) Daily or more frequent updates on eruption levels	LEVEL 1: Minor eruption	Centuries
		LEVEL 2: Moderate explosive eruption	Centuries
		LEVEL 3: Strong explosive eruption	Centuries
		LEVEL 4: Massive explosive eruption	Centuries to millennia

Table 4.4 Summary of Colour-Code Conditions and associated U.S. Geological Survey (USGS) responses for volcanic unrest in Long Valley Caldera and the Mono-Inyo Craters region (Hill et al., 2002, p.2). [1]USGS response for a given condition will include the responses specified for all lower conditions. [2] Estimated recurrence intervals for a given condition are based primarily on the recurrence of episodes of unrest in Long Valley Caldera since 1980, the record of M>4 earthquakes activity in the region since the 1930's, and the geologic record of volcanic eruptions in the region over the past 5,000 years.

The colour code is defined as ‘a graded measure of our concern about how a given level of unrest might threaten local communities with a possible volcanic eruption’ (Hill et al., 2002, p.5). Again, there is growing recognition of the need to reflect concern about volcanic threats building on the recognition that the risk depends on the local population and particular volcanic activity. To date, LVO has never moved out of a Green level, despite extended periods of elevated activity that fell within ‘normal’ criteria. Although there are rigorous criteria for each alert level, the final decision is made by the LVO SIC, partly because there is a lack of history in precursory activity, and because ‘personal judgement and experience will inevitably play a critical role in decisions on the transition from one colour-code to the next’, (Hill et al., 2002)(p1). Consequently, the emergency response agencies at Mammoth Lakes developed a preliminary plan outlining the response of each agency depending on the colour code issued.

During ongoing unrest LVO had the opportunity to test out different VALS, to determine what worked and what didn't (i.e. using colours rather than the alphabet) and how to make decisions about assigning alert levels using sophisticated criteria, even though these may be overridden by the SIC on the basis of personal judgement. LVO staff drew three major conclusions as a result of the handling of the crisis first, understanding the science is key to providing long term forecasts and short-term predictions. Second, constant attention and major time commitment are required to establish and maintain effective and credible working relations with civil authorities and the public, which can be enhanced by long-term continuity with scientific personnel and a stable policy with responsibilities clearly outlined. Third, the threat of an impending volcanic crisis will test goodwill and trust built over time (Hill, 1998).

These insights however, do not reflect the enormous impact of economic and political issues on the warning system. VALS may provide an ‘intuitive, easily understandable framework for gauging and coordinating a response to developing volcano crises', but the problems seen at LVO highlight the need to consider the impacts of volcanic warnings, in addition to effective communication, considered 'the single most important element – to mitigate the risk from potentially hazardous volcanoes' (Hill et al., 2002, p.5).

4.2.4 Alaska Volcano Observatory (AVO)

The history of AVO is quite different from that of other observatories, as it was driven entirely by the needs of aviation clients, thereby introducing a different set of stakeholders and different spaces of concern within the USGS. The eruption of Mt. St. Helens in 1980 produced vast quantities of ash that shut down several jet engines (Miller and Casadevall, 2000). Whilst this caught the attention of the aviation authorities it was not until near tragedies that action was taken. From 1978-1992 there were 23 incidents involving aircraft that inadvertently encountered volcanic eruption plumes (Miller and Casadevall, 2000). The most dangerous effect is engine damage resulting from ash melting and coating the turbine blades when it enters the jet intakes, causing the engines to stall (Neal et al., 1997, Miller and Casadevall, 2000). Fortunately, all affected aircraft to date have managed to restart their engines, although usually only after a severe loss of altitude.

In 1982, following the near-crash of a British Airways Boeing 747 caused by volcanic ash from Mt. Galunggung in Indonesia, the International Civil Aviation Organisation (ICAO) initiated the Volcanic Ash Warnings Study Group (VAWSG) to standardise information provided to flight crews about volcanic eruptions. By 1987, a number of provisions for volcanic ash warnings had been adopted in aviation protocols, including SIGMETS (significant meteorological information) and NOTAM (notice to airman), and by 2003 the Volcanic Ash Warnings Study Group was replaced by the International Airways Volcano Watch Operations Group (IAVWOPSG) (OFCM, 2004). A consortium of U.S. federal, state, and private sector parties worked to develop an improved EWS and protocols for ash avoidance in the heavily travelled North Pacific air routes. This resulted in the growth and increased capacity of AVO, founded in 1986, and the formal adoption of the 'Alaska Interagency Plan for Volcanic Ash Episodes' (Madden et al., 2008) that documents specific responsibilities and protocols for each agency before, during, and after a volcanic event. Endorsed by the International Civil Aviation Organisation (ICAO), this multi-agency early warning system has been emulated in a number of volcanic regions around the world. AVO was the first observatory that had to deal with a wide diversity of clients, all with differing technologies and systems, and to deal with users who were this time global.

In 1986, just prior to the founding of AVO, Augustine Volcano in the Alaskan Cook Inlet erupted generating eruption clouds that disrupted regional air traffic (Casadevall et al., 1994). Volcanologists at the then USGS office in Alaska worked with University of Alaska Fairbanks

Geophysical Institute (UAFGI), and the Alaska Division of Geological and Geophysical Surveys (DGGS) to forecast the volcanic activity and advise the Federal Aviation Authority (FAA) and U.S. Air Force. By March 1986, this cooperation was formalised as AVO with the responsibility of monitoring the four major Cook Inlet volcanoes: Augustine, Spurr, Redoubt and Iliamna.

During the eruption of Redoubt on December 15th, 1989, a Boeing 747 aircraft lost power in all four of its engines, glided over 4km down restoring the engines only 1km above the nearby mountain peaks (Brantley et al., 1990). Whilst no-one was hurt in the incident, the damage to the relatively new aircraft was estimated to have been US$80million (Steenblik, 1990). This costly event widely affected commercial and military aircraft operations near Anchorage, causing the re-routing or cancellation of flight operations. This seriously affected the Anchorage economy since Ted Stevens Anchorage International Airport handles more international air freight dollar value than any other airport in the U.S., and remains one of the largest cargo hubs in the world (airport-technology.com, 2010). Staff at the then small AVO began working with the FAA to develop a specific VALS for large ash plumes and clouds that might impact aircraft. AVO used a number of new techniques to remotely monitor the volcanoes using seismic and GPS data, satellite images (remote sensing and thermal imagery), and with ground and pilot observations they were able to issue timely warnings. Since volcanic ash poses a threat to aviation safety whether the aircraft is in the air or on the ground, avoiding ash completely is the only way to guarantee no damage. The aviation community regarded the risk of ash as more clear-cut than for ground based hazards, however, there is additional uncertainty in knowing how much ash is in the atmosphere in the first place, which depends on the interrelation of two complex systems, the volcano and the weather. The Icelandic ash crisis in 2010, has since highlighted that even clear-cut approaches to ash hazards may not be acceptable in different contexts, in this case Europe, due to the serious economic and social losses associated with grounding aircraft to avoid ash.

AVO developed and began using its aviation colour code system in February 1990, during the Mt. Redoubt eruption. Unlike the VALS for LVO and CVO, the code needed to specifically communicate ash hazards. The AVO SIC and head of the VHP came up with the idea, as recorded during email correspondence from the AVO SIC in 1990 (FOIA archives) to senior VHP scientists at Menlo Park:

> [We] desperately needed a simple device to communicate to the airline industry the activity, or anticipated activity of Redoubt volcano. I sprung it on the large AVO group (maybe as many as 30 people mostly from CVO, Menlo Park, etc) at the next morning's staff meeting in Anchorage. Given the fact that we had geologists, seismologists, lahar specialists, tephra people etc., the proposed warning scheme almost immediately ballooned to a 6 x 6 matrix (!) so as to satisfy everyone. After the meeting was over, we went back to the original 4-colour scheme.

This quote highlights the complexities involved in designing VALS; the more people involved in its design, the more complex it becomes as everyone has to account for their particular concerns. A highly complex VALS would be beyond realistic capabilities. Given the need for quick warnings, the AVO SIC and VHP team chief scientist decided on a simple colour traffic light system (AVO senior scientist 8). This system had already been established in South America, specifically because local populations easily understood it. Whilst this was an undemocratic decision, it was the foresight that a VALS at AVO needed to convey a clear message quickly to the aviation sector that ultimately led to its success. Called the 'aviation colour code for concern', the emphasis was on how concerned the users should be on the actual or potential volcanic activity. The use of the word 'concern' suggests that risk was the basis for issuing an alert level, and that risk mitigation measures were directly targeted (AVO senior scientist 8 / VHP manager 4). The colour code was developed to consistently 'describe the status of the volcano when a potentially hazardous event was in progress or was expected' (Brantley et al., 1990, p.26). In addition, an update report was issued with further information.

The original colour code was designed around four colours, with descriptions specific to the geography and monitoring stations located on Mt. Redoubt (Brantley et al., 1990, p.26). However, just one day prior to the eruption of Mt. Spurr in 1992, a more generic form of the colour code used for Mt. Redoubt was issued, shown in Table 4.5. The alert levels increase in concern from Green at the top, to Red at the bottom. The description section is largely focused on seismic data and explains the level of activity at the volcano, with a plume height of 7.5km (25,000 ft)[11] used as a cut off between the Orange and Red codes, since most cruising aircraft fly above this height.

[11] Aviation users and USGS scientists refer to heights in feet.

Colour	Description
Green	Volcano is in its normal 'dormant' state
Yellow	**Volcano is restless.** Seismic activity is elevated, Potential for eruptive activity is increased. A plume of gas and steam may rise several thousand feet above the volcano which may contain minor amounts of ash.
Orange	**Small ash eruptions are expected or confirmed.** **Plume(s) not likely to rise above 25,000ft above sea level.** Seismic disturbance recorded on local seismic stations but not recorded at more distant locations.
Red	**Large ash eruptions are expected or confirmed**. **Plume likely to rise above 25,000ft above sea level.** Strong seismic signal recorded on all local and commonly on more distant stations

Table 4.5 Level of concern colour code used for the eruption of Mt. Spurr, 1992 (Keith, 1995, p.5)

Although AVO had the capability to provide timely eruption warnings and help prevent aircraft encountering volcanic ash, a number of volcanoes in mainland Alaska and the Aleutian Islands remained unmonitored due to their remote location and lack of funds. In 1996, AVO obtained new Congressional funding through the FAA and was able to install volcano monitoring networks on the Alaska Peninsula and Aleutian Islands (Brantley et al., 2004). AVO also developed collaborations with the Kamchatkan Volcanic Response Team (KVERT) created in 1993 by the Russian Academy of Sciences Institute of Volcanic Geology and Geochemistry and the Kamchatkan Experimental and Methodical Seismological Department. Today they still work together to provide volcano information to the flight paths from Asia to America (Kirianov et al., 2002).

With increased monitoring capabilities, came recognition of increasing diversity of volcanic behaviour, which led to a number of modifications in the colour code. Following the 1996 Akutan seismic crises, the VALS description was split into 'intensity of unrest at volcano', and a 'forecast' (see Table 4.6). However, by 1998, the older simpler colour codes in Table 4.5 above, were back in use suggesting that the forecasting element may have been too specific, making it too restrictive, and implying that volcanic activity could be forecast more accurately than actually possible in a majority of cases.

Colour	Intensity of Unrest at Volcano	Forecast
Green	Volcano is in quiet ‘dormant’ state	No eruption anticipated
Yellow	Small earthquakes detected locally and (or) increased levels of volcanic gas emissions	An eruption is possible in the next few weeks and may occur with little or no additional warning
Orange	Increased number of local earthquakes. Extrusion of a lava dome or lava flows (non-explosive eruption) may be occurring.	Explosive eruption is possible within a few days and may occur with little or no warning. Ash plume(s) not expected to research 25,000 feet above sea level.
Red	Strong earthquake activity detected event at distant monitoring stations. Explosive eruption may be in progress.	Major explosive eruption expected within 24 hours. Large ash plumes(s) expected to research at least 25,000 feet above sea level.

Table 4.6 AVO’s level of concern colour code in 1998 (Waythomas et al., 1998, p.33)

The vested interest of the aviation sector enabled AVO to benefit from additional funding and advancement in satellite technology to provide more accurate monitoring and forecasting capabilities. By July 2007, AVO had established monitoring networks on 31 of Alaska’s 41 active volcanoes. Since a number of volcanoes remain unmonitored and it is not possible establish the volcano’s characteristic behaviour, they are designated a ‘non-assigned’ (NA) status, rather than Green (AVO scientist 6). Not only was technology aiding volcano monitoring, but it was changing the way that AVO communicated information and warnings through the development of a sophisticated website and database, reflecting the levels of technology the aviation sector uses and demanded from AVO. The success of the AVO colour code of concern meant that pilots requested its use throughout the U.S. This set the scene for not only nationalising the AVO VALS, but also using it as a global standard. This is discussed further in section 4.3.

4.2.5 Yellowstone Volcano Observatory

YVO, created in 2001 by the USGS, University of Utah, and Yellowstone National Park is the youngest of the five observatories. Inauguration followed long-term monitoring and geological investigations of the Yellowstone caldera volcanic system, dating back to the 1959 Hebgen Lake magnitude 7.5 earthquake. YVO aimed to strengthen scientist's abilities to track activity in the highly active caldera that could result in hazardous hydrothermal, seismic, or other volcano-related activity (Lowenstern et al., 2006, Christiansen et al., 2007). It was later seen as beneficial to establish a VALS for use during heightened activity. The move was at least, partly driven by increasing interest in Yellowstone following broadcast of the BBC / Horizon / PBS Nova 'Supervolcanoes' documentary in 2000. Although the SIC wanted to establish a VALS, which version to adopt was not clear; AVO's, CVO's or LVO's? Given that Yellowstone is a caldera, LVO's VALS appeared the most suitable, but in addition, there was a need to have an aviation code in place (YVO scientist). The question of which VALS should be adopted at YVO contributed to the idea that standardisation of the VHP VALS might be a good practical solution.

4.2.6 The need to merge Volcano Alert Level Systems

By the late 1990s, the VHP was operating three different VALS at CVO, LVO and AVO. The CVO SIC felt this could potentially generate devastating confusion. Cascade volcanoes also occur in California therefore, users in California may not be aware of the VALS used at CVO since they are more familiar with the VALS used at LVO. In addition, there was increasing pressure from the aviation sector for the colour code of concern to be adopted throughout the U.S. On October 6th 2004, CVO adopted the AVO colour code for ash, incorporating it into a new-updated VALS, as can be seen in Table 4.7, with levels based on numbers 0-3, a more detailed description summary and some forecasting information in addition to the actual eruptive behaviour. Relative to the prior VALS used at CVO, the order of words changed from 'Extended Outlook Advisory, Advisory and Alert' to 'Notice of Volcanic Unrest, Advisory and Alert'. The four colours of the AVO colour code of concern were added, but not the accompanying descriptions.

Alert Level	Description Summary
Information Statement (Level Zero)	• Includes usual events such as steam bursts, small avalanches, rock falls, and minor mudflows • Usually short lived volcano-related events, but some may be hazardous • May also be issued to provide commentary about notable events within any staged alert level during volcanic unrest
Notice of Volcanic Unrest (Alert Level One)	• Volcano is restless • Significant anomalous conditions that could be indicative of an eventual hazardous volcanic event • Most likely anomalous condition would be sustained, elevated seismicity • Expresses concern about the potential for hazardous volcanic activity but does not imply an imminent hazard.
Volcano Advisory (Alert Level Two)	• Processes underway that have a significant likelihood in culminating in hazardous activity, but evidence does not indicate that a life – or property – threatening event is imminent • Used to emphasize heightened concern about a potential hazard
Volcano Alert (Alert Level Three)	• Precursory events have escalated to the point where a volcanic event with volcanologic or hydrologic hazards threatening to life and property appears imminent or is underway

Table 4.7 Alert levels for Cascade Range volcanoes revised in 2004 (CVO, 2004)

Volcano alerts in the Cascades have become increasingly important to federal and state agencies and the public. When Mt. St. Helens showed renewed signs of volcanic unrest from 2004-2005, there was an unexpected appetite for real-time information from the public, driven by the development of electronic media (Sherrod, 2008, Frenzen, 2008). In response to a rise in alert level and issuance of information statements, the number of inquiries at CVO rose significantly, as shown in Fig. 4.2, illustrating that media phone inquiries (daily counts, in brown colour) and public web activity (striped) generally spiked following changes of alert level and prominent volcanic events, such as steam and ash explosions. These CVO web site statistics illustrate the event-driven demand for online information and the interest VALS generate. In turn this places significant pressure on the scientists who feel they have to get the alert level change 'right'.

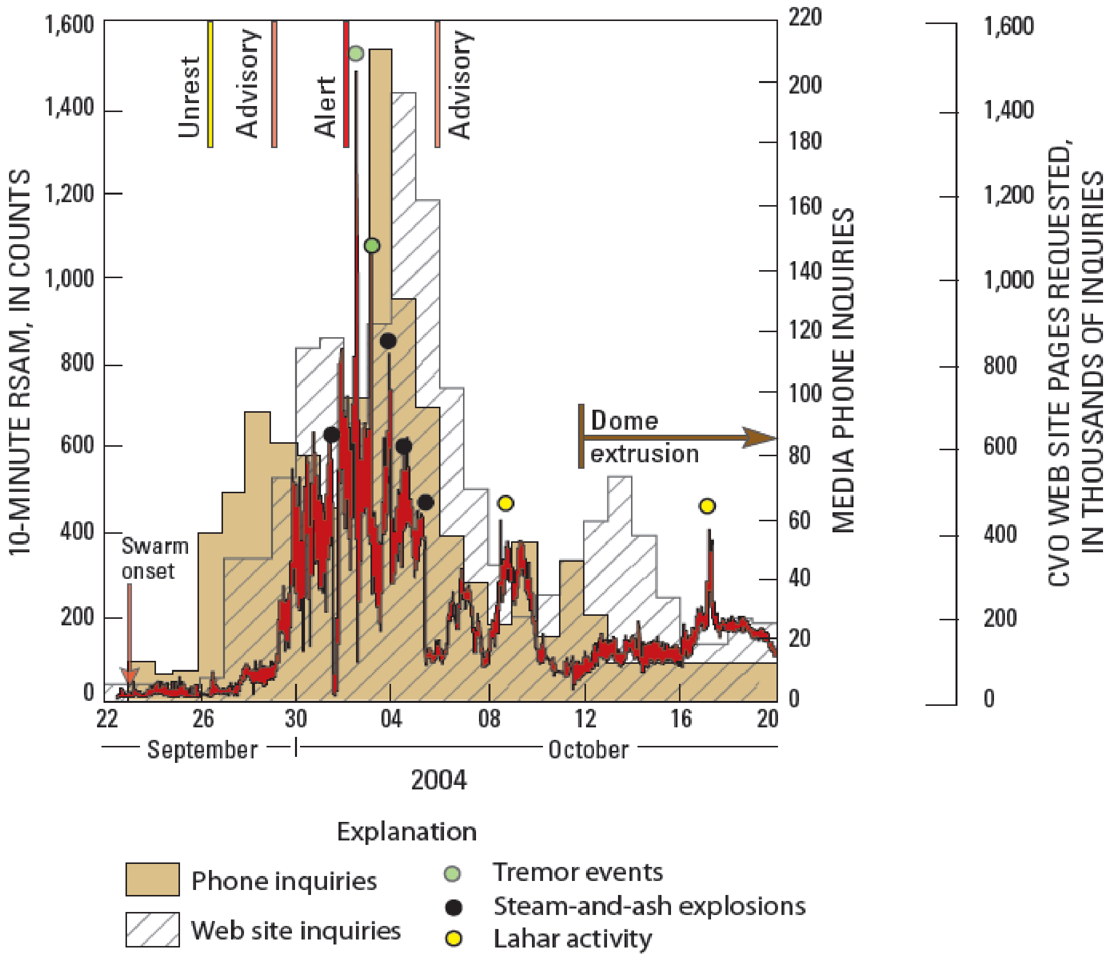

Figure 4.2 Relation between volcanic activity, alert levels, volume of media inquiries to the CVO, and number of web pages requests from the CVO website during the first weeks of unrest at MSH (Driedger, 2008, p.513)

Whilst the federal and state agencies were able to use and understand the newly established VALS during the 2004 crisis, in 2003, CVO staff working on the volcano-response plans for Mt. Baker and Glacier Peak were asked by their workgroup stakeholders whether it would be possible to change the names of the alerts to those used by the National Weather Service (NWS) for flood and tsunami warnings, i.e. Advisory, Watch and Warning (CVO user – emergency manager 3). Email correspondence from the scientists involved with the coordination plan to senior VHP staff in January 2003 (FOIA archive) informed staff that 'a change to [National] Weather Service alert titles would prevent confusion during volcano crises and that a single alert scheme would be more useful for educating the public about hazard alert levels'. This meant that there was a shift in the criteria for VALS toward education and user focus. Since a number of the agencies in the workgroups deal with flood issues regularly, and the U.S. Forest Service were considering adopting the NWS alert titles at the time for forest fires, it made sense to make all the terms standardised if possible, making it absolutely clear for all emergency responders. This led to questions about the rationale behind the current alert level titles, and whether it was possible to adopt standardised terminology for use at all the different volcano observatories?

4.2.7 Summary

Through these volcanic crises, the VHP and USGS learned a number of lessons. Email correspondence between a senior scientist at Menlo Park and other senior VHP staff in February 2004 (FOIA archive) highlights some of these. First, ʻthere is a need and mandated responsibility to communicate monitoring and other scientific data to emergency management officials in a clear and understandable manner'. Second, 'to establish and maintain scientific credibility, it is essential to tell officials what we know and do not know, what we think we understand or don't understand etc. The officials and the general public must never get the misconception that we scientists always know "everything ’. Third, ʻwhat we know or do not know will vary from volcano to volcano, depending on the amount and quality of available scientific information, extent of monitoring, etc. Even at well monitored and well understood, volcanoes, we can rarely anticipate with any certainty [about] what the volcano will do next'. All these issues, communication, credibility, and local knowledge, have been addressed in the literature review, where the volcanic crises presented also demonstrated the need for good communication, education, trust and credibility, and the need to understand the uncertainties and complexities involved in generating scientific knowledge about volcanic activity. Additionally the USGS has learnt the role of social, cultural, economic and political contexts in the design, use and effectiveness of VALS. The evolution of the VALS at the USGS tells a powerful story of the impact of media, travel, economic development and globalisation as it intersects with, and changes the definition of risk.

Within two decades, the USGS's VHP has evolved in response to a number of crises and warning systems changes, few of which were the result of in-depth consultation or design, but driven by need, usually over a short time frame. In this context, the evolution of the VALS provides a perfect illustration of the theory of social construction of technology (SCOT) (Bijker et al., 1987). Shaped and driven by politics, economics, and safety, the VALS used by each observatory were tailored to local physical aspects (volcanic unrest, types of volcanic hazards, and monitoring capabilities available) and social factors (design of the VALS, terminology, user demands and needs). Therefore, it is questionable whether there was a need for uniformity across the different volcano observatories. Yet, pressures to adopt a national aviation code, and users demands for the CVO VALS to comply with National Weather Service terms suggested that nationalisation of VALS was worthy of discussion, and this would require consultation with the USGS's external partners and the users of the VALS. Within the USGS management there was growing concern in having different conventions within the VHP whilst promoting uniformity for aviation processes. The question of standardisation was not only being considered at observatory level (bottom-up), but also at a national and policy level (top-down). These pressures are discussed below.

4.3 National perspectives

At the same time, in the late 1990s, when discussions within the volcanological community began to consider the idea of developing a global standard for VALS for use by all countries, there were serious discussions about adopting the AVO VALS as an international standard by ICAO for the aviation community. It was, however, the events of 9/11 in 2001 that triggered a number of significant changes within U.S. Emergency Management and Security policy that provided the final catalyst to standardise warnings, almost returning the VHP full circle to the original warning system set up in 1977. The impact of increasing globalisation, the diversification of values within different user groups, and finally new U.S. policy became issues that influenced the VHP and USGS as an institution, rather than at each observatory.

Three key issues placed pressure on the USGS, as an institution, to develop a standardised VALS: U.S. internal policy on emergency management, globalisation, and tensions within the USGS. The following section discusses these three issues before reviewing the implications of these factors.

4.3.1 The impact of 9/11 on U.S. security policy

Following the 9/11 terrorist attack in 2001, U.S. Congress passed the Homeland Security Act of 2002, creating the Department of Homeland Security (DHS), to improve coordination between the different federal agencies that deal with law enforcement, disaster preparedness and recovery, border protection and civil defense. The Department was assigned responsibility for protecting U.S. territory from terrorist attacks and responding to natural disasters. In 2002, the Department developed a Homeland Security Advisory System, a colour coded terrorism risk advisory scale, created to accommodate the Presidential Directive to provide information relating to terrorist acts to federal, state, and local authorities and the public (see Fig. 4.3). A number of USGS staff were consulted with respect to the design of the code (VHP manager 6). Although some procedures at government facilities are tied into each alert level, it is typically disregarded due to its apparent ineffectiveness, often staying at one alert level for years rendering it meaningless (CVO user – emergency manager 2). This code was even less useful for the public who had little idea what to do with each alert level, other than be vigilant.

Figure 4.3 Department of Homeland Security Advisory System (US Department of Homeland Security, 2010)

In 2001, emergency managers from state and local government, industry, academia, and the non-profit community came together at a public warning summit to discuss why not one single public warning system had been activated during the 9/11 event. From this summit a partnership for public warning (PPW) was created to assist the federal government in the assessment of the emergency alert system (EAS), a platform for the nation's public warning capabilities (Partnership for Public Warning, 2003). The PPW developed a national strategy addressing the EAS and Homeland Security advisory system, recommending use of one integrated hazard warning system with standard terminology and threat scales that promote interoperability and the dissemination of warning across multiple platforms. As a result the PPW began discussions that led to the interoperability standard alert and warning of the Common Alerting Protocol (CAP), something the USGS had to comply with (Oasis, 2008). This demonstrated a shift to value warning dissemination as key criteria in EWS, and a shift in governance where previously experts sought to manage risk, to one where everyone is considered as already at risk.

The Emergency Warning Act of 2003 (S. 118) passed by Congress to develop and coordinate a national emergency warning system (e.g. EAS), required that the Secretaries of Commerce and Department of Homeland Security ensured that comprehensive, easily understood, emergency warnings were issued for every U.S. risk, whether from floods, hurricanes or terrorist attacks. The Commerce Department would be responsible for developing new technologies to issue warnings, and Department of Homeland Security would be responsible for developing uniform standards for warnings. In 2004, one year after discussion and vetting, the National Incident Management System (NIMS) was accepted as a structured framework to:

> Guide departments and agencies at all levels of government, nongovernmental organizations, and the private sector to work seamlessly to prevent, protect against, respond to, recover from, and mitigate the effects of incidents, regardless of cause, size, location, or complexity, in order to reduce the loss of life and property and harm to the environment (Department of Homeland Security, 2008, p.1).

All federal departments were required to adopt the NIMS, working with the National Response Framework to provide the structure and mechanisms for national-level policy for incident management. A core component of the NIMS is to enable effective and efficient incident management and coordination by providing a flexible, standardised incident management structure (Department of Homeland Security, 2008). To do this, three key elements were developed; the Incident Command System (ICS), Multiagency Coordination Systems (MACS), and Public Information that provide standardisation through consistent terminology and established organisation structures i.e. Joint information Centre's (JIC's). The NIMS has been adopted by all U.S. Emergency Management agencies so they all operate on a standardised platform throughout the U.S. Terrorism had taken over crisis management and as a consequence, policy to standardise the systems for procedures and warnings across a multi-hazard platform, dominated the 2000s and consequently the VALS at the USGS.

4.3.2 The influence of globalisation

The First International Symposium on Volcanic Ash and Aviation Safety in 1991 helped raise awareness about aviation ash hazards (Casadevall et al., 1991, Casadevall et al., 1994). However, it was not until 1998, when the International Airways Volcano Watch (IAVW) was established, that standardising volcanic ash warnings internationally within the aviation community was addressed. IAVW was established by the International Civil Aviation Organisation (ICAO) and the World Metrological Organisation (WMO) to formalise international arrangements for monitoring and providing warnings in the form of standard warning messages (via SIGMETs and NOTAMs) (WMO, 2007). Due to the difficulty in providing accurate volcanic activity forecasts for ash clouds, global airspace was divided into nine different Volcano Ash Advisory Centres (VAACs) by the WMO, each responsible for a section of airspace (see appendix D). VAACs are responsible for coordinating and disseminating information on volcanic ash to the aviation sector and to issue volcanic ash advisories (VAA) that outline what can be seen in satellite imagery, pilot reports, observatory information, forecast trends and other available information. The IAVW coordinates the volcano observatory, VAAC, WMO and the aviation companies, making this the first global volcano early warning system that reflects the globalisation of airlines (Lechner et al., 2009) (see appendix E).

In 2004, ICAO documentation incorporated the AVO colour code chart in its 'Handbook on the International Airways Volcano Watch', with one modification; the removal of the specific height threshold (7.5km / 25,000ft) as the criterion for distinguishing between the Orange and Red alert levels (ICAO, 2004). By September 2005, the AVO colour code of concern was formally adopted in principle by ICAO to notify the status of a volcano for the purpose of supporting operational decisions to issue warnings (via NOTAMS, SIGMETS and VAAs) globally. ICAO specifies that 'the colour code describes conditions at / near the volcanic source circa the time of eruption and is not intended to describe the hazard potential of the drifting ash cloud itself at locations distant from the volcano or after the volcano has stopped erupting'

(ICAO, 2005, p.5-9). This is an important limitation, since the colour code focuses on the ash plume rather than distal, dilute, ash clouds that can, as demonstrated by the Eyjafjallajökull eruption, also cause serious disruption.

In contrast, no consensus had developed for an internationally standardised VALS for ground hazards. In 1996, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) asked several scientists to explore the use of VALS in different volcanic regions of the world. At the 'Cities of Volcanoes 2' conference in Auckland, 2001, there was significant interest and discussion among the participants about VALS and their usage and inconsistencies during a workshop. It was suggested that the 'global volcanological community should accelerate work towards developing and adopting a universal scheme that conveys information, in a consistent manner, about changes in conditions at any restless volcano, regardless of location or the institution(s) monitoring it' (Tilling, 2001, p.144). Ideally, this system should be 'solely established by scientists, based on volcanic phenomena, with no involvement of civil authorities', and easy for users to understand (Tilling, 2001, p.144). It is not clear why other stakeholders such as civil authorities involved in volcanic crises should not be part of this process, however, this may reflect the way volcanologists regard other actors in emergency management, and / or the way they perceive themselves. Although a universal VALS was not agreed upon for ground hazards due to insurmountable challenges, the discussions that took place did contribute to the development of nationally standardised VALS (including New Zealand and the U.S.).

Discussions on ground based hazard VALS focused only on physical hazard aspects, with little consideration of the social issues or context relating to the users of the VALS or policy implications; it is no surprise this focus on science led to failure in achieving a globally standardised VALS. The literature review highlighted the importance and role of decision makers, users and stakeholders in VALS, and the need to consider local contexts of culture, economics and politics. Lessons learnt from the history of USGS crises also reflect these findings. Excluding users from discussions about ground-based hazard VALS is possibly one of the key reasons why it never happened or became formally discredited as an idea. Although the aviation colour code was standardised, it is important to note that ash hazards differ greatly from ground hazards in that all stakeholders use highly sophisticated technology and deal with only one hazard, ash, and this hazard will dissipate in time enabling a return to normal activity, unlike ground hazard impacts which can last for decades.

4.3.3 Tensions within the USGS

At an observatory level it became clear that users of VALS were not only diverse, but required different information over varying temporal and spatial scales. At an institutional level, there were new demands to provide VALS that complied with U.S. disaster policy and develop standardised warning systems like the many other U.S. agencies use (e.g. for tsunamis, hurricanes, forest fires). This meant that public and emergency responders would understand warnings no matter where they were in the country. It was argued by USGS staff that the VHP's diverse range in VALS provided a fragmented appearance, lacking consistency, and complicating the advisory role VDAP plays when discussing which VALS would be suitable. Lastly, the President himself wanted to have a simple system whereby he could quickly see the relative danger levels of a hazard, and this required standardisation (VHP manager 6).

A standardised VALS offered a number of advantages to the VHP. During a crisis VHP staff are deployed from all the observatories to help maintain 24 hour coverage, so by using a standard VALS everyone would be familiar with it. In addition, it theoretically means that when warnings are issued they are uniformly understood by the media and public throughout the U.S., as well by the VHP team, partner organisations, and users, many of which collaborate or work with a number of different volcano observatories.

In 2001, it was clear the USGS faced a number of problems. How were the observatories going to implement the VALS adopted by ICAO, whilst maintaining their existing systems? HVO had no desire to have a VALS, YVO wanted to use a VALS but was not sure which one to pick, and CVO and LVO operated two different VALS even though some Cascade volcanoes are in California where the LVO code was known and used. This raised a number of fundamental questions such as: what is the rationale of a standardised VALS? How can a single alert level carry the essence of emergency information to non-volcanologists, concerned agencies and publics? If there were different codes for different clients would this generate more work and cause confusion?

The national and global events that triggered standardisation, predominantly via policy, occurred at the same time that emergency managers in the Cascades requested to use the National Weather Service terms in the VALS. It was this synthesis between local and national pressures that finally led to serious discussions for the USGS to standardised VALS. The meeting of bottom-up and top-down demands meant that the VALS had to change. This was a challenge the VHP had so far avoided; how does one incorporate local variations and needs already developed at the volcano observatories, with uniformity? Was it possible to standardise VALS when the uniform USGS system developed in 1977 had already been proved a failure?

While the concept of having a standardised system seemed a logical solution for USGS management, in practice there were strong reasons why this might be untenable as this email correspondence for senior management at AVO to senior scientists at Menlo Park written in June 1997 (FOIA archives) outlines:

> Everyone thinks their system works best for their volcanoes. […] Local difficulties in communication channels / abilities and volcanic settings, in particular hazards, demand some flexibility in wording, presentation etc. Systems in place seem to be working so there is not a lot of incentive to change (plus, the inertia factor is high). The AVO system, developed principally for airline use, works well for that important and global customer. Hence, what has followed is the formal adoption of a similar colour code with slight modification by ICAO.

This chapter has demonstrated how the USGS's VEWS and VALS have evolved through a number of volcanic crises, and adapted to changing circumstances including the growing number and sophistication of users, and the availability of technology at both local and national scales. VALS at the USGS are social constructions driven by local social needs, as the SCOT model suggests (Bijker et al., 1987). How these values could be maintained when providing a uniform VALS for larger scale users was the toughest question the VHP faced when standardising their VALS, particularly given that in Hawaii frequent levels of communication between scientists and users rendered the VALS meaningless. The implementation, implications and use of the standardised VALS are reviewed within the following empirical chapters, providing a window into the operationality of VALS and the usefulness of standardisation as a method for managing the many complexities involved.

Chapter 5. Managing complexity using a linear system

This chapter reviews the capacity of the standardised volcano alert level system (VALS) to manage the complex systems involved in volcanic crises, using qualitative data collected during the fieldwork. In the first section, the process of standardising the VALS is discussed by addressing the difficulties encountered in trying to agree upon the design (i.e. numbers and types of levels), and criteria of the VALS between the five diverse observatories and a wide range of users, each with different concepts of what a VALS is. The standardisation process is analysed using a social constructivist framework, exploring the social factors that played a significant role in this process. The second and third section addresses some of the complexities that the standardised VALS is unable to cope with in practice including the diversity of physical hazards, and organisational complexities of the USGS and users, respectively. In the final section, the capability of the standardised VALS to effectively capture and reflect complexities to provide warnings, is analysed, raising questions about the ability of a linear VALS to manage complex systems that are emergent and adaptive, often with high levels of uncertainty.

The data in this chapter are predominantly taken from interviews conducted with the USGS volcano hazards program (VHP) scientists (referred to as 'scientists') at the five different observatories in which they are based, and relates specifically to the development and use of the VALS. In addition, material from interviews conducted with local, state, and national users of the VALS (referred to as 'users') is also incorporated to provide their perspectives of how they use the VALS and apply it within their own organisations. A majority of the interviewees have worked with the USGS or been involved in volcanic hazards for many years and are able to reflect on both the locally developed and the standardised VALS that have been in place at each observatory. The experiences of each individual and their involvement with the volcanic crises outlined in chapter 4 provide the context from which they shape their views. Often there is consensus in the scientists’ opinions across the different observatories, and between the observatory scientists and users of the VALS, however, there are some conflicts in opinions that raise issues that these groups have to deal with to make the VALS work. Data are also used from the archive released under the Freedom of Information Act (FOIA), including the emails of different staff within the VHP discussing the standardisation of the VALS, which provides insights into the thinking processes and rationale behind certain decisions. There is no other known record of information relating to this process.

5.1 Standardisation of the USGS volcano alert level system

Chapter 4 provided a contextual background to the local and national factors that eventually led to the standardisation of the volcano alert level system (VALS) at the USGS. This section reviews the long and difficult discussions involved in achieving a standardised VALS. Obtaining a consensus was the most difficult aspect, partly due to the diverse range in observatories, users, and the existence of locally developed VALS. The concept of a VALS is explored to establish what VALS are supposed to do, and review whether the design fulfils these needs. The implementation of the standardised VALS provided a catalyst for further levels of standardisation in associated communication tools. Throughout the whole standardisation process, social factors strongly influenced the choices in the design of VALS, demonstrating the importance of social contexts above the role of science, making it a challenging process for volcano scientists, whose training is in a different approach of pure or applied sciences.

5.1.1 Obtaining consensus

A number of factors contributed towards the need to develop a standardised VALS. Discussions were taking place over a proposed national-scale effort by the VHP to ensure that volcanoes are monitored at a level commensurate with the threats they pose called the National Volcano Early Warning System (NVEWS). Should the NVEWS program be funded (which it was in 2009, as discussed in chapter 4), then more volcanoes would be monitored resulting in an increased use of the VALS. Email correspondence from a senior HVO staff member to VHP management and staff in April 2003 (FOIA archives), stated that the way in which information on volcanic activity is communicated is critical to their effectiveness. In addition, the report for USGS Science Strategy 2004-2008, suggested one of the five year goals of the VHP should be to 'evaluate the effectiveness of existing VHP alert-level notification schemes from unrest and eruptions in collaboration with national partners and customers and national and international aviation industry' (VHP USGS, 2003, p.34). For these reasons, and those already outlined in chapter 4, the USGS began to investigate the viability of developing a standardised VALS.

In 2003, the need to review the USGS VALS resulted in the VHP team chief scientist putting together a panel, the 'standardisation committee', charged with determining if a single alert level notification scheme could be developed to cover all possible volcanic hazard scenarios, and if no generally-applicable system could be determined, what the next options were (CVO manager). The committee consisted of a representative member from each observatory along with the project chief of the World Volcanic Activity and Aviation Hazards project. The panel was chaired by a member of staff at CVO (involved in the initial request by emergency managers to adopt National Weather Service (NWS) terminology). The requirement to comply with other federal agency alert systems and adhere to the U.S. Emergency Alert System (EAS) and Common Alert Protocol (CAP) meant that warnings must be technologically advanced using specific computer programming (AVO collaborator 2).

The single most contentious aspect of the entire process was the design of the VALS; i.e. how many VALS and levels to use, whether to use words or colours, whether the descriptions are based just on volcanic activity or forecasts, and the criteria for each alert level. This took much longer than expected, due to diverse opinions about how to meet users demands and requirements, and about what information the VALS should communicate (CVO manager / VHP user – VAAC). At the same time the aviation colour code was under discussion for adoption by the International Civil Aviation Organisation (ICAO), restricting the possible designs for a VALS.

The standardisation team initially tested a number of pre-existing (although slightly adapted) VALS within the VHP on Cascade volcano coordination groups to obtain some user feedback. VALS presented were from CVO, LVO and AVO. The results demonstrated that the coordination groups preferred the CVO VALS, but using NWS terminology (of advisory, watch and warning), and combined with the AVO code for aviation hazards. Whilst this result may have been somewhat biased given the test was conducted with Cascadian users already familiar with the CVO VALS, the final VALS design was clearly influenced by these preferences.

In May 2004, based on the test results of the Cascadian coordination groups preference for different VALS designs, a white paper written by the standardisation committee reviewed the feasibility of a single unified VALS for all U.S. volcanoes (Gardner et al., 2004a). The main debate was whether there should be a single VALS used throughout the VHP, rather than locally developed ones, to minimise confusion during future eruptions and to avoid the development of new VALS by observatories without one i.e. HVO, YVO. The white paper reviewed the feasibility of using a single unified VALS for all U.S volcanoes. The rationale for designing a single VALS rather than a dual one (with one VALS for aviation users and one for ground hazard users) is that ‘some eruptions affect only ground-based communities and others only the aviation sector, but explosive eruptions at volcanoes that are near major communities, or that are large enough that the ash falls on populated areas, will affect both’ (Gardner et al., 2004b, p.38). It was perceived by the standardisation committee that there was more to be gained by combining these two user communities with one system, than by having two separate systems. The white paper stressed that any proposed system should not disrupt currently effective communication protocols between the observatories and their users and partners. A unified alert-level notification scheme was put forward based on the VALS the Cascadian coordination group preferred (see Table 5.1). Although only one VALS is shown, it was designed so that aviation users refer to the colour terms and users involved in ground hazards refer to the NWS terms.

There are two important things to note about this proposed VALS. First, at the Watch / Orange level, two descriptions were assigned to distinguish between sustained signs of unrest for a possible eruption, and an eruption is underway but only poses a localised hazard. Creating a fifth level so that each alert level can have a distinct description was disregarded as there is no equivalent 'fifth' level in the NWS terminology. Additionally, there was a strong consensus by the USGS to avoid confusion with the five tiered U.S. Homeland Security colour-coded system, which was regarded as ineffective (HVO scientist 2), as well as the desire to keep the design simple. There were also issues about what colour to assign a fifth level as this would require a move away from the traffic light system already adopted, known and regarded as effective, particularly by the aviation sector (AVO scientist 5). Second, in line with a request from ICAO, the 7.5km (25,000ft) boundary between the Orange and Red alert levels was removed, with the provision that plume heights should be stated in all alerts. The white paper proposed that, as before, any change in alert level should be accompanied with additional activity information and potential outcomes via information statements and updates that provide the scientific rationale.

Colour	**Term**	**Description**
Green	Normal	Normal non-eruptive state; typical background activity
Yellow	Advisory	Elevated unrest above known background activity
Orange	Watch	Escalating or sustained unrest indicates eruption likely, timeframe variable. OR, eruption underway that poses a localized hazard (e.g., lava flows, lahars, or hydrothermal activity , or low-altitude ash plumes in largely uninhabited areas)
Red	Warning	Hazardous eruption is expected within hours or is underway

Table 5.1 Proposed unified alert-level notification scheme (Gardner et al., 2004a, p.2)

In October 2004, as the white paper sat on the VHP team chief scientist's desk for sign off at CVO, Mt. St. Helens began erupting. The massive media interest in the eruption generated extraordinary levels of work at CVO and so the white paper was not signed off. Consequently, CVO had no choice but to use their old VALS that their users already knew; a crisis is not the time to change warning systems as it can generate confusion (CVO manager). During this delay, changes were made to the VALS as the debate over the design of the VALS continued and became increasingly diverse following the input of different partners and users. During 2004 and 2005, discussion focused on whether the VALS should be split into two, a ground and an aviation VALS, driven strongly by some members of the standardisation committee, particularly those that work within the aviation sector (CVO manager / CVO senior scientist 2). These discussions resulted from concerns over only using one VALS; 'the sticking point was one colour really can't capture activity in the way that is relevant to both ground and aviation' (VHP manager 1). Email correspondence from AVO senior management to the VALS standardisation committee in September 2005 (FOIA archives) outlined concern that ground hazard users, and the public, would use the colour code instead of the NWS terms, which might create confusion. Therefore, the issue that led to the split of the single VALS into two separate VALS appears to have been the need to provide a separate tailored product for aviation users, given their financial investment into the VHP (particularly at AVO) and their different needs. A pilot needs to access warning information quickly due to the fast speeds in aircraft whereas for ground hazard users, a lead-time is required to inform and educate the necessary stakeholders.

5.1.2 The final design

In March 2006, after three years of long, complex, discussions, the agreed standardised VALS was implemented as a dual system. The ground hazard alert notification system reflects the level of activity / conditions at the volcano and the expected or ongoing hazardous volcanic phenomena using NWS terminology (Table 5.2). The aviation colour code (adopted by ICAO) is based on the initial colour code developed by AVO in 1990 (Table 5.3). The description associated with each alert level is based only on activity at the volcano; not on the risk, or any other hazards that may occur within close proximity of the volcano. For the first time a ‘Watch’ was also assigned a dual meaning (like Orange) for both heightened precursory unrest and minor eruptive activity, as both require close monitoring but do not necessarily have immediate major hazardous effects. Criteria for de-escalating activity were also added into the description. The odd thing is that the NWS terms that usually describe meteorological hazards are not used to describe the ash hazards influenced by meteorological systems, but the ground hazards (AVO collaborator 3).

NORMAL	Volcano is in typical background, non-eruptive state or, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to non-eruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, OR eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Table 5.2 Volcano Alert Levels (Gardner and Guffanti, 2006, p.2)

GREEN	Volcano is in typical background, non-eruptive state or, after a change from a higher level, volcanic activity has ceased and volcano has returned to non-eruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, after a change from a higher level, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain OR eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely OR eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Table 5.3 Aviation Colour Codes (Gardner and Guffanti, 2006, p.3)

For most eruptive activity, the ‘alert-level term’ and ‘code colour’ change together (e.g. Yellow and Advisory). However, because some volcanic eruptions generate hazards that affect ground and aviation communities differently, the VHP decided that in these cases the alert level and colour code can move independently:

> For example, an eruption of a lava flow that threatens a community but produces no significant ash might warrant a volcano alert level of Warning but an aviation colour code of Orange. On the other hand, an eruption that produces a huge cloud of volcanic ash that does not drift over inhabited areas might warrant a volcano alert level of Watch and an aviation colour code of Red (Gardner and Guffanti, 2006, p.4).

The USGS argued that decoupling the top two levels of both VALS created the flexibility needed to accommodate end members in the spectrum of volcanic activity; lava flows and large ash clouds. Whilst this created flexibility in the use of the VALS, there was concern that this might lead to inconsistencies between the volcano observatories that could create confusion for the users and the public.

The final decision to split the VALS was not unanimous. Staff at AVO were not keen since they used the colour codes for ground hazards, as they rarely deal with volcanic activity that affects large populations, other than from ash. In contrast, HVO favoured the split as it gave them the flexibility to be at Warning / Orange should Kilauea or Mauna Loa have lava flows that affect large populations but have minimal ash emissions (HVO senior scientist 4). Splitting the VALS into two was seen to provide more flexibility to accommodate not only different volcanic hazards, but eruptive styles, and ground and aviation based user communities.

AVO was the first observatory to adopt the new mandated VALS since they already operated the aviation code. On 1st October 2006, CVO adopted the new VALS as Mt. St. Helens became stable enough to change VALS without confusing users; it was assigned Watch / Orange. No formal notices about the change in VALS were issued, and there was minimal coverage by the media (CVO user – media), which is perhaps a reflection of the public's lack of interest in VALS. Later in 2006, HVO, LVO and YVO adopted the VALS, although LVO were less keen to adopt a new VALS having just redesigned their VALS in 2002 (LVO senior scientist 1). Each observatory had responsibility for educating their relevant users and populations of the standardised VALS.

In order to educate users and the public, a USGS Fact Sheet was produced (Gardner and Guffanti, 2006) that outlined the new VALS, the underlying rationale for standardisation and how they operate. The four key requirements for the VALS were summarise as being able to: '1) accommodate various sizes, styles, and duration of volcanic activity; 2) work equally well during escalating and de-escalating activity; 3) be equally useful to both those on the ground and those aviation; and 4) retain and improve effective existing alert notification protocols' (Gardner and Guffanti, 2006, p.1). Section 5.2 addresses the ability of the VALS to accommodate different volcanic activity and hazards, but it is important to note that these four requirements focus largely on the volcanoes' activity and do not address issues of risk.

5.1.3 Definition and concept

Although the USGS are mandated to provide warnings, whether these warnings should take into account local social, political and economic considerations is contested between the scientists. VALS are difficult to define because terms such as risk, hazard, activity, warning, alert and concern are often used interchangeably by scientists and users. This, in part, is the result of unclear definitions of these terms within the disaster management community, but also because of the close nature of these terms and the difficulty in separating science, uncertainty and risk (see chapter 2).

Defining what a VALS does is critical to establishing whether or not it is serving its purpose, and to determine if stakeholders (scientists, users and other actors) share a common understanding. The general consensus from all interviewees indicated that the purpose of a VALS is to alert the users, communities, individuals, and operators as to what the state of the volcano is in a short, concise, brief manner to which they can gear their responses (AVO senior scientist 1 / HVO scientist 1). Therefore, VALS are regarded as a tool to communicate quickly, excluding technical details, about the nature of unrest and possible hazards, so that in one word, such as ‘Red’, a large and diverse range of people know what the conditions are (HVO scientist 2). There is a common understanding between stakeholders that an alert level alone cannot provide all the information required for users to make decisions. They are seen as a flag or semaphore to raise awareness by providing a ‘heads up, pay attention, something has changed, you need to look at reports, updates for information statements, or listen to advice from federal agencies’ (CVO Senior Scientist 2). This implies that VALS are only able to communicate what volcanic activity is occurring. A scientist in the standardisation committee outlines the purpose of VALS in three key parts; as a ranking system, that is volcano-centric and used to communicate with non-volcanologists.

> It is a ranking system, so you have a way to describe change, either in terms of increasing intensity or decreasing intensity. It is primarily to describe conditions at or near the vent of a volcano, it is not to generalise about hazard levels everywhere because they vary depending on where you are in relation to the volcano. It has to be about the volcano, volcano-centric. It’s a ranking system, and it is a way to speak to non-volcanologists (VHP manager 1).

Generating a specific definition for a VALS proved far more challenging than establishing its purpose. As with designing a VALS, defining them begins to reveal the complexities involved in how they function in theory and in practice. Section 5.3.2 explores some of the emerging issues from users relating to defining and designing VALS, that demonstrate why the process of standardisation was such a difficult and time consuming process.

The USGS Factsheet on the standardisation of VALS states that: 'by themselves alert-level terms and code colours do not convey enough information for those in affected communities and aviation to make decisions regarding specific courses of actions' (Gardner and Guffanti, 2006, p.4) therefore, there is a clear need to provide supplementary information. One of the longest debates during the standardisation process was establishing the exact wording of the criteria or description for each alert level (CVO senior scientist 2). However, the description appears to be less meaningful in practice given that supplementary information is provided. This is further evidenced by additional levels of standardisation in warning messages that accompany the alert level, and in producing visual representation of the alert levels, which is reviewed below.

5.1.4 Further levels of standardisation

Once the new standardised VALS was implemented, a number of knock-on changes were made to retain and improve effective existing alert notification protocols. Since VALS cannot operate in isolation, it was a logical progression that the messages that accompany an alert level would also be standardised. Most of the volcano observatories already issued a number of information statements reviewing: significant changes in activity; status reports (current, daily, weekly, other); and summary reports that recap ongoing events, forecast scenarios, special hazard statements, and announcement in changes in procedures, formats, protocols, or capabilities (see chapter 7 for further details).

Led by AVO, which had the most resources available to review and launch computer and web-based products, the VHP developed more consistent messages by consolidating previous formats into three categories: *event driven* (urgent) messages designed specifically to fulfil users' requirements using a Volcano Observatory Notice for Aviation (VONA) for the aviation users and a Volcano Alert Notification (VAN) for ground hazard focused users; *time driven* (scheduled) status messages; and general *information statements* (USGS VHP, 2007, Guffanti et al., 2007). Additional information is provided within the VANs and VONAs to comply with the Common Alerting Protocol (CAP) guidelines. These messages are available via a Volcano Notification Service (VNS), modelled on the USGS Earthquake Notification System. By providing a more systematic database with specific input fields, it was possible for the USGS to improve messages and make them quicker to disseminate. In contrast, HVO wanted to maintain their individual prose styles in information statements (HVO senior scientist 5).

In 2007, as part of the roll out of the National Volcano Early Warning System (NVEWS), a technical information product sub-group identified demand for a number of map-based hazard information products (Guffanti et al., 2007). Senior levels of federal agency management and government requested a webpage to show the current alert level status of each volcano in the U.S., using a map, with clear links to current monitoring data and further information (particularly for high threat volcanoes). In response, the VHP redesigned their website, and designed an interactive map showing the volcanoes and their current alert levels (Fig. 5.1).

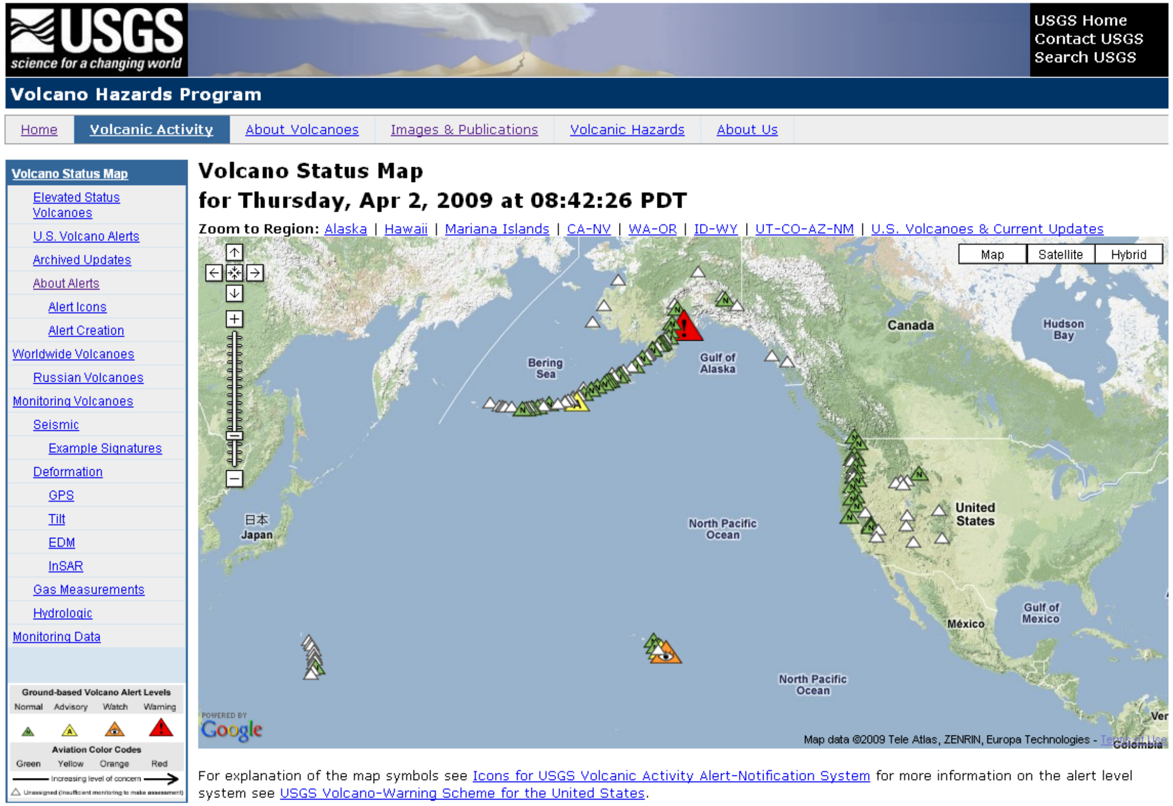

Figure 5.1 Volcano status map (VHP Website, 2009b)

This raised the issue of how to represent the alert levels on a map. A number of icons were developed to represent each level: 'N' was used for Normal and 'A' for Advisory, but Watch and Warning were assigned a watchful eye and an exclamation mark respectively to distinguish between the two 'W's' (Fig. 5.2). These icons were developed by staff at the Menlo Park, following only limited discussion with the standardisation committee, and are becoming established as shorthand for the alert levels. It is interesting that the development of the alert level icons involved much less consultation than for the initial VALS (YVO scientist).

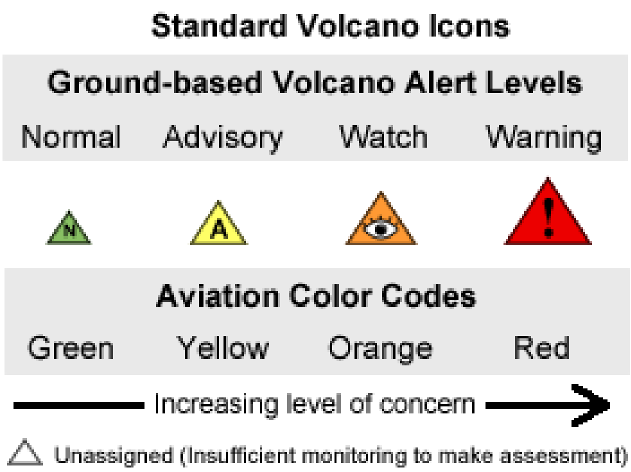

Figure 5.2 Icons for USGS Volcanic Activity Alert-Notification System (VHP Website, 2009a)

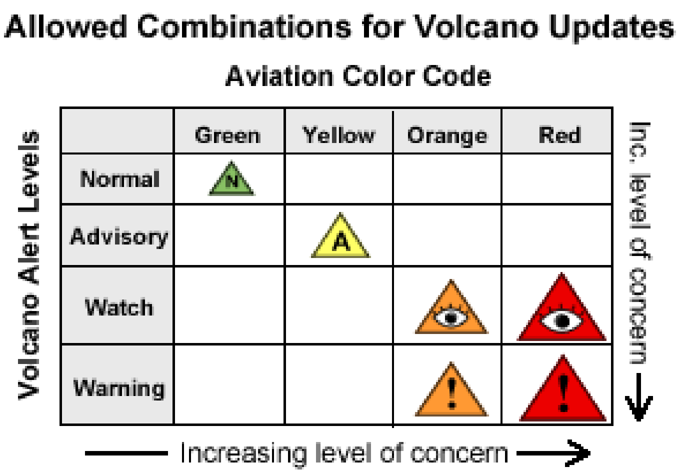

Figure 5.3 Allowed combinations for volcano updates using te standard volcano icons (VHP Website, 2009a)

A key question that emerges is whether or not the design of the standardised VALS is adequate to fulfil the concept and purpose of a VALS. The standardised design is based on prior designs of VALS used at AVO, CVO and LVO, and, therefore, there are no radical changes in the design for these observatories. It follows a linear progression reflecting increasing levels of volcanic activity in four different alert levels. Given that the perceived consensual purpose of a VALS is to obtain the attention of users or stakeholders so they can quickly gauge what is happening at the volcano, VALS may be successful at getting attention, but without additional information they appear less useful (explored further in chapter 7).

5.1.5 The social construction of VALS

On reflection, the decisions made about the final design of the standardised VALS were significantly different from what was agreed following the 2004 white paper. Only a small number of staff were involved in these final decisions, partly because of pressure from USGS directors to have something in place following slow progress. Throughout the whole discussion process it was clear that the final design was constrained by a number of set requirements such as the use of the AVO VALS. A quote from one of the key scientists involved in the process at CVO summarises the strong influences on the design:

> We didn't have a completely blank slate to work with, we couldn't hatch our own system from scratch. We were working in the context, and the context was that there is this colour code that the aviation industry had adopted and there was this National Weather Service code that not only a lot of ground-based managers adopted, but apparently also wanted us to use, and so given those two things I don't really see that we have a choice (CVO scientist 3).

This quote indicates that the VALS design was not driven by what would be seen as the 'best' design in terms of providing a volcanic warning, based on scientific knowledge and the capabilities and resources involved. In contrast, the process was dominated by the demands of the users of the VALS, and their relationship with the volcano observatories (e.g. Cascade emergency managers) and the USGS as an institution (e.g. aviation sector). The pressure to accommodate aviation demands due to the financial benefits that the aviation sector provided to the VHP was of key importance at a time, post-9/11, when all Federal Agencies were feeling the Bush Administration's squeeze on funding resources (CVO manager / LVO senior scientist 1). The pressure for the VHP to adopt common and widespread terminology along with the increasing use of NWS terms (at the time also adopted for tsunami warnings) was logical. However, volcanic hazards are very different from meteorological ones, and the NWS bases its warnings on probabilities. As the general levels of volcanic activity is insufficient to allow development of such probabilistic models (as discussed in chapter 2), the NWS terms in the VALS are used in a different way from that of meteorological hazards (discussed in section 5.3.2).

The pressures to accommodate users' institutional needs and demands demonstrate that VALS are a socially constructed system, designed around the social and political requirements at the time of discussion. The VALS standardisation process is constructed by the choices made in the design and the way it evolved, that were predominantly based on social factors (Bijker et al., 1987). First, the rationale for rejection of numerous designs of the VALS was based on social reasons, not on the physical characteristics of volcanic activity and hazards; second, the design was based on what was seen as 'best' for the users (CVO scientist 11); third it was seen as 'best' for the USGS to accommodate their users rather than develop their own system (CVO senior scientist 2); finally, whilst there were competing designs for the VALS all with the potential to provide slightly different solutions to the problem, it was the social factors that determined the selected design. The process of developing a technological artefact (in this case the VALS) reflects a multidirectional rather than traditional linear model, where the 'successful' stages in the development are not the only possible ones. The standardised VALS is an example of a socially constructed system that was not a linear process, but multidirectional, with competing models and differing user requirements.

Since aviation and ground hazard users have very different contexts in which they use VALS (shaped by their institutional and organisational requirements), it seemed logical to separate the two elements, maintaining 'interpretative flexibility' (Bijker et al., 1987, p.27;47). By establishing two VALS rather than one it was possible to accommodate the key different groups involved with their different requirements, by using different designs and enabling decoupling of the highest two alert levels. At this point, the closure in the debate over the VALS design occurred rhetorically; when the scientists and two key user groups saw the problem as being solved. Closure on a design is not permanent, as seen from the change in the VALS from the white paper in 2004 to that established in 2006, as changes in the user groups, policy, or confusion / lack of understanding or flexibility could drive the VALS design to change (as seen historically at LVO). In the future, it may be that advanced technologies or warning systems could cause conflict as further standardisation occurs within the U.S. or on a global scale. One of the key tests to show the success in the design of the standardised VALS will be the next large volcanic crisis in the U.S. The rest of this chapter discusses the implementation and experiences of using the standardised VALS so far and addresses some of the emerging complexities.

5.2 The inherent complexity of volcanic hazards

The design of the standardised VALS is based on a linear model, where increasing volcanic activity leads to a rise in volcano alert level, and a respective drop in alert level for decreasing volcanic activity. Application of the standardised system at the observatories between 2006 and 2008 (when this research was conducted), has already encountered a number of limitations that affect its ability to provide an effective warning. This section reviews one of the key complex issues that emerge from the data that the standardised VALS are unable to reflect: the complexity of volcanic behaviour and hazards. This section first explores the implementation of the VALS at the observatories; second, how time and space affects how VALS operate; third, the development of hazard specific warning systems; and finally, the implications of using the volcano-centric standardised VALS are discussed. Issues relating to organisational complexities such as USGS and VHP institutional issues, and those of users are addressed in section 5.3. All these issues contributed to the difficulty in establishing the standardised design and in defining a VALS. In practice, the elements VALS attempt to manage and communicate are much more complex.

5.2.1 Using the standardised VALS to convey hazards

Initially the standardised VALS was intended to be sufficiently flexible to permit interpretation by each observatory:

> I don't think an effort was made to standardise from observatory to observatory the criteria for colours, it was very much left to the local observatory and that in part was done to satisfy each observatory's concern about the legacy of communications with their local populations and so folks want to retain whatever flavour or practice they had in place (AVO senior scientist 2).

The final design was intentionally designed to enable the flexibility required by the observatories to cater for local hazards and volcanoes by de-coupling. Yet, the new VALS raised a number of problems, predominantly at HVO, which had no prior experience of using a VALS. HVO had to assign active volcanoes an alert level and discuss them at science meetings, which they had never done before. One HVO scientist said 'all of a sudden we are debating about what colour Mauna Loa should be rather than focusing on *the science and what it means*' (HVO scientist 2) (author's emphasis). These initial debates to assign alert levels took up a lot of time: for example when assigning Mauna Loa an alert level conflict arose because, although it had shown signs of unrest in recent years, staff who had worked at other observatories felt it did not warrant a Yellow / Advisory alert level since it gave little scope to issue a higher alert level should further abnormal activity occur. There was clear conflict between those scientists at HVO who had worked with VALS before and understood the strategic aspects of how VALS work, and those that had no experience with them and used the description of the VALS as a strict criterion, indicating that how they work in practice, is not the same as how they operate on paper (HVO scientist 2). Another major problem at HVO was assigning Kilauea an alert level. Given the large scale of the volcano, with several eruptions occurring in different locations (both on the summit and east rift) they discussed developing VALS for different parts of the volcano, although this was never developed (HVO scientist 2). There was also confusion about using the ground and aviation VALS because Kilauea does not emit much ash, certainly not enough to affect anything other than local tourist aircraft that fly around the volcano. However, because Kilauea is erupting continually, it has to be at alert level Orange / Watch, even though ash levels were negligible (prior to the Halema'uma'u Crater in 2008). It was not possible to assign Yellow / Watch because the standardised VALS only enable decoupling on the top two alert levels (HVO senior scientist 6). Since in Hawaii, emergency agencies are generally not concerned about Kilauea's activity unless there is some new or anomalous behaviour, or lava flows are heading towards populated areas or tourist sites, the alert level loses its meaning as it never changes and is unable to relay the urgency of new information locally (HVO scientist 2). For all these reasons many scientists and the local users at HVO felt VALS were useful for strato-volcano[12] types, but less so for large calderas like Kilauea (HVO scientist 2).

At AVO there have been a number of volcanic crises that posed a risk to aviation, yet very little risk to local ground populations, as the area is uninhabited. Despite much debate at AVO, however, the VALS have never been decoupled to reflect this difference in risk because some scientists argue there is always the risk that someone may be close to the volcano, fishing, or camping for example (AVO senior scientist 2 / AVO senior scientist 5). The new standardised VALS is forcing AVO to think more about ground hazards than before, and the decision not to decouple the VALS means that AVO do not wish to take advantage of the flexibility that has

[12] A strato-volcano, is a tall conical volcano built by strata from previous eruptive activity. These volcanoes typically display periodic explosive activity, and there are a number of them in the Cascades region in the U.S.

been offered to them, as it could create problems should people be killed because they did not issue the appropriate alert level. This demonstrates that scientists at AVO are keen to follow a precautionary approach for accountability reasons. In contrast to HVO and AVO, CVO and LVO have not had many concerns with the new standardised VALS, other than adjusting to the new terms, because it is similar to what was in place before (LVO user - Mammoth Lakes town).

The problems faced by each observatory may be seen as 'teething pains' but they highlight the difficulties of using a standardised VALS rather than a locally developed one that can accommodate local contingencies. Whilst the VALS has been designed to decouple the top two alert levels to provide more flexibility, it is not being made use of at AVO, and at HVO there is a demand to make the VALS decouple even further since eruptive activity at Kilauea is regarded as normal activity. All these inconsistencies indicate that to make a standardised VALS work at each observatory is very difficult, and is not working as well as hoped.

5.2.2 The spatial and temporal complexity of volcanic hazards

The standardised VALS has two systems, both relating to eruptive activity at the volcano, but focusing specifically on ash and eruptive hazards (i.e. lava and pyroclatic flows). However, there are numerous hazards that can occur within close proximity of a volcano, whether it is active or not, and these occur in different locations (geographically) and at different times. Many of these hazards are excluded from the standardised VALS, which relates only to the occurrence of eruptive activity at the volcano. Many scientists felt that VALS should convey information about all volcanic hazards, whether they are proximal to the volcano i.e. volcano-centric, or distal. They recognise that in practice this is very difficult to implement within the confines of a simple VALS. Some scientists were unsure whether VALS should represent volcanic hazards that can occur when the volcano is inactive such as landslides or lahars. However, the main rationale for limiting the VALS to being volcano-centric is that conveying spatial and temporal aspects of a hazard with one alert level is difficult and can change over time. A good example is provided by the 1999 eruption of Pichincha in Ecuador, on which the USGS Volcano Disaster Assistance Program (VDAP) team worked. The volcano sent a plume of ash to over 7.5km (25,000ft) and affected three communities: the aviation community who were concerned with the ash plume of moderate concern (an Orange alert); the towns of Nano and Yaya, 10-20km from the summit that were evacuated due to high concern from pyroclastic flows (a Red alert); and Quito City upwind of the activity that would receive a light dusting of ash of low concern (a Yellow alert). With three different levels of concern, but only one alert level to issue, how is an alert level decided? Despite the claim that VALS are about the user's needs, in practice this does not seem to be the case; the risks vary spatially. One VHP manager stated that to make a VALS work, it has to be volcano-centric:

> If you make [VALS] a level of concern, hazard concern strictly, then which group are you talking about? That's why you have to make it primarily […] about what's happening at the volcano (VHP manager 1).

Timing is critical when issuing an alert level; equally, an alert level implies the time frame in which a hazard may be expected. Some scientists said information should be provided as soon as possible, by changing the alert level to reflect new information; others said the timing needs to be strategic, either to provide further scientific certainty or accommodate the needs of the local community or users. Each observatory requires resources to provide a timely alert level. Email correspondence from senior AVO staff to the standardisation committee in July 2005 (FOIA archives) stated that 'a major determinant of the colour-coded changes for short-lived events is how fast you can make the decision and disseminate information'. To help make warnings faster the process is streamlined with fill-in-the blanks information releases ready to go (i.e. VAN and VONA messages). The VALS used previously at LVO had an assigned timeframe for each alert level to prevent 'yo-yoing' (VHP manager 6) between alert levels as volcanic activity changed, yet this was not adopted in the standardised VALS, presumably to facilitate greater flexibility. Email correspondence between a CVO staff member and the standardisation committee in March 2003 (FOIA archives) highlighted that 'ultimately the time frames most important are the ones that encompass times required for critical mitigatory action, such as how long it takes to evacuate the area'. These local contingencies are discussed further in chapter 7, and raise questions about who is the expert in deciding when to change alert level, and how do scientists and users cope with issues relating to incertitude?

5.2.3 Warning systems for specific volcanic hazards

As reviewed in chapter 1, the different characteristics of each hazard can affect populations at varying distances from the volcano and, often it is not possible to monitor the likelihood or potential for a hazard event until it happens. Some scientists expressed the view that a warning can only be truly issued after the event has begun (CVO collaborator 2), therefore the only way to measure if a lahar has developed, or where an ash cloud is moving, is to monitor them individually. Therefore a number of the observatories have developed independent alert level systems for different hazards that require specifically tailored warning systems given the nature of the hazard. The adapted warning systems are presented below.

Volcanic gases resulting from volcanic unrest or activity can kill, but for many they are an unpleasant smell and can cause respiratory problems. Following a small explosion in March 2008 at Halema'uma'u Crater (Kilauea summit), a vent was created that continues (to date of writing) to emit a plume of highly concentrated sulphur dioxide (SO_2) volcanic gas, and some ash, which can cause vog; a term used to describe a haze caused by gases being emitted into the air and mixing with water vapour and sulphur particles. The focus of HVO activities shifted from destructive lava flows to local ash aviation hazards and concern over public health safety from the high concentration of sulphur dioxide in the plume. In response, HVO, with Kilauea National Park, established a sulphur dioxide alert level system to reflect the level of sulphur dioxide within the park for the safety of employees (and visitors), based on Occupational Safety and Health Administration (OSHA) safety standards (Hawaii Volcanoes National Park, 2008), (HVO scientist 1). However, the sulphur dioxide also affects local populations outside the National Park, including the island capital Hilo and even Honolulu on Oahu Island during strong trade winds. The populations around the volcano placed pressure on the Hawaiian civil defense to develop an alert level for the gas since it poses a health risk (Hawaii State Dept. of Health and County Civil Defense, 2008), (HVO user – emergency manager 1). In response, they developed an alert level based on the U.S. Federal Agency of Health alert system. Consequently, there are now two different codes for sulphur dioxide levels, which are shown below in Table 5.4 and 5.5. Both alert systems use a colour code to represent the levels of concern (HVO considered colours as less confusing than numbers or using words), but unfortunately using two different models generated confusion for the public (HVO user – emergency manager 1). At the time of research, HVO focused more on the sulphur dioxide alert system, than the VALS, as the issue of sulphur dioxide affected the local population's quality of life more than that of lava flows. This clearly indicates the inability to adapt the VALS for important and ongoing hazards, to the extent that HVO developed their own system.

Condition	Recommended Response
GREEN *Trace*	*Sensitive Groups*: Highly sensitive individuals may be affected at these levels *Everyone else:* Potential health effects not expected.
YELLOW *Light*	*Sensitive Groups:* Avoid outdoor activity *Everyone else:* Potential health effects not expected, however actions to reduce exposure to vog may be useful
ORANGE *Moderate*	*Sensitive Groups:* Avoid outdoor activity and remain indoors *Everyone else:* Potential health effects not expected, however actions to reduce exposure to vog may be useful
RED *High*	*Sensitive Groups:* Avoid outdoor activity and remain indoors *People experiencing respiratory-related health effects*: Consider leaving the area *Everyone else*: Avoid outdoor activity
PURPLE *Extreme*	*Sensitive Groups* as well as everyone else*:* Avoid outdoor activity and remain indoors *People experiencing respiratory-related health effects:* Leave the area and seek medical help *Everyone*: Leave the area if directed by Civil Defense

Table 5.4 Sulphur dioxide information. Sensitive groups include children, and individuals with pre-existing respiratory conditions such as asthma, bronchitis, emphysema, lung or heart disease (Hawaii State Dept. of Health and County Civil Defense, 2008)

Condition	**Response**	**Gas Levels**
GREEN (Good)	Business as usual	<300 ppb
YELLOW (moderate)	Basic protective actions Dispatcher alerts staff Inform visitors of hazard	>300 ppb 2x15-min averages
ORANGE (unhealthy-for sensitive groups)	Moderate protective actions Relocate/cancel nature walks and other outdoor work	>500 ppb 15-minute average
RED (unhealthy)	Extended protective actions Consider closing entrance station and Visitor Centres	>1000 ppb 15-minute average

Table 5.5 Sulphur dioxide advisory levels (gas levels are determined by the Air Quality Index by the U.S. Environmental Protection Agency) (Hawaii Volcanoes National Park, 2008). Within the last year, two further levels have been added: Very Unhealthy ≥ 3 ppm 15-minute average (colour purple), and Hazardous ≥ 5 ppm (colour burgundy)

At LVO, volcanic gases are also an important focus, being one of the few volcanic hazards that has killed people in the caldera. In 2006, three ski patrol staff died of carbon dioxide (CO_2) poisoning when they fell into a fumerole that had melted through the snow (LVO user – Mammoth Lakes town 2 / LVO user – emergency manager 1). The popular Horseshoe Lake on the south side of Mammoth Mountain is monitored for carbon dioxide following 170 acres of tree kill in the area in 1990 (Sorey et al., 1996), (LVO senior scientist 1). There is a clear demand by locally affected populations to provide warnings about dangerous levels of gases. At both HVO and LVO the predominant hazard encountered on a daily basis is gas, yet this hazard is not reflected in the VALS as it does not necessarily relate to eruptive behaviour.

Lahars pose a serious threat since they can travel at velocities up to 80 kph down valleys towards populated areas, usually facilitating a warning of less than an hour in which to evacuate vulnerable populations (Scott et al., 2001). As a result, rapid warning systems have been specifically designed for lahars (Lockhart and Murray, 2004). At CVO, this is a significant concern since large lahars have occurred on many of the Cascade volcanoes, travelling significant distances, some greater than 50km over what is now highly populated or industrialised land. One example is the Electron Mudflow, a lahar derived from slope failure on the west flank of Mount Rainier about 600 years ago (Crandell, 1971), that has not been correlated with an eruption of the volcano, which suggests that lahars may occur even without volcanic activity from loose debris on the volcano. This mudflow was more than 30 meters deep where it entered the Puget Sound, not far from the City of Seattle. Should this event happen again it would be devastating for the populations in the volcano's valleys, and impact the large industrial areas in the Puget Sound affecting critical infrastructure along the West Coast of the U.S. Therefore, there was a need to bring together scientific expertise, with an understanding of the vulnerable populations, infrastructure and businesses to develop effective warnings, and encourage a precautionary approach towards a lahar.

VALS cannot usefully be applied to lahar hazards for three reasons: first, they are difficult to forecast; second, they can occur in the absence of eruption; and third, a volcano could be at Advisory / Yellow alert level yet a lahar could be generated. Acoustic Flow Monitors (AFMs) have been developed to detect lahars using seismic signatures for large flows that trigger a warning (Dorava and Meyer, 1994). They are designed with a 'dead man' which is a log in the river, released in the flow and then detected further downstream to make sure that the warning is not false i.e. just triggered by an animal or flooding. The responsibility for issuing these warnings lies with NWS since they have the communication infrastructure and staff 24 hours a day to facilitate the quick response needed, which the USGS cannot support (CVO scientist 9).

AFMs are installed at a number of volcanoes around the world and provide a vital warning system for debris hazards that, historically, have caused over 50 percent of all fatalities in volcanic eruptions since 1902 (EM-DAT, 2008). In addition, to understand the possible routes lahars may take down a volcano, various models have been developed to simulate the typography and possible flow routes and speeds. The USGS model, Lahar-Z, has been used all around the globe to establish where to place AFM's and where vulnerable populations are located (Schilling, 1998).

Significant ash eruptions can produce plumes stretching vast distances, and with strong winds ash clouds can travel independently of the plume, yet remain an aviation hazard. Whilst ash clouds are partly the responsibility of the NWS and the VAACs, the University of Alaska Fairbanks developed the 'PUFF' model, a volcanic ash tracking model that shows the distribution of ash given current meteorological conditions or forecasts, aiding flight planners for flight routes (Mastin et al., 2009, Webley and Mastin, 2009, Webley et al., 2009). The PUFF model is used by the Alaskan NWS and VAAC, and the U.S. Air Force Weather Agency (AFWA). Therefore, in the case of ash, numerous agencies work together to provide a warning, bringing together different warning systems and models, and differing levels of expertise and technology.

Ash can also affect ground populations, significant distances from the volcano, as seen from the eruption of Mt. St. Helens where Yakima city, 90km from the volcano, received 100-130mm of ash (Tilling et al., 1990). AVO and the Anchorage NWS have worked together to draft and propose a matrix of ash-fall severities to be used in standard warning messages (see Table 5.6). This matrix links accumulations of ash with impact thresholds (such as roof collapse, or roads impossible to drive on). Using NWS products (i.e. ash fall statements, advisories, and warnings) this information is issued providing guidance, with each of the five levels of ash warning, encouraging people to take some action such as remain indoors or protect electronics.

Term	Accumulation (mm)	Impact thresholds	NWS products	Key call to action elements
Trace or dusting	<0.8mm	Minor irritant, very low impacts for most	Special Weather Statements (SPS), Public Information Statements (PNS), Marine Weather Statements (MWS)	Avoid excessive exposure to ash which is an eye and respiratory irritant. Those with respiratory sensitivities should take extra precautions
Light	0.8-6.4mm	Possible crop / animal, equipment / infrastructure problems; widespread clean up likely	Ash fall advisory (NPW, ZFP, CWF), Marine Weather Statements (MWS)	Protect electronics and air intakes. Minimise driving and listen to your local radio stations for further info
Moderate	6.4mm - 25.4mm	Ash removal efforts significant	Ash fall advisory (NPW, ZFP, CWF), Marine Weather Statements (MWS)	Seal windows and doors. Avoid driving and listen to your local radio stations for further info
Heavy	25.4 mm-100mm	Weaker roofs begin collapse at ~100mm	Ash fall advisory (NPW, ZFP, CWF), Special Marine Warning (SWS)	Remain indoors unless absolutely necessary and listen to your local radio stations for further info
Very heavy	100-300mm	Roof collapse, damage to trees, services interrupted	Ash fall advisory (NPW, ZFP, CWF), Special Marine Warning (SWS)	Remain indoors unless absolutely necessary and listen to your local radio stations for further info
Severe	>300mm	Roads impassable, severe infrastructure damage, heavy biotic loss	Ash fall advisory (NPW, ZFP, CWF), Special Marine Warning (SWS)	Remain indoors unless absolutely necessary and listen to your local radio stations for further info

Table 5.6 A draft proposed matrix of ashfall severities to be used in standard warning messages (Neal et al., 2006). N.B. Some of the size categories are not mutually exclusive.

Volcanic hydrothermal activity is regularly encountered at the calderas of Long Valley and Yellowstone. Both observatories monitor activity from geysers and nearby rivers and evaluate the chemical composition of the waters as an indication of potential volcanic unrest or activity. At LVO there has been recent attention at a new small geyser in Hot Creek River near Mammoth Lakes town, which caused some deaths and some severe burns among careless, often drunk swimmers in the river (LVO user - USFS). The area is now closed off and is monitored closely by the U.S. Forest Service staff. Once more, the VALS does not cover hydrothermal hazards, which are particularly abundant in large calderas, and can pose safety concerns, particularly at a significant tourist location such as Yellowstone National Park.

On a larger scale, many volcanoes in Alaska are islands or are near coastlines, so that when either pyroclastic or debris flows occur, the material produced can displace water creating significant tsunamis. Tsunamis are detected by a tsunami warning system (TWS) operated by the NWS who issue an advisory, watch or warning (NOAA NWS, 2010). It is the responsibility of the NWS to issue tsunami alerts, although they collaborate with the USGS prior to any volcano-related tsunami alert issuance to clarify details. Secondary volcanic hazards are often issued by other agencies who have developed a number of specific warning systems to cope with the spatial and temporal factors involved. This indicates the difficulty for a single VALS to encompass the wide range of hazards that occur, given that other federal agencies also have mandates to warn of these hazards. Volcanic hazards are complex because they are diverse, have secondary effects, and cut across the boundaries in institutions that are responsible for their monitoring.

5.2.4 The implications of a volcano-centric alert level system

From the above information, it is clear that the standardised VALS only represents eruptive volcanic activity, mainly lava flows or pyroclastic flows or ash, near the volcano. In addition, many volcanic hazards have their own alert / warning system or modelling tools to provide warnings or forecasts. This raises the question of how useful is a VALS when it only represents a proportion of the possible hazards? A scientist at CVO stated that in the future it is likely that VALS will need to review the many flow hazards that volcanoes generate:

> We are heading to an alert level system that deals with eruption behaviour involving the intrusion of hot rock, to viewing volcanoes as the sites of origin of catastrophic flows that can occur anytime and escalated risks that won't be fully incorporated into our system of escalating alert levels (CVO scientist 4).

The scientists still see a role for a standardised VALS, despite the legal responsibility other agencies have to issue warnings for some volcanic-related hazards, because a volcano's activity remains the primary focus for the other alert or warning systems, given that a majority of hazards correlate to volcanic activity. Restless caldera activity is the most common exception to the rule, where every day smaller non-eruptive hazards can still significantly affect the quality of life for local populations.

The ability to determine criteria for each alert level is complex, as demonstrated from the aforementioned example from HVO to assign alert levels to Kilauea and Mauna Loa. Each volcano has its own behaviour patterns or 'character' as the scientists described it (AVO scientist 9), making it difficult to use standard monitoring parameters to judge the volcano’s level of activity. Background activity for one volcano, such as Veniaminof (Alaskan peninsula), includes significant seismic tremors, which if seen at neighbouring volcanoes would be highly concerning (AVO scientist 6). Therefore, it is important that the scientists get to know the volcano and its 'normal' behaviour to determine any abnormal activity that may lead to a discussion about changing an alert level; this could be regarded as tacit knowledge. Local scientific knowledge is important and there needs to be some flexibility when assigning appropriate alert levels. For the scientists at AVO, establishing background activity levels can often be challenging as not all the volcanoes have adequate monitoring equipment, or capabilities given their remote locations. Severe weather frequently damages equipment, and cloud coverage can prevent satellite images confirming a volcano is erupting, which can leave AVO scientists with little data on which to base their assessments of what is happening at the volcano. Equally, volcanoes can behave in ways not observed before, such as the lateral blast seen at Mt. St. Helens in 1980. These ‘black swan’ events (see chapter 2) occasionally surprise the actors in a VALS.

The unique individual behaviour of a volcano, each with a diverse range of hazards makes monitoring, understanding the activity, and issuing a warning for a volcano alert a highly complex process. A key problem highlighted by a scientist at YVO is that ‘there needs to be flexibility because nature is continuous, and when we make discreet 'bins' to put natural activity into, we sometimes don’t do a good job’ (YVO collaborator). Categorising nature into these 'bins', effectively one of the four alert levels, creates a dilemma since ‘more bins make it more complicated, and fewer bins give you more times when activity doesn’t really meet the criteria that you have established’ (AVO scientist 3). A vast majority of the scientists identified with this problem but defended the use of the standardised VALS as the best possible solution for the problem of volcanic warnings, given available time and resources; it is ‘an implicit probabilistic risk assessment […] that is encapsulated in the colour code’ (AVO scientist 4). Developing 'bins' or alert levels may be the consequence of historical VALS that became naturalised into the daily operations of the observatories. The idea of developing a radical new design of VALS, that may be more flexible to accommodate the diversity of physical hazards seen at volcanoes throughout the U.S., was never pursued. Two of the scientists interviewed proposed designs for a more flexible VALS, but were informed by the standardisation committee that they may be too confusing for users (AVO scientist 4).

There is a constant drive by policy makers to organise things, such as nature which is a continuum, into boxes, or 'bins'. Yet, the individual characteristics of each volcano's behaviour question the ability and usefulness of a VALS to convey these variables. Interviews with scientists repeatedly indicated it was the number of physical hazard complexities involved in the design process of the standardised VALS that resulted in the process taking so long (CVO manager). Some scientists, as this one at AVO outlines, reflected on standardisation criticising that a 'one size fits all’ is not necessarily the best approach to adopt within VALS:

> I have been a sceptic about this standardisation all along, mainly because I look out across the globe and see so many different situations and scenarios, that I think it could be difficult, that it might not be informationaly sound and correct to try and cookie cutter something that applies in every situation [to] every volcano everywhere. Now many of my colleagues completely disagree with me on this […]. I always feel like modern society needs to box everything into organised cubicles and have something that applies to everything. I'm just not sure that this really lends itself [to that process] (AVO senior scientist 1).

Despite some concerns about the standardised VALS, a majority of staff felt that it is useful, regardless of its design or operation because without them it is not possible to disseminate information easily. This following quote from a CVO scientist on the standardisation committee captures the dilemma of using a simple VALS to communicate complex messages:

> It's a very tricky business; any time you try to communicate a complex message in a simple way, it's very, very difficult. You still have to do it, it is still necessary, it's still important, but it's difficult because volcanoes are so complex and diverse and situations are so different, it's just fundamentally different if you have a volcano doing a certain thing within reach of a large population centre, or not, whether you are intensively monitoring a volcano or whether it is out in the middle of the Aleutians and you have very little monitoring. It's very hard to standardise, because the situations you are trying to describe in a single colour or single alert level can just be so varied (CVO senior scientist 1).

With this dilemma, it seems that any standardised VALS is setting itself up for a hard task. However, it appears the problems that arise are more to do with the linear design of the VALS than the concept of using a alert level as a semaphore to convey important information.

5.3 The organisational complexities of volcanic hazard warnings

The previous section discussed how the standardised VALS manage the diverse range of volcanic behaviour and hazards. This section aims to review how scientists and users are positioned within the standardised VALS, demonstrating the organisational complexities involved in its operation. This section raises questions about how scientists and users negotiate complexities in practice, and this is discussed further in relation to decision-making in chapter 6, and to communication in chapter 7.

5.3.1 Institutional issues for USGS scientists

Institutional factors such as the epistemic culture of the observatory can strongly influence the VALS' capability to work in practice. The complex dynamics of USGS policy, governance and operations have a profound effect on the resources, required to provide an effective VALS, such as funding for monitoring capabilities, staff resources, and protocols for issuing warnings. Education and outreach are essential components of the broader VEWS in order to ensure that stakeholders are aware of VALS and how they work, and this requires staff time and resources. However, the biggest constraint in resources discovered during this research, is the structure of job promotions. This section outlines some of these institutional dynamics and constraints.

The traditional focus of the USGS, and the VHP in particular, has been academic research and the publication of papers. To be promoted within the USGS is partly dependent upon the quantity and quality of papers published by the applicant, alongside his or her citation record. Some highly active VHP scientists have been known to withdraw from volcano monitoring activities to publish further papers, in order to be promoted (AVO senior scientist 1). Equally, there are VHP staff who have dedicated their lives to assisting at volcanic crises around the world, or developing new monitoring equipment or software to improve monitoring capabilities, but were not promoted because they did not publish enough papers (AVO senior scientist 1 / CVO scientist 15). In this context, the role of monitoring appears to be secondary to traditional academic work. Yet, it is the requirement to fulfil the Stafford Act (to provide warnings of volcanic hazards) that drove the VHP to develop volcano observatories in the first place. At CVO, LVO and YVO volcanic activity occurs periodically, so a majority of the scientists focus on their research, but at time of crisis take on a monitoring role. Unfortunately, this institutional environment, along with extended periods of volcanic inactivity, does not provide incentives to improve warning capabilities. Although this ethos is changing, numerous staff have not received financial rewards via promotion for their achievement in saving lives (CVO management). This makes the USGS quite different to other Federal Agencies such as NOAA (NWS) and NASA, where promotions are based on both monitoring performance and research into the phenomena monitored. Both research, monitoring, and crisis management are equally important (VHP manager 1). Research provides the knowledge to better process monitoring data, and monitoring data can generate new research increasing knowledge about volcanoes. One possible reason for the USGS's historical focus on academic publications is the legally required five-year review of the VHP conducted by academic institutions such as the National Research Council and the American Association for the Advancement of Science (National Research Council, 2000, American Association for the Advancement of Science Research Competitiveness Program, 2007). Their focus on academia and the drive to publish papers may explain why the VHP maintains an academic approach to their research conducted. A realignment of values in both monitoring and research would reflect those used at other agencies, and encourage more time to make volcanic hazard warnings, communication and education more effective.

Due to the flat hierarchical structure of the VHP, it has been possible to easily exchange and discuss data between the volcano observatories, which has enabled the VHP's knowledge base to improve. Although each observatory has its own culture and identity; emails, meetings, workshops and conference-calls keep the whole VHP in frequent communication with one another, sharing problems and solutions. In addition, staff are permitted to move to another observatory to assist in a crisis, or to move for a number of years as part of a 'tour'. Databases and internal communication web tools are becoming increasingly standardised between the observatories, for example, the database used at AVO is slowly being adopted and adapted at the other observatories, which will enable even better communication and access to monitoring data, volcano records, and discussions on volcanic activity or anomalies with colleagues no matter where they are located (AVO collaborator 2). This facilitates communication of information and ideas between the scientists within and between the volcano observatories, and is partly a positive result of the academic ethos adopted within the VHP.

Historically all observatories (except YVO which had not been formed) had an ‘outreach officer’, appointed to coordinate volcanic hazard warning education and outreach events with institutions and vulnerable populations to volcanic hazards (Adleman et al., Unpublished). At the time of writing only CVO and LVO have an outreach officer, with AVO and HVO no longer able to afford the additional position. Interviews with current and past outreach officers indicated the role is extremely challenging (although personally hugely rewarding) since it was conducted in addition to other research or management responsibilities (CVO scientist 4 / HVO senior scientist 3). There are constant requests for scientist interviews, presentations and information by the media, educational institutions, academic institutions, the public, and users of the VALS (Driedger, 2008). To accommodate this demand, scientists throughout the observatory build relationships with specific groups. Scientists have differing levels of interest in outreach and some are better communicators than others and so the work is divided amongst those best skilled for the responsibility. To fulfil the demands of the role of outreach, more staff time and financial resources are required. Given the importance in training stakeholders about VALS and how they work, as part of compliancy with the Stafford Act, in practice, the role of outreach is under-valued (CVO scientist 5).

At the time of research the USGS, like many agencies under the Bush Administration, were struggling to reconcile slashed budgets and increasing duties (VHP manager 6). This severely constrained the ability to expand or maintain monitoring equipment, employ new staff and increase outreach responsibilities. Unfortunately, reducing employment contracts is not uncommon in federal agencies and this can impact users of the VALS who may have developed a relationship with a particular member of USGS staff, and vice versa. While there will always be financial constraints, the restrictions imposed by the Bush administration placed the VHP in a particularly difficult scenario. At the time of fieldwork there was no anticipation that important projects such as the NVEWS program would be funded, and numerous other smaller but beneficial programs were shelved. One reason the VHP survives through extensive funding cuts is that a significant proportion of the scientists have emeritus scientist status, retired, yet still working, in particular at Menlo Park (VHP manager 6). There has been concern about the lack of new younger staff within the VHP and the reliance on retired emeritus staff to maintain the VHP (National Research Council, 2000). In the near future, there is likely to be a gap once retired staff leave permanently and newer staff have not yet built up experience or expertise, particularly for volcanic crises.

With constraints on funding and an aging staff the VHP, like any other institution, has problems that change over time. Changes in governments affect funding resources as certain politicians place more value on science than others (VHP manager 6). Technological developments have changed the way scientists communicate across thousands of miles, and the increasing demands of the media and public for information relating to potential volcanic hazards are a burden on the VHP scientists time during a crisis. Given the legal mandate for the USGS to provide notification for volcanic eruptions to enhance public safety and reduce losses through effective forecasts and warnings based on the best possible scientific information, it appears that this still does not play a central role in the VHP institutional structure. The struggle between the research and monitoring staff is one that continues, and possibly reflects the need for the academic culture to shift to a more 'mode 2' style approach, where the focus is to bring together interdisciplinary groups together to work on the problems that impact people (Gibbons, 1994) (see chapter 2). The ramifications of remaining in a 'mode 1' type of knowledge affects the ability for scientific knowledge to translate into effective warnings. There is a need to move from the epistemic authority of volcano science to the need to engage with users, whilst remaining locked in an academic culture that rewards publishing. This requires engaging with users more, as seen in other federal agencies such as the NWS, who have dedicated staff for monitoring and warning responsibilities. The complex science involved in understanding volcanic behaviour, raises questions about whose expertise counts in determining a volcanic hazard.

5.3.2 The users of the VALS

There is a diverse range of VALS users, ranging from emergency managers to land owners (U.S. Forest Service, National Monuments, private land) who are generally local, to partner organisations (collaborative universities and institutes), state geologists, and the NWS, which are regionally at state-level, and the aviation sector (VAACs and Air Traffic Control), which are national. Managing all the demands and expectations from such a diverse range of users remains challenging for the scientists. This section first reviews the users' perspectives on the purpose and definition of a VALS; second, discusses issues relating to the terminology and use of the alert levels; and finally, the difference between ground based hazard and aviation users, highlighting the diversity of users involved, at a range of scales from local authority to international organisations. All these factors highlight organisational complexities of the users, that contribute to the difficulties in operating a VALS.

Scientists frequently define VALS as a tool designed for use by the public (CVO scientist 16); however interview data and ethnographic observations indicated that VALS are predominantly used by local emergency managers and other federal agencies rather than the public. This is an important point given that a significant proportion of discussion during the standardisation of the VALS focused on developing a VALS that would not confuse the public. Emergency managers stated that the public generally want simple but effective information that will enable them to establish whether a volcanic hazard or event is going to affect them and, if so, to be able to obtain further information (CVO user – emergency manager 2). Therefore, although the VALS is available for the public, they tend to rely on their local emergency managers for guidance (CVO user – emergency manager 1). Whilst the volcano observatories interact frequently with the public, particularly for educational purposes, in practice the USGS VALS appears to be a tool to communicate with different users.

How an alert level is defined and what it means depends on the user, and their institutional requirements for the alert. For example, an employee within the Alaska NWS uses them as a 'trigger to do more, pay more attention' (AVO - user NWS 2), as emergency managers in the Cascades respond through preparation and opening the lines of communication. Federal users see VALS as a tool to acquire their attention from their many other duties outside that of volcanic hazards, which are usually not common occurrence (except for Hawaii) (AVO user – NWS 2). Therefore, for many users, including some scientists, a specific definition of a VALS was not seen as important. Some went as far as not understanding the need to have a VALS at all as explained by this senior scientist at HVO:

> I think the whole alert level thing is […] an attempt to better communicate with the public, media [and] help scientists convey the message. Most people put too much emphasis on that and not enough with the basic problem which is communication between scientists and non-scientists (HVO senior scientists 4).

This viewpoint was particularly prominent at HVO where there was concern that the information accompanying the alert level would not be read. The information communicated by an alert level between the scientists and users is context driven and this could be a consequence of their individual and institutional experiences and expectations from historical VALS, which have shaped their understanding and expectation of VALS (discussed further in chapter 6).

The implementation of the standardised VALS has raised questions about the use of the NWS terminology within the standardised VALS for ground hazards (Watch, Advisory, Warning), and the confusion they generate. First, NWS terms are generally defined as shown in Table 5.7 however, there are different definitions used for these terms within the NWS for different hazards such as hurricanes, tornadoes, and snowfall. Second, the NWS scheme is itself often regarded as ‘confusing’ because it is based on confidence levels and probabilities of events occurring (CVO user - NWS), as the VALS is not. The NWS use their alerting scheme in a different way to that of the VALS. Rather than escalating and de-escalating through the VALS in a progressive order, the NWS alert assigned depends on the probability of the event occurring. Consequently, the NWS terms have designated timeframes for each issued alert, which relate to the likelihood of the event occurring. Third, the NWS terms, as used in the VALS, are used in a ‘different order’ to most NWS products (AVO user - NWS 1). Instead of the order used in the VALS of a Normal-Advisory-Watch-Warning alert, at the NWS the order of alert is Outlook-Watch-Advisory-Warning (see Table 5.7). It seems odd that emergency managers have become familiar with the order as used by the VALS rather than the NWS one, hence requesting its use in the VALS. Unfortunately it was not possible to ascertain why this was. Fourth, most scientists found it difficult to remember the order of severity of the NWS terms as used within the VALS. Equally it would appear that the ‘public don’t really understand NWS terms, but you got to pick something’ (CVO user - media). Scientists expressed concern that the NWS terms have no rationale in their order and that people generally like visual things to remember, such as colours, which are more instinctive (AVO collaborator 3). Finally, some interviewees commented that the NWS terms are misleading and not very logical; ‘Warning doesn’t say something is going to happen, it just says "warning" and implies it is going to happen’ (LVO user - Mammoth Lakes town 2). Equally Watch sounds like, ‘watch your step’, and Advisory ‘you need to take advice and do something’ (AVO user – NWS 2). Therefore, there are inconsistencies with how the NWS terms are used and understood for different hazards and by different groups, adding an additional level of complexity to the VALS since there are already established perceptions about what these terms mean by users in the context of probabilities, risk, and levels of concern.

Outlook	Issued to advise all users of potential wind storm conditions in the 3-5 day period
Watch	Issued when conditions are favourable for hazardous wind conditions to develop, but its occurrence, location and / or timing is still uncertain. It is intended to provide enough lead time so that those who need to set their plans in motion can do so. Watches are issued for events forecast to begin in the 12 to 48 hour time frame.
Advisory	Issued for events which don't quite reach warning limits, but are of significant inconvenience and may be hazardous if caution is not exercised. Advisories are issued for events forecast to begin in the next 12 to 36 hours.
Warning	Issued for events that can be life threatening or can cause significant damage to property. Warnings are issued for events that are imminent, occurring, or forecast to begin in the next 36 hours.

Table 5.7 The NWS definitions used for hydrological events (wind, flooding etc.) from email correspondence between staff at NOAA to the standardisation committee (at CVO) in April 2003 (FOIA archives)

To add to confusion, a significant proportion of scientists and users refer to the VALS, either for ground or aviation hazards, using the colour terminology, even though it is only applicable to the aviation code. Traffic light signals such as this are an international convention (AVO senior scientist 8), and easy to understand since they are used every day by people and drivers around the world (VHP manager 2). In contrast, emergency managers do not like the use of colour codes, partly because of the failure of the Homeland Securities Terrorism Alert System, which has become 'devalued' (CVO user – emergency manager 1) by staying only at alert level Orange, and thereby losing its meaning. This same argument could be extended to Kilauea volcano, which has always been at Orange / Watch alert level. The ground hazard VALS are still frequently referred to as a colour by both users and scientists, adding confusion as to whether an alert level relates to ground or aviation hazards.

The alert level helps communicate a sense of urgency, but the actual terminology of it can generate confusion and other issues for users, partly because they have a historical institutional context in which they use warnings within their own area of expertise. Consequently, it is clear that the terminologies of alert levels are not straightforward and simple, but contextualised by their meaning and use, as Hall (1980) outlines in his theory of encoding and decoding messages (discussed further in chapter 7).

Some scientists argued that the colour code is not especially relevant to the aviation sector as it could easily adopt a different code, as this quote from email correspondence from senior AVO staff to other agencies involved with aviation at Anchorage sent November 2003 (FOIA archive) states:

> In essence, there needs to be an information gatekeeper ensuring that only information of a particular shape and form is allowed into the aviation arena for use by WMOs [World Meteorological Organization] and VAACs [Volcanic Ash Advisory Centres] [..]. Whether this information, in part, takes the shape of colour code or numerical descriptors is actually of less significance than ensuring adequate prescribed information is fed into a predetermined way to the aviation sector, and it can be used in a uniform procedural manner.

This quote begs the question: if the design of the colour code is not that important to the aviation sector, why did it have such a large influence on the design of the standardised VALS design when it does not hold much value within the community? Senior USGS managers who deal with the aviation sector argued that aviation needs are quite separate from other users and the VHP should be encouraged to produce prescribed information (VHP manager 1), but in practice it seems less important what is actually used.

The standardisation of the VALS was not just a national initiative. ICAO adopted the aviation code globally. Yet, most VALS around the world are not ICAO complaint. In fact, at the time of research, no-one outside the U.S. has adopted the ICAO aviation colour code, primarily because many volcanically active countries (e.g. in South America) do not have funding for the resources required to issue these codes in addition to ground hazard warnings (VHP user – VAAC). The Washington VAAC works with numerous countries to help notify pilots of potential ash clouds and volcanic eruptions to provide some level of information to the aviation sector. It seems acceptable that a level of standardisation on a global scale may take more time and be far more complex than on a national scale. However, the 'Washington VAAC doesn't even put colour codes in the VAAC's messages' because pilots may 'misinterpret as the ash *cloud* is yellow' (VHP manager 1) (author's emphasis). This indicates there is confusion as to whether the volcano, ash plume or ash cloud is being assigned the colour code. Additionally the colour code is actually an optional field in the Volcanic Ash Advisory (VAA). Interviews with aviation users stated that pilots do not really pay any attention to the colour codes, but just the reports and information they receive as a VONA or VAA (VHP manager 1 / VHP user - VAAC). It is odd that the pressures to serve the aviation sector, that led to the splitting of the VALS during the design process of the standardised system, would result in such little practical impact. It appears that a key problem for the aviation sector is that there are no colour codes for ash clouds (VHP manager 1). Although this is being addressed via the development of the PUFF model at University of Alaska Fairbanks, VONAs were designed to be 'more specific for what VAACs need like direction of movement, speed, height of ash and plume' (VHP user - VAAC). The VAACs pass the VONA onto the pilots and airlines. So what role does the aviation colour code actually play? As a VAAC employee states: 'having a colour code though still helps us, even though we don't put it in our VAA, it still helps us understand which volcanoes we need to monitor' (VHP user - VAAC). It provides a level of screening whereby aviation users only pay attention to volcanoes if at Orange / Watch or Red / Warning, helping them to manage the many volcanoes they monitor (up to 500 at the Washington VAAC) since volcanoes are not the only hazard they monitor (others include tropical cyclones). Pragmatically, the colour code provides a vital filter to help with the 'work load' (VHP user - VAAC) and highlights the limitation of institutional resources to have sufficient staff to monitor potential hazards. Therefore, VALS have an important role to play in establishing how much awareness users should have in relation to a volcano and its activity, in order to enable quick and effective focus for users who may be preoccupied with other aspects of their job; in effect it provides an organisational tool for them.

5.4 How effective are linear VALS in managing the complexities involved in volcanic hazard warnings?

The design of the standardised VALS is that of a linear system. Yet, the data presented in this chapter and in chapter 4, suggest that VALS interact with a number of complex issues; scientific, social and institutional. Table 5.8 provides a summary of these issues for each observatory and reviews how the VALS has been adapted to cope with them. From this Table it is clear that the linear standardised VALS is unable to accommodate the flexibility required to cope with these complex issues at each observatory.

Observatory	HVO	AVO	CVO	LVO	YVO
Scientific issues	• On-going activity • Fairly predictive behaviour • Slow moving lava flows • Chance of explosive behaviour	• Fairly predictive behaviour • On-going activity • Consistent hazards	• Fairly good understanding with some forecasting models • Plenty of case studies to compare • Variety of hazards	• Difficult to interpret • Limited knowledge of caldera behaviour • Wide variety of volcanic hazards	• Highly complex • Usually surficial hazards • Difficult to interpret • Long lead up to eruption expected
Social issues	• Historical memory of activity • Influences land planning • Insurance concerns for home owners	• Not largely populated due to on-going activity and remote location • Affects aviation users, both civil and military	• Often part of a National Park due to natural beauty • Nearby hazardous locations can be highly populated with critical infrastructure • Tend to be fertile farm lands	• Can give long term notice, but volcano may erupt with short notice • Raising awareness for hazards, especially with tourists	• Too active to be populated • Well known due to media documentaries • Popular tourist location
Institutional issues	• Constant communication and awareness between scientists and users • Highly monitored volcano	• Remote locations makes it difficult to monitor • Collaborates with UAF and DGGS partners making decision-making more complex	• Highly monitored • Must liaise with land owners i.e. National Parks and Forest Service • Particularly focused on media interest	• Need to work with local businesses i.e. the ski area • Liaises with land owners and managers i.e. U.S. Forest Service	• Collaboration between different land owners and managers i.e. the National Park • Highly monitored for research • Collaborates with partners and a number of universities on research activities
Adaption of VALS	• Developed alert level system for sulphur dioxide hazards • Not used due to constant eruption of Kilauea volcano	• Focused on aviation users • Not usually concerned with ground hazard alerts	• Developed lahar early warning system (AFMs)	• Gases pose significant hazard • Alert level never changed	• Hydrothermal activity not reflected by VALS

Table 5.8 Summary of the different influences at each observatory and their impact on how the VALS is used.

Scientists expressed the view that the standardised VALS solved the needs and concerns of the two key different user groups, however many of them still feel that the VALS has a number of shortcomings, as this scientist from AVO observes:

> [The] complicated reduction of all of these factors (risk, hazard, activity) and boiling that down to a simple number [means] inevitably if you do that, something is going to be lost. You can't just project a ten dimensional problem down to one dimension and expect it to retain all its complexity (AVO scientist 4).

Yet this reduction to a simply designed VALS is precisely what has happened, largely to fulfil U.S. Government requirements to manage these complexities and provide information for other federal agencies in a standardised manner. This reflects on whose expertise matters to managing risk and developing regulation.

Some of the underlying institutional dynamics of the USGS are shaped by the need for authority (or expertise) to retain accountability and credibility. To maintain credibility, there is great pressure to assign the 'right' alert level, despite all the complexities and uncertainties (AVO senior scientist 1). Yet, there seems to be an implicit assumption that the users, federal agencies, government and public cannot deal with these uncertainties, complexities or unknown risks. The work of Wynne and Stirling indicate that the public in particular can deal with these ambiguities well, if informed correctly (Wynne, 1996, Stirling, 2003); therefore it could be implied that sophisticated users would also understand.

This chapter has reviewed the difficulties faced in designing the standardised VALS and the influence of social and institutional factors on this process. It is clear from the data presented that VALS are unable to deal with a number of complex systems, whether they relate to the physical hazard or organisational issues because of their linear structure and lack of flexibility. Therefore, by using a linear system to communicate a warning, it hinders the ability of it to reflect the complexities involved. In particular, the alert level descriptions limit the flexibility of the system to provide alerts that reflect activity for certain volcanic styles, in ways that are meaningful. The role of VALS to fulfil policy is to provide a tool that manages the complexities involved in providing volcanic warnings, but in practice this is limited by the design. How is it possible to manage a complex world via a linear system? The next two chapters will detail how this happens in practice, and in turn unpack the black box of VALS by revealing how they operate, and how the actors involved work around the constriction of the linear VALS design to make it work more efficiently, providing an opportunity to review how VALS may be reconceptualised.

Chapter 6. Decision-making: negotiating uncertainty and risk

Decision-making is a core component of volcano alert level systems (VALS). There is a series of decisions made throughout the system, ranging from what the monitoring data is indicating about volcanic behaviour, to how this affects the alert level, whether to change the alert level and when, and what information to communicate to users and stakeholders. Once an alert level is issued, users interpret it and may discuss with the scientists in further detail, to decide what actions to take and when. For the scientists, decisions mostly revolve around the complexities of a volcano's behaviour and are shaped by the institutional dynamics of the USGS, Volcano Hazard Program (VHP), and the observatory. The users' decision-making has to consider the physical complexities, in addition to the social complexities of their respective institutions and the vulnerable populations and infrastructure for which they have responsibility. This chapter argues that in practice, the complexities that VALS aim to manage imply that it is not possible to separate scientific knowledge and the consideration of risk when making decisions on which volcano alert level to assign. This is important because this study shows that the 'first mile' of the volcano early warning system (VEWS) is critical and far more complex than expected.

This chapter reviews how decision-making operates in practice when applying the VALS. Interview data and the ethnographic study, undertaken at all five observatories, provide a rich body of evidence to suggest that decision-making is a complex and iterative process. The previous chapter introduced that the decision to change an alert level is often not exclusively based on the physical aspects of volcanic activity, as intended by the design of the standardised VALS. Although elements of risk are considered by the scientists in their decision to change an alert level, high levels of uncertainty limit these decision-making capabilities. From the fieldwork, three key stages of decision-making within VALS have been identified which this chapter reviews. First, there is the difficulty for scientists of interpreting scientific data and making decisions about what the volcano is doing when dealing with complex volcanic processes and high levels of uncertainty. Second, social factors influence the scientists' decisions to change alert levels and therefore highlight the influence of risk rather than science in making these decisions. Third, the gap between the scientists and users, and the influence of management and institutional factors on this process. By investigating the decision-making processes within a VALS it is possible to understand how VALS work operationally, and investigate in more detail the limitations that a linear design imposes. This chapter will highlight, that there is controversy that emerges over who the expert is in making decisions relating to volcanic risk, and how different experts work together to mitigate a potential volcanic crisis.

6.1 Constructing scientific knowledge

In order to provide a timely warning for volcanic hazards to communicate to the users, it is important for the scientists monitoring the volcano to accurately interpret scientific data, provide the best information about current activity, and generate reasonable forecasts for potential hazards. As already discussed in the literature review, the levels of complexity in volcanic processes and hazards make them difficult systems to understand, and given their infrequency and incomplete scientific understanding, there are many uncertainties involved in volcanic crises. This section will review in more detail the difficulties faced by scientists in constructing their scientific knowledge and developing forecasts, and the tools used to aid this decision-making process.

6.1.1 Obtaining and interpreting scientific data

Before scientists discuss what alert level volcanic activity should be assigned, there is a rigorous process of establishing exactly what is going on at the volcano. This process is often dependent upon the monitoring capabilities of each observatory to provide scientific data. The ability to set up and maintain monitoring equipment, interpret and analyse the data, and develop forecasts appears to be determined by available funding for such equipment, staff, and access to data, not just in the U.S., but also globally. These resources enable scientists to discuss the data and to establish which alert level should be assigned to the current activity of a volcano. In any situation, there are going to be 'incomplete data sets, some individual familiarity, pattern recognitions' that play into the understanding of a volcano's behaviour (AVO senior scientist 5). So far, monitoring capabilities have been predominantly limited by funding resources. In recognition of the need to establish 'a proactive, fully integrated, national-scale monitoring effort that ensures the most threatening volcanoes in the United States' (Ewert et al., 2005, p.3) the USGS developed their National Volcano Early Warning System (NVEWS) program that aimed to meet the monitoring standards expected by other U.S. federal agencies. Some scientists expressed concern that NVEWS would focus the activities of the VHP on monitoring rather than research, but the premise of NVEWS was 'not to abandon research, but step-in, providing a reliable service that is a core function, not an afterthought' (VHP manager 1), providing background records of the activity of a volcano over a period of time. To implement this, an updated and universal IT framework was required. The standardisation of the VALS and subsequent new communication products and databases, helped develop a unified IT platform to cope better with more monitoring data, which is discussed in the next chapter on communication.

An effective monitoring capability is vital to scientists as it provides the ability to view the volcano and its many 'symptoms' during volcanic unrest. The more monitoring equipment on the volcano, the easier it is to determine what is going on (CVO scientist 13). However, there can be a point where too much data is more of a hindrance than a benefit (CVO user - USFS 1). New monitoring techniques can capture events that happen at volcanoes that have never been seen before, and can involve the public who have access to live data or webcams online (in particular at AVO[13]) that can create new debates between scientists, users, and the public about the activity of a volcano. One major disadvantage of increased monitoring data is it requires more resources to analyse, discuss and understand in relation to the activity of that volcano. For many of the more active volcanoes, there are large data-streams every day from numerous seismic and GPS stations, satellite images, webcams, and gas monitoring equipment that need to be processed via computer programs before even being viewed by a volcanologist. Many software programs exist to process raw data, such as 'Earthworm' a processing module for integrating regional seismic network data, although often these programs are not completely standardised between the five observatories. This creates issues when trying to correlate data and look at patterns of volcanic behaviour, so there is a strong rationale to standardise the format of all scientific data, although standardising data formats can institutionalise a bias.

Due to the very large quantities of data that feed into the computer systems at all the observatories, an automated system has been set up so that should specific monitoring signals exceed established parameters, an alarm will be raised. For example, if an earthquake of magnitude three or more occurs, or more than two magnitude three earthquakes occur within a space of 24 hours, then an alarm is triggered and the scientists responsible for that particular data set at each observatory are alerted by a bleeper they carry. At the observatory, scientists rotate the 24-hour role between them every week and are responsible for responding to automated alarms or odd observations. This places a huge reliance on technology, so it is important that a scientist vets alarms raised in case there are errors within the system, either

[13] See: www.avo.alaska.edu

from technology, or rational explanations for odd behaviour such as severe weather conditions, helicopters (that can affect the sensitive equipment) or explosions.

Faults can also occur within the telemetry involved in getting data from the volcano relayed back to the observatory. Telemetry is a costly process that requires a lot of maintenance and can be affected by severe weather or volcanic activity; therefore, a few dedicated VHP staff monitor and maintain the telemetry systems. Developing automated systems makes monitoring more manageable in an age where there are vast quantities of data. Data are stored and used for research purposes as it may help understand the dynamics of an event and establish relationships between different data sets. Yet, it is important to note that every automated alarm system used has its parameters designated by a scientist making their selection subjective. In addition, these parameters are different for each volcano.

As discussed in chapter 5, each volcano has its own ‘personality’ and therefore time is required to characterise and understand the normal background activity of a volcano before deciding whether or not it is behaving abnormally. This is one of the principal reasons supporting the NVEWS program; so that the VHP can be proactive rather than reactive. The following quote from a scientist at CVO highlights the individuality of volcanoes by providing an analogy:

> When I try and describe this problem to people I often use a medical analogy. You know there is a tremendous amount of information about the population of people, about the percentage of people who will have heart attacks […] but when you come down to one person, you can’t say ‘well you are going to have a heart attack at the age of 63’. We can say that 35% of population will have a heart attack by 63, but we can’t say anything about an individual (CVO senior scientist 7).

Understanding a volcano is ‘part science, partly an art’ (CVO senior scientist 7), since volcanoes can behave in unexpected ways, and recognising patterns of behaviour for a volcano is critical to understand what that volcano is doing and to generate accurate forecasts. To do this requires both monitoring data and research into the meaning of the data. Occasionally, a volcano does something unexpected or not seen before, a 'black swan'. Like medical patients ‘volcanoes can have long-term illness or heart attacks’ (AVO senior scientist 5). Clearly, shock events generate significant discussion and research, as often there are no known examples of a volcano behaving in that particular way. Volcanologists around the world are currently working towards developing a global database for volcanic events and behaviour called WOVOdat so that during a shock event it may be possible to compare data anomalies with other volcanoes that have done similar things (WOVO, 2010). At a national level a database has been established for U.S.

volcanoes, and the VHP, with collaborative research staff who have conducted extensive research on a volcano, can provide expert opinions on its particular behaviour patterns.

Although monitoring data can provide specific measurements about what is happening at the volcano, it is far more difficult to interpret what these measurements imply about the volcano's behaviour. Decisions made have to integrate many different aspects; not just the monitoring data but the experience of the scientist interpreting the data, managing the uncertainties, ambiguities and ignorance involved, and the expectations of the users. All VHP observatories have procedures in place for various committees to convene if abnormal monitoring data is identified, either by automated alarms or observation. Commonly, the committees include the scientist in charge (SIC), their deputy, and representatives from different or relevant scientific groups within the observatory such as seismic, deformation, gas and ash, and satellite imagery. Together they review the data, interpret it, and establish possible scenarios for forecasts. This involves discussing the data, historical behaviour at the volcano or similar volcanoes, and the value and significance of one particular data stream (i.e. seismicity) versus several different streams (ground deformation, geochemical anomalies). This process of discussion, in essence, is dependent on the expertise of the scientists, discussed below in section 6.1.2.

Further complications arise when the scientists review possible forecasts, particularly useful to users. Forecasting volcanic behaviour has greater uncertainties than determining volcanic activity, especially since volcanoes, unlike many other hazards, can sustain unrest or eruptions for long durations. The predictions made by the VHP during the early eruptions of Mt. St Helens in the 1980s were more accurate that those usually possible for volcanic activity, due to the recurring nature of the eruption at that time, but today forecasts are used, to reflect greater uncertainties. Forecasts are presented via three possible scenarios: worst, best and most likely. The main goal has become to ‘alert people, tell people as much as we can. Whether it is right or wrong is less important’ (HVO senior scientist 3). This quote highlights the importance of communicating information, and accepting that this information is uncertain is critical. Many users have difficulty in distinguishing between a prediction and forecast; a prediction is a precise statement of the time, place and nature of impending activity, as a forecast is an imprecise statement (Swanson et al., 1985). A scientist in Hawaii stated that ‘we try and use precise language in science but the public does not speak this language’ (HVO collaborator). Therefore, there are complications not only in developing forecasts based on current monitoring data, but also in the interpretation of them by users and their understanding of the uncertainties involved (discussed in section 6.3).

6.1.2 Deciding an alert level

The description of an alert level provides a criterion as to which alert level should be assigned yet a lot of time is spent discussing at which alert level a volcano should be. Clearly, the scientists feel a burden to get the definitions of the alert level 'right', and help the users in their decision-making responsibilities. Although an alert level does not convey risk, it does express levels of uncertainty as seen in Orange / Watch and Red / Warning where the description states: 'hazard is imminent, underway, or *suspected*' for a warning (author's emphasis), but there are no specific forecasting elements other than indications of an imminent eruption. The exclusion of risk largely relates to issues of accountability, and the desire to defend the alert level assigned, as summarised by a member of the standardisation committee:

> We wanted to make sure that we could always come back and defend why we were in that colour code on the basis of activity at the volcano. It gets, I'll admit, a little fuzzier when you're in Watch and Warning, especially Watch, because we are making a determination about hazard (CVO senior scientist 2).

This quote highlights that the ability to assign an alert level based solely on activity at the volcano is a challenge since there are areas of fuzziness or uncertainty. Although the USGS is unlikely to be sued on issues of accountability since it is part of the U.S. Government, the VHP does not want to be seen as providing false guidance if an alert level is issued too early or late.

Whilst some scientists feel that 'the language that goes along with [VALS] is as important or more important [than the alert level]: it's what we convey verbally in the accompanying language that is important' (AVO scientist 6), it is clear that VALS still play an important role in volcanic hazard warnings. A user of VALS at AVO emphasised that VALS enable the: 'technical folks [volcanologists] to evaluate a risk and translate the urgency of that action to us' (AVO - user emergency management). Chapter 5 highlighted that the purpose of a VALS is to translate the urgency of information to users so they can generate an appropriate response. But in practice how does an observatory decide to go from one alert level to another?

By empowering an experienced member of the observatory staff to decide the alert level, rather than the USGS director as protocol demanded during the early years of LVO, experienced staff at the observatory can make the decision rather than USGS management, who may have no experience of working in a volcano observatory or understanding of volcanic behaviour and the uncertainties involved. It is the responsibility of the scientist in charge (SIC) to allocate an alert level, which establishes a clear line of authority in the observatory. This role is a rotating one, whereby they have responsibility for the observatory for 3-5 years before it is passed onto the next elected SIC. All SICs are highly experienced scientists both in conducting research and monitoring volcanoes. Senior scientists are normally nominated for the role, which is decided by the VHP management staff. Typically the SIC will consult with observatory scientists to obtain a consensus before making the final decision to assign or change an alert level (CVO senior scientist 2). Arguably a SIC knows how to make these decisions, because they have been exposed to the process for years. It also means that each volcano observatory tends to have a flat hierarchical structure, resulting in fewer struggles over power and authority.

The process of interpreting monitoring data in order to establish a volcano's activity and set an appropriate alert level usually occurs during a meeting between the scientists at the observatory, held either regularly (daily, weekly) or infrequently (monthly) depending on the activity of the volcano. During fieldwork at CVO in 2008, I was able to attend such a meeting to decide the volcano activity and alert level of Mt. St. Helens. The volcano had not shown much sign of activity for a while and there was discussion about dropping the alert levels from Yellow / Advisory to Green / Normal. Nearly all CVO staff attended the meeting, with the University of Washington (their academic partner) and other agencies dialled in by telephone to participate in the debate. In addition, technology enabled all participants to present their interpretations of data. The decision-making process was democratic in that each specialist scientific group (i.e. seismologists, geochemists) presented their data, the possible interpretations, and their consensus. Other scientific groups asked questions about the data, often leading to discussion. Following the views of all specialist groups, the group as a whole discussed the implications of the data presented, and what the data inferred about the volcano’s current activity. In the meeting I attended, a significant proportion of the scientist felt that Mt. St. Helens was no longer showing signs of being active, but there was some data that suggested that it was not entirely inactive. Consequently, the SIC made the decision to keep the alert level at Yellow / Advisory and review the data in a month, when if no further activity occurred it would be downgraded. At CVO the process is regarded as democratic in that the SIC follows the consensus on most occasions, unless they are privy to additional information, usually relating to other social or institutional factors (CVO senior scientist 2). Throughout the process there was no use of probabilistic models or event trees (although they could be used to guide discussion); just open discussion and debate was used to make decisions. In practice, there is an apparent mismatch between the way decisions are made at the USGS and investment of academic time into models like event trees. This section goes on to explore why a deliberative approach is adopted rather than a rigorous mathematical or scientific one.

The observatory scientists employ a number of methods to manage the scientific uncertainties involved. Many of the scientists interviewed endorsed the use of event trees, but mostly in crisis situations. Event trees are most popular with the Volcano Disaster Assistance Program (VDAP) team when aiding in crises abroad, using them as probabilistic models upon which to base decisions. A majority of scientists interviewed felt that event trees provide a 'very effective way for both the scientists to think through the logic of sequence of events and the accumulative probabilities […] give you a good sense of the uncertainties involved in the full process' (CVO senior scientist 7). Bayesian Event Trees (Marzocchi et al., 2006, Marzocchi et al., 2007), are used within the VHP as a tool for stimulating discussions among themselves or with other actors about the likelihood of events. Some scientists expressed concern at their use; 'it's all a fairly subjective expert opinion thing, but you base it on what the behaviour of this volcano was in the past and ask what it is capable of doing, what do you think is the likelihood?' (CVO scientist 8). This quote recognises the 'art' required in the process of making decisions based on scientific data.

Using a probabilistic approach is problematic in that it requires input from a number of different volcanoes, and in any one crisis 'each volcano is unique and so you might get generalities out of probabilistic assessments, […] but it's really more than generality that you really want to know about that particular volcano' (HVO senior scientist 5). Some of the scientists regard an alert level as an 'implicit probabilistic risk assessment' (AVO scientist 4). Yet for some it seems inevitable that event trees will be used more in the future as they provide a semi-quantitative basis for decision making, and that alert levels could be tied into these forecasts from event trees (VHP manager 3), as Aspinall and Cooke have already explored (1998). Most importantly, using quantitative methods for deciding alert levels provides an audit trail of the decision-making process, which is critical when scientists are concerned about issues of accountability. Developing understanding about what is currently happening at a volcano and its likely behaviour is quite a different process to that of other hazards, simply because so little is known. Whilst such statistical models exist for volcanoes, they are not necessarily useful since 'what is not communicated [to the users] is any sense of the uncertainty of that number' (CVO scientist 3). People have different perceptions of risk and so view percentages dependently (Slovic, 2000). Using human judgement, rather than probabilistic models, means that decisions can also incorporate experience (albeit only the experience of the scientists involved), which probabilistic models cannot factor into the calculations they use.

Currently, the three forecast scenarios (best, worst, most likely case) are provided to users rather than providing a numerical and probabilistic breakdown of the likelihood of each scenario. By not using risk models and basing their decisions on consensus between their expertise, it enables greater flexibility to consider the ambiguities and possible ignorance involved. However, it is important to remember that 'the conclusions established through scientific negotiations are not definitive accounts of the physical world. Rather, they are claims that have been deemed to be adequate by a specific group of actors in a particular cultural and social context' (Knorr-Cetina and Mulkay, 1983, p.95). This is reflected through the development of a consensus to issue an alert level and establishing what information to release.

In the absence of significant databases on each volcano and their behavioural characteristics, human judgement plays a vital role in interpreting what is going on at the volcano. Alert levels are not simply changed because some seismic activity meets some criteria level, 'it has to be a conscious, scientific decision whether we change levels […] you just can't do it by modelling, you can't do it by theoretical methods. There is no magical threshold at which at some point the volcano erupts' (VHP manager 4). At AVO one senior scientist provides a representative view of the process, outlining the difficulties in deciding when to change and the role uncertainty plays:

> There is a big difference between ramping up the colour code and ramping back down. We tend to ramp up relatively quickly, and then probably tend to stay at colours for longer than we should. With 20 / 20 hindsight we probably ought to ramp up sooner than we do. We always seem to be 'look at this', and this comes into how we forecast volcanic eruptions and many people are upset or bothered by the fact that it is still as much an art as is it is a science. It doesn't come from the idea that we understand this is what is going to happen and we can assign a probability to it and say well, we understand exactly what's happening at this volcano and it is going to erupt next Tuesday (AVO senior scientist 5).

Therefore, the decision to change alert levels is a subjective one, although it appears that scientists want to issue a warning based on as much objectivity as possible. However, the desire to not adhere to criteria for the alert level, indicates that the scientists are aware of the need to interpret large sets of data, rather than pigeon hole one set of data on which to make decisions.

A scientist from AVO outlines that the decision-making process is also different for varying stages of volcanic activity, especially if volcanic eruptions are imminent:

> The early colour code decisions are more *strategic* in nature. I think when you get towards an eruption they are much more *tactical*; you know an event just happened, what do you do? And those [decisions] have to be very quick. The early strategy of […] 'how [are] you going to get people buying into the idea that things are changing and it could lead into an eruption' are much more strategic and involve a large group of people. When you get down to tactical responses the damage has happened and it typically involves a much smaller group of people who have to be on top of the game in realising that something significant just happened, because then the timeframes are compressed and [people] really want to get things out as quickly as possible (AVO scientist 3) (author's emphasis).

This quote indicates that the type of volcanic activity affects the strategic and tactical response to change alert levels, whether it is quick, changeable or significant. This alludes to the consideration of risk when changing alert levels, but also indicates the strategic use of VALS to create awareness of something occurring at the volcano. Therefore, VALS can be regarded as a strategic tool. This can also be seen in the quote below from a scientist at CVO who explains that sometimes the decisions of the VALS in the observatory do not reflect true levels of volcanic activity or even concern:

> Internally, we tend to be a little out of sync with the colour code that we present to the public, and the reason for that is we see something is going on, we watch it for a little while and we ramp ourselves up before we ramp the colour code up, and then on the reverse side ramp down, before the colour code ramps downs, that's our own way of dealing with these things (CVO scientist 3).

There is one other major factor influencing the decision to change an alert level; the concern that subsequent events will show the decision to have been a 'bad call' (HVO scientist 1). It is a case of 'professionalism' (AVO collaborator 1) and the SIC wants to make decisions that are defendable to their peers and the government. There is always the concern that an event will happen once an alert level has been downgraded and that this may affect the credibility of the VALS and the observatory. One scientist at AVO had a number of philosophical discussions with their colleagues about this dilemma and states that there are two key schools of thought on this issue depending on how conservative you want to be:

> One school of thought says that if there is a geophysical anomaly then you are completely ok to go to Yellow and if nothing happens then fine, that's just the way the world works but you have done your job because there was a geophysical change. The other school of thought would say it doesn't matter, we can't say we know enough about it to know for sure if activity goes up or down whether that means something is going to happen. So in such a case it is better to be conservative i.e. don't risk being wrong, and not change colour code until you are really certain that something is going to happen (AVO collaborator 1).

This provides evidence that in some cases a more precautionary approach is taken, and in others a more reactive approach. There is a battle between these two approaches, driven by the scientists approach to uncertainty. A scientist who adopts a precautionary approach recognises that their role goes beyond doing their job, and that users may be interested in this information, no matter how irrelevant the scientists think it is. Equally there is a need to not over-concern users with information that may be irrelevant - this is the fine line they balance. For many, it is the Orange / Watch alert level that creates the most ambiguity as this scientist from the standardisation committee describes:

> Orange to me is a clutch mechanism, as in a car. A clutch harmonises the speed of two very different spinning gears, Yellow and Red; on, off; erupting, not erupting. That's a huge difference in spin power and so the Orange has to be a clutch mechanism. [It] helps slow the Red down and sometimes it helps speed the Yellow up (VHP manager 1).

Orange / Watch alert level presents a problem, because it involves two descriptions for the VALS, with one predicting imminent eruption, and the other describing an already occurring but non-threatening eruption. There is also general concern amongst scientists that an alert level should not be at a single status other than Green / Normal for too long, otherwise the alert level loses its meaning and impact as the public or users get complacent about it, much like what has been seen with the Homeland Security Terror Alert System. For places like Hawaii, the constant eruption means the alert levels is at Orange / Watch, but for the users this becomes meaningless as it is the 'status quo'. Therefore it seems the VALS is trying to encompass several roles into its dual systems – a forecasting tool with warnings, and a reportage tool describing what is happening at the volcano, such as an eruption.

With concerns about how to assign a volcano alert level and when to ramp-up and reduce the levels, the complications that certain levels such as Orange / Watch present, and the worry of being wrong makes assigning an alert level a highly complex process. Essentially, this 'forces the scientist to think about the alert levels rather than the science' (HVO senior scientist 5), rather than conducting free flowing discussions, to rank the possibilities of what is going to happen and then release this information.

> You have to pretend to understand the volcano well enough to know you can go, 'aha, we now go onto another level'. That's when you start fooling yourself. It's obviously vitally important to understand the volcano well enough to know that it's time to go from one level to another, but vitally important is not the same as being able to do it (HVO senior scientist 5).

What this implies is that scientists are spending a lot of time and effort trying to do something that is not possible. Given uncertainties about complex volcanic behaviour, this may seem an obvious observation yet, it is one of the most profound in supporting the idea that it really is difficult to manage complex situations using a linear process, and so far we have only reviewed the physical complexities and the uncertainties involved in making sense of the science.

6.1.3 Decision-making with scientific uncertainties

Scientific uncertainty remains a focal point for the scientists and the best way to try to establish the uncertainties is to generate discussion between the scientists so that all the different data, views and perspectives can be analysed. Between the scientists and users there is a dependency on communication and interaction when changing an alert level to consider what the risks involved are. In the light of significant uncertainties in scientific knowledge of volcanic behaviour and the complexity of the physical processes involved, the USGS essentially follows, unknowingly, a post-normal science (PNS) approach, involving open discussion between different groups of scientific expertise to try and maximise understanding of volcanic behaviour and to develop the best forecasts as possible. It can be said that in these circumstances 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1993, p.744). Although, however, there is often (but not always) an extended peer community of scientists, partner organisation experts, and external experts of a particular volcano during these discussions (as I witnessed at CVO), this expertise is still limited to that of the scientific community. Therefore, the expertise of the users is not considered, or that of local populations who may be highly sensitive to volcanic behaviour. This means that the discursive process is not completely reflective of PNS as it does not review the perspectives and values of each stakeholder (actors) through representation. Despite this, section 6.2 highlights that there is still consideration of users and their values when determining alert levels, and the amount and type of information issued by the volcano observatory.

Philosophical and sociological knowledge of scientific knowledge (SSK), as reviewed in chapter 2, highlight the difficulties involved in constructing knowledge relating to a volcano's activity, with aspects of inductivism, falsification, scientific values and conduct all playing a role in the quest to understand volcanic behaviour and processes, in addition to the unknown, or 'black swan'. SSK states that knowledge itself is socially conditioned, and this can be seen by the experiences and process by which the scientists make their decisions: lengthy discussions are conducted with several different scientific expert groups through deliberation and exploring the possibilities, trying to place the most rational explanations within contexts of high uncertainty and considering the risk of failure to provide appropriate warnings. These methods of debate have become institutionalised as formal procedures within the VHP where scientific knowledge is reviewed in context of wider society dynamics which, follows a SSK approach to decision-making as outlined by Martin et al. (1995b), where persuasiveness or networking abilities are used within the scientific community to discuss the possible options. However, in practice a positivist approach is used to close the debate and make a decision, since it is the scientist's expertise that is used, rather than 'group' expertise generated from collaborating with users.

6.2 Considering risk when assigning a volcano alert level

When the VALS was standardised, it was clearly stated in documents that the decision to assign an alert level should be based on the activity of the volcano, thus automatically excluding any consideration of the hazard or risk (Gardner and Guffanti, 2006). One could assume that volcanic activity is the only criterion for an alert level, yet, nearly every VHP interviewee discussed during their interview the role that risk plays in assigning an alert level, making the process less 'black and white' than many assume. This section reviews the scientists' consideration of risk when deciding an alert level, and highlights that negotiating between science, uncertainty and risk is one of the core decision-making processes that occurs within the VALS black box, not just by the scientists, but also by the users.

As described in chapter 4 and 5, local contingencies at each observatory and each volcano are important, affecting decision-making and the setting of alert levels. Often, scientists consider these contingencies, and their impact on risk by reviewing their users' needs and circumstances, institutional issues, and social, economic and political factors. A scientist at AVO described the compromise of balancing volcanic activity and risk in deciding alert levels as a 'dangerous game, as the job is to be aware of risk, but the job is really to provide a scientific basis [on which] to make decisions' (AVO collaborator 1). Most scientists acknowledged difficultly in not considering risk and hazards within their decision-making processes, since they are concerned for people's safety. Despite these concerns, there are differences between the scientists' perception of risk, for example, the level of potential risk may determine how conservative the scientists are when issuing an alert level. Whilst scientists seem comfortable generating forecasts, they have typically shied away from evaluations of risk, largely because they do not see themselves as experts in risk. Questions from users and the public like 'should I fly today', or 'how much ash can a ship ingest before it stops?' are seen as risk decisions. Most observatory scientists stated they felt uncomfortable in answering such questions and a scientist from AVO highlights why there is a dilemma in approaching these questions, which are nearly always asked:

> Those are risk decisions, and those aren't things that we as volcano scientists should be involved in. But it is always the question you get asked; should my kids go to school today? Should we not have school today? We play around the edges there and try […] to put the information in terms that allow people who are making decisions on risk to make informed decisions. But we have to be very clear, careful, not to slip into that realm […or you] end up in a place you shouldn't be as [you] don't know all the factors that affect these decisions (AVO scientist 3).

Despite discomfort in relation to dealing with risk, this remains a factor that is considered by the scientists when assigning alert levels or writing information statements. The influence of politics, economics, and institutional and user protocols will be discussed to demonstrate how they influence the decision to change an alert level. First, a scientist from CVO explains the influence of politics of assigning an alert level:

> Change in a colour code is not necessarily purely volcanic, it is also political [...] Sometimes a volcano can be 'burping' but not really affecting anybody, and in that respect we may not change the colour code. And other times when it is doing the exact same thing but a pilot saw and reported it, we would have to do something about it, so the politics is driving it a little bit. There has been speculation that sometimes people leave [alert levels] at slightly elevated levels so to have a bigger political profile at Washington D.C. I've never officially heard of that happen or not, but it could (CVO scientist 10).

Clearly political factors affect VALS operation, as demonstrated during the Long Valley crises during the 1980s to 1990s when the VALS were changed several times due to political pressures (Hill, 1998). There are also economic drivers. When an Orange or Red aviation alert level is issued, many airlines have procedures in place to reroute around the erupting volcano to avoid ash, but this requires extra fuel. This is expensive, from not only the cost of extra fuel, but also the additional weight of the fuel, which reduces energy efficiency (VHP user – VAAC). Aviation companies do not want to continue precautionary actions at great costs if unnecessary. Since there are economic repercussions if the SIC assigns aviation alert level Orange or Red, they want to make sure their decisions are defensible. This pressure can result in some erupting volcanoes not assigned as an Orange or Red alert level since it may not be considered to pose any significant risk for aviation users (AVO scientist 4). In addition, the decision to go to an Orange / Watch alert level is also not made lightly because according to VHP institutional protocols, it requires the observatory to go into 24-hour watch mode (except at HVO). This is a costly process because the observatory requires additional staff, and the normal functions are put on hold whilst they focus on the volcanic crisis. Economic influence is also relevant to ground based hazards, as emergency managers can align their response actions with specific alert levels, affecting a SIC's decision to assign particular alert levels (CVO senior scientist 2). Therefore a SIC may be hesitant about issuing a Watch alert level if they know that the response will be too drastic for the event, yet the emergency managers would comply with the established procedures. It is inherent that describing a change in the hazard infers there should be a response to that risk (CVO collaborator 1). Many scientists felt that whatever alert level is issued, it is less meaningful than how users have to respond therefore, the message accompanying an alert level change is tailored to each circumstance.

Subtle social factors can also can play on a SIC’s mind. For example, in 1997, at LVO following significant unrest, the SIC had to decide whether to change the alert level up to Yellow / Advisory; but there was a complication: ‘we knew that the ladies [skiing] downhill world cup was scheduled for Mammoth Mountain later that week or something, so these are the insidious kind of things that inevitably influence what you decide’ (LVO senior scientist 1). Although the SIC was close to raising the alert level they waited a few hours and the activity subsided. The downhill race was not key in the decision to not change the alert level per se, but it was a consideration because the potential media interest and consequences should the race be cancelled due to safety could have been devastating to Mammoth Lakes town if nothing had happened. On the contrary, if the activity had worsened, then the USGS would be blamed for not providing adequate warning.

All these examples illustrate the difficulties involved in making sound decisions and demonstrate that there is a negotiation occurring between the perceived risk by the scientists and the needs and capabilities of the local users. This makes the decision to change an alert level a fine line that the scientists have to balance between the science and risk. In contrast, a few scientists indicated that if an alert level needed to be at a certain level it would be set no matter what pressures there may be:

> If it needs to be at Orange, we are going to go to Orange, but we are not going to be flippant with it. We are just not going to cover ourselves by going to Orange, we are going to say, here is the criteria, here are the reasons, we are at Orange regardless of who, how it affects our users economically (AVO senior scientist 1).

The decision to change an alert level requires interpretation, analysis, discussion and action within a tight timeframe depending on the speed of the volcanic activity. At AVO, an eruption can be sudden, requiring a speedy change in alert level, and so the SIC may make that decision without much consultation or discussions with colleagues except for those who observed the monitoring data. In many cases, significant time is taken to consider the implications of assigning alert levels, rather than telling the concerned people the information as soon as possible. In some sense, this facilitates more negotiation between understanding the science, uncertainty and risks involved. However, some scientists argue that the danger of discussing which alert level to assign is that so much time is spent discussing that the information does not get out quickly enough, and this drains the resources of the scientists rather than freeing them up to keep an eye on the volcano's activity (discussed further in section 6.3).

If a scientist considers potential risks when deciding to change an alert level, then the decision is a compromise between the uncertainties of the volcanic system, and the risks involved in the local context and for the users. Often the scientists understand who and where vulnerable populations are, and can take into consideration the expected type of activity and hazard and how that will affect different areas, and over what time scale. For example, lahars are confined to valleys, but only a short warning notice can be generated. Although this information is communicated to the users, an understanding of the vulnerable populations and possible threats may influence the speed, or level of information provided to these groups. Therefore, whilst risk is not officially part of the warning decision-making process, it becomes an implicit component by shaping the urgency to change alert levels, whether the change of alert level is useful for users, how long to maintain alert levels, and what kind of information is issued with an alert level change.

Ultimately, risk is contingent on the location of the volcano and the vulnerability of the surrounding populations or infrastructure, much as the uncertainties of the volcano are contingent on that particular volcano and its historical behaviour. Therefore, the decision-making is dependent on local contexts. The consideration of local contexts, in both the science and social aspects, results in a number of feedback loops in the decision-making process that occur over time depending on the changing physical and social factors.

Managing the different elements of incertitude is clearly an issue that continues to challenge the scientists at the USGS volcano observatories. It has been paramount to establish that the decision made about which alert level to assign is influenced by the risks involved, which, in turn are influenced by the relevant social, political and economic factors. This decision-making process is subjective and a socially negotiated process of the circumstances (physical and social) by the scientists involved. The scientists interviewed argued that they do not have enough certainty or expertise to exercise judgement of alert levels based on risk, yet in practice the VALS are manipulated to help raise awareness and get the attention of users if the relationships between the them are not strong or frequent. The next section reviews the specific impact of this interaction with users when making decisions about what is going on, and how alert levels are established and acted upon.

6.3 Integrating scientists and users in the decision-making process

A key question emerges about who is the expert when providing a warning if risk is considered? Is it the scientist who understands the science and related uncertainties or is it the users who understand the local risks? There is a gap between these two sets of expertise that needs to be negotiated in order to make the warning effective. In a volcanic crisis there are plural values at stake so all relevant experts may usefully discuss together in a manner suggested by post-normal science so that all stakeholders represent their values; although during a crisis, in pressured circumstances, not all stakeholders may be available to contribute to these discussions. Yet, for legal reasons, the decision process between the scientists in assigning a VALS is based on activity at the volcano, and the decisions made by the users for the best appropriate action are kept separate. The following quote from an AVO scientist highlights the concern by scientists as to whether decision-makers will respond to alert levels by making the 'right' decision:

> The idea that what we say impacts the movement of other groups in their actions appropriately comes up, because a lot of us have an idea about we think those groups should do, but that may not be what they do do. […] We have to basically rely on them to make correct decisions (AVO scientist 7).

Therefore, it is clear that the division in decision-making is not as distinct in practice, as it is in theory. This section aims to review the gap between the scientists and users in making decisions based on alert levels to argue that in practice, responding to an alert level is far from clear-cut and is itself a close negotiation between many actors (scientists, users, and others) within the VALS that involves complex and adaptive feedback.

6.3.1 'Mind the Gap'

There is a clear dilemma in thinking between the scientists' desire to remain neutral and report on the scientific information only, which is their expertise, and the importance of providing information on hazard and risk information, which are regarded by many to be an essential component of providing an effective warning. A scientist at HVO described the gap between the decision-making capabilities of the scientists and users with a useful metaphor (HVO scientist 1). Between the two groups of actors is a line, and the distance between these two groups changes as they walk towards or away from the line. If the gap is narrow and the groups nearly meet at the line dividing them, then the groups involved are interacting and communicating well to try and close the gap of knowledge in decision-making. However, in some circumstances the gap is bigger, reducing the communication and interactions involved in decision-making. This can be due to a number of reasons including the limitation of knowledge by the users of the VALS, or even personality clashes. This creates a wide gap in how each group decides to use warning information, and the size of the gap changes over time as this HVO scientist describes:

> I have been doing this for so long, […] through so many transitions of both the mangers and SICs. They would have very different styles, so you see this gap getting wider and narrower and shifting around with things working better or not as well. It's tricky, it's a tricky business (HVO scientist 1).

All U.S. federal agencies take responsibility for their decisions and do not want to be accountable for mistakes. So what exactly is this gap? A scientist from HVO stated that 'the corollary with observatories issuing an alert level is that they know what the repercussions are of issuing them. The higher the alert level, the more action the public officials have to put pressure on the scientists, I don't think that is right' (HVO senior scientist 5). There is a divided view amongst the scientists as to how much they assist emergency mangers in making decisions for response actions. Clearly the legal remit lies with the users involved, not the USGS who are supposed to only advise on the sciences i.e. volcanic activity. But one could argue what is the point of telling people about the science, if they do not understand the implications: is this an effective warning? A VALS does not relay the uncertainties involved with the scientist's decision to assign an alert level. Some scientists stated that 'I don't think that we scientists should strive to make the jobs of public officials any easier, I think that we should tell them honestly what we don't know as well as what we know, they have tough choices to make and should not be spoon-fed' (HVO senior scientist 5). This quote highlights the struggle that the scientists have to provide a 'picture' of science being simple and straightforward to users, when in fact, as we will discover, many of the users are more than aware of the uncertainties. Tough choices have to be made, and these are choices that can be a matter of life or death, so it is essential for decision-makers to understand the uncertainties involved when they make their decisions.

6.3.2 The need to integrate different expertise

So why do users sometimes get 'spoon-fed' by scientists? First, scientists can provide confusing information in the face of large uncertainties. If scientists are uncertain about a volcano alert level assigned, they tend 'to run on a bit with descriptions and putting in qualifying statements' (CVO scientist 11). This can lead to confusion for the users, by providing a 'pre-digested sense of how concerned they need to be at the moment' (CVO scientist 11). In other words within information statements the scientists can provide strong indications as to the level of concern, in addition to the activity of the volcano. Second, users such as emergency managers typically deal with severe weather, fires, or car accidents on a frequent basis. Since volcanic activity is generally infrequent it is not something that emergency managers or other users such as land owners may be particularly aware of or have expertise in. In fact, some scientists relayed examples of decision-makers denying the existence of a volcano within their area of responsibility, making the provision of a warning challenging (CVO scientist 13). Even if decision-makers acknowledge the threat of volcanic hazards, few will have a good understanding of volcanology or the implications of different volcanic hazards, such as ash, or the possible risks that hazards pose (e.g. for asthmatic people). Therefore, there is a gap in the understanding of the hazards and the risks they pose by the scientists, and an understanding of the social risks involved by the users. Scientists have knowledge and experience not just of volcanology, but how hazards impact people. However, they do not know all the social risks involved, although they can process the most obvious ones, since as already reviewed in section 6.2, scientists consider some of these elements of risk in assigning an alert level. However, scientists do not always know the land, infrastructure, emergency resources, or social activities occurring at each vulnerable location at the time, which may impact the judgement of a user in taking action. Conversely, users do not necessarily understand the potential hazard, so there is also a gap in expertise between the scientists and users. To reduce this gap, a user may turn to the scientist for more guidance, as this scientist from HVO describes:

> If we are in a large population at risk, the geologists are going to be sweating bullets anyway because they are the ones that have to interpret the information for emergency managers, and they know that. For emergency managers, even though it's very much their decision what to do with those people at risk, it is not the scientists' decision, yet emergency managers will lean on you as hard as they can and they will come back and blame the scientists for whatever decisions are made. So the scientists are in the hot seat no matter what, and what we normally factor for is to just communicate and put out as plain and consistent a message as possible (HVO senior scientist 4).

The VHP scientists feel a moral obligation or responsibility to help as much as possible, as often users may not have had any experience with volcanoes at all, or even visited an active one before. Scientists often get asked off-the-record questions such as 'what would you do in this situation' and 'tell me what you really think' when assessing a change in volcano alert level or some new issuance of information (VHP manager 4 / CVO scientist 6).

> What the official wants is certainty, 'can you guys tell me what day and what hour it will erupt?' All we can do is tell them based on the information we have, 'this is probably what might happen, we can't give you a time window exactly' (VHP manager 4).

Difficulties in pinning down 'what, where and when' for volcanic activity or a hazard creates uncertainties that are difficult for users to manage (AVO user – NWS 1). Even though a user often appreciates the uncertainties involved, they still have to make a decision. Often probabilities or statistical tools to convey the uncertainties are seen as useful by the scientists if they put 'it into context without getting too mathematical for the officials that they can apprehend a little easier' (VHP manager 4). However, scientists are concerned that non-scientists may not understand probabilities very well, or know what to do with them. Rather than try and evaluate the information provided, many scientists have said that decision-makers react based on their judgements:

> In reality a lot of emergency managers probably say, 'ok, you are not supposed to tell us whether to evacuate but what would you do if you were living in this place?' So the line between us providing advice and them making decisions is, I don't think it is ever as quite an abrupt a line as we would like it be in an ideal circumstance (CVO scientist 6).

Users want to know with the best scientific information what the situation is likely to be. This places the scientists in a very difficult situation, as they are more than aware of the uncertainties involved and some of the potential risks. Many scientists said they did not like to be put in the position of providing their own judgement, in case they turned out to be wrong, but many users argued differently, as this aviation user at AVO stated:

> Whatever decision you make it will be better than your customer, because you will be making an educated guess and they don't have the educational background training that you [scientists] do. You need to make your best guess for them, and that is what we need these guys to do; don't worry too much about getting it to exact, just get your best guess out there, and be confident about it. If it is too 'wishy washy' we have to throw it out anyways (AVO user – NWS 2).

The high uncertainty, changing behaviour, and sometimes long durations involved in volcanic behaviour lead to another problem; changing alert levels regularly. The scientists feel it is important that alert levels do not yo-yo from one alert level to another, as they believe it will cause confusion between the users, and may possibly lead to an information overload for them. In contrast, users of VALS can be more sophisticated than the scientists give credit for, and many users (aviation in particular) would like to have a more sensitive VALS that yo-yo's more to reflect the current thinking about the activity. Most users expressed that they appreciate the challenges involved in changing alert levels but they want to obtain the information as quickly as possible so they can pass it onto their users (such as pilots), and changes in alert levels are an acceptable method to do this (AVO user – NWS 2 / VHP user – VAAC). So there seems to be a disconnect between what the users want (information, no matter how certain) and what the scientists provide to enable users to make the best decisions, and not unduly concern them. However, there may also be a disconnect between users' ideal, and the practical in these views.

Not only is there a gap in decision-making between the actors, but the size of the gap changes over time as events unfold and there is emerging clarity over the situation, as this scientist explains:

> Early on when unrest first begins, all you know is that something is happening, you don't have any idea where it is going to go, and it isn't until you get further and further into the episode of unrest where you can actually start to apply some windows, forecast windows, and for the highest level of certainty that forecast window is going to be short, right before the event (VHP manager 3).

Scientists are often unable to obtain any clarity about what a volcano is going to do until hours before it happens; unfortunately this is not useful from an emergency manager perspective. Such an impossibly narrow window is not helpful, yet that is the scientific reality. Therefore, more work is invested in providing specific warnings and additional information sources, as the picture of the volcano's activity becomes clearer with time using various different communication tools (see chapter 7).

VALS create additional problems as outlined by this user in the Cascades who described the process of reviewing the change of an alert level and the accompanying information with CVO scientists before they actually officially issue it:

> My biggest feedback to you is that this all takes time […]. Basically after the action in 2004, I said I thought that it was dangerous actually; that they got state emergency managers and people like x just sitting around deciding what the words [for the information statement] are going to say, and I said 'you know we need to call the Monument, and let them know. I don't care what it says we just need to know that something has changed'. To be sitting worrying about what the three sentences are is silly. […] There is this tension between wanting to have everything be just right and needing to get the word out (CVO user - USFS).

This process of over-deliberation is debilitating for this emergency manager, who feels the most important aspect of decision-making is to provide the information that something could happen as soon as possible so that those closest to the potential volcanic activity can make appropriate and timely decisions given their circumstances. In these cases, the precision of information is not the key factor. This raises questions about the efficiency of VALS and whether the process is overtly consumptive of time, providing little benefit to the scientists or users.

Generally, the scientists want to provide the media with information as soon as possible as the demand is huge, and there is a fear expressed by some scientists that if they do not provide the media with good information quickly, they may resort to other less trustworthy sources, as seen at Mt. St. Helens eruption in 1980 (Saarinen and Sell, 1985). Therefore, time is pressured when making decisions during rapidly changing volcanic activity or if there are vulnerable populations with significant interest in activity.

6.3.4 Closing the 'gap'

One of the greatest difficulties for the scientists is establishing and maintaining relationships with user agencies. Whether a scientist is better qualified than a user, given both their knowledge and experience, is difficult to establish but there is a case where users find it difficult to make decisions about a hazard they are unfamiliar with and do not necessarily have enough scientific knowledge to comprehend the implications of the warning provided. Therefore, it makes sense for the scientists and users to work together and combine their expertise, as the methods suggested by post-normal science encourage (Funtowicz and Ravetz, 1993). Developing protocols and coordination groups at the observatories has helped formalise the relationships between the two groups so they can discuss issues and learn about potential hazards prior to an event, so to be better prepared. Not all users can develop these relationships though, as they may be limited by available funding, time, resources or even stubborn characters. In these cases, the gap between the actors involved expands and is further exacerbated by a lack in clarity of the roles and capabilities of the different actors involved in managing a crisis. Whether it is possible to create a new position where someone acts as a mediator between the science and risk elements is questionable, but the USGS was not considering this for the future. Within the National Park Service, emergency management agencies and the National Forest Service, staff are constantly rotating or moving to gain new experiences and obtain promotions. This makes it hard for the scientists who have remained consistent over decades, to maintain the required relationships and make sure all user decision-making staff that may be affected by volcanic activity are adequately engaged with them.

Many interviewees, both scientists and users, argue that VALS provide a bridge for the gap in decision-making between the scientists and user groups:

> How do you make the bridge between the scientific data, to practical actions that the officials can take? Alert level systems are part of that, they are part of that bridge and it is something you make the transition with. It is where science and reality kinda meets the road (VHP manager 4).

But how can a VALS bridge this gap when it is just a semaphore system to signal information about volcanic activity and is unable to relay the complexities involved in reality such as the uncertainties and risks? If anything, the VALS makes the process far more complicated than it needs to be, as this Hawaiian scientists explains, reflecting perhaps on the U.S. culture's dependence on federal agencies:

> I feel like society has become too dependent on those land managers, and we have lost the resilience we once had with sensible thinking people, and that we want a colour, we want a wording, and we want those agencies to take care of everything. I think it is the wrong direction, I think people need to be reimbued with 'here is the information, make some logical decisions' (HVO scientist 2).

The gap between the decision-making of the scientists and users can be exacerbated by a lack in clarity of the roles and capabilities of each in managing a crisis. To some extent, there is already a vast amount of work done to prevent reliance on just the VALS by developing protocols and procedures such as a telephone 'call-down' to make sure users are aware of new information quickly, with information tailored to their needs. These protocols provide clarity of each actor's role and capabilities (discussed in chapter 7), but it is important to note that these additional products, outside of VALS, do play a role in decision-making and help the VHP fulfil the Stafford Act's requirements to provide a warning of potential volcanic activity.

6.4 How are decisions made within VALS in the context of complexity, uncertainty and risk?

Decision-making is at the very core of how VALS work. By focusing on this process it has been possible to open the black box of VALS and see how VALS work in practice. Decision-making is a complex process, in part the result of the complex physical and social systems involved, and the negotiation between science, uncertainty and risk that occurs when assigning an alert level or providing other information as guidance. Clearly scientific knowledge about volcanoes cannot just be ring-fenced, it is subject to influence by knowledge of the potential hazards and risks involved. However, this chapter has demonstrated that the design and structure of the

VALS itself presents further complexities. The rigidity of the alert level criteria generates discussion for the scientist about how and whether they should change an alert level or not, and if so, when. The uncertainties involved make this process even more complex, and on top of this there is a consideration of risk by the scientists in this decision-making process. Since VALS are unable to convey uncertainties and risks, a range of different procedures and protocols are used instead to communicate this information, demonstrating the limitations of VALS. VALS need to convey complexity because the hazards they manage are complex, but the VALS is a linear tool, unable to convey complexity, and subsequently creates additional problems in the decision-making process that are not necessary.

In practice, there is a breakdown in the boundaries of knowledge and expertise. A scientist or user is no longer a single expert in a volcanic crisis, so to make a warning effective, communication between them is required. This chapter has shown that 'recognising the social role of scientific uncertainty will help us to see how many of our problems about risk are deeply cultural and cannot be overcome simply by the application of more and better science' (Jamieson, 1996, p.43). Although, multi-directional communication with scientists and users is not part of the recognised VALS process, nearly all interviewees had been involved in negotiated decision-making between different expertise in crises. Communication between the scientists and users generates feedback between the two groups to negotiate the concerns of the scientists and the needs of the users, which may influence the decision to change alert levels or issue further information. Since decision-making processes involve a number of feedback loops, they do not fit in with the linear design structure of the VALS.

A VALS operates differently from how it is envisaged in theory. This is because scientists are aware of the threats of the hazard, the uncertainties involved, and the fact that there needs to be guidance for users, all of which are seen as part of adopting a precautionary approach. For situations like this, i.e. within post-normal science contexts, it is necessary to apply the precautionary principle which states that 'if there is a threat, which is uncertain, then some kind of action is mandatory' (Sandin, 1999, p.891). This fits in with the ideals of mode 2 knowledge and post-normal science that have led to transdisciplinarity, the management of uncertainty and extension of the peer community, participation and communicative rationality, and the precautionary principle. All these different approaches support communicative rationality; extended peer communities to include stakeholders in understanding their needs, requirements and values; and high uncertainties where risk is socially constructed, and the stakes are high (Haag and Kaupenjohann, 2001, p.54). Consequently 'all of these processes challenge the established authority and monopoly of science to define reality' (Haag and Kaupenjohann, 2001, p.57). This means that knowledge is socially contextualised so that reliable knowledge will be tested under concrete local circumstances (Nowotny, 1999). Scientific models have to be evaluated for the particular problems within decision-making processes, which are unique in each case. Unfortunately, standardisation does not provide this flexibility. When events cannot be predicted the local variables, and temporal and spatial contexts gain importance. Therefore, a 'multiplicity of endo-perspectives [internal perspective] thus obtains priority over a universal exo-perspective [external perspectives]' (Nowotny, 1996). This supports the idea that important factors to be considered, given the uncertainties, need to be by local stakeholders rather than on a national level by people external to what it going on. To be able to do this there is a need to develop transparency within the system to involve stakeholders to obtain mutual learning (Haag and Kaupenjohann, 2001). This is already happening within the black box of VALS via decision-making, negotiations and communication networks, discussed further in chapter 7. However, the rigid standardised VALS using four alert levels, as designed by the USGS, does not fit with this precautionary approach that is happening in practice, and is consequently making the warning process more difficult for the scientists and users, who are both already aware of their limitations in knowledge and expertise.

Chapter 7. The role of communication within the standardised volcano alert level system

The previous two chapters have demonstrated that communication is essential between the different actors within the volcano alert level systems (VALS) to manage the many complexities involved and aid effective decision-making. This chapter focuses specifically on the role and forms of communication, reflecting on the ability of the standardised VALS to communicate a warning to both local and global users. The essence of a warning is the provision of meaningful information from experts to those that need to act. The processes of communication, like those of decision-making, are iterative, with constant interaction and feedback between users, scientists, and other actors. For any warning to be successful, the people who need to act must understand the warning and make decisions to reduce the loss of life or economic impact of any volcanic hazard. Drawing predominantly on interviews conducted with users of the VALS and the literature on communication and expertise (discussed in chapter 2), this chapter argues two main points. First, it suggests that for VALS to be effective they need to incorporate local context into communication tools, decision-making processes, and the planning and development of the VALS. Second, the chapter argues that in practice VALS are a part of a broader communication network, a complex adaptive system, which has the flexibility to adapt to local contexts and the changing nature of the hazard, as well as the circumstances of the population. To do this, the chapter examines the importance of local contingency or context, and how this is accommodated and communicated within the standardised VALS.

7.1 Standardisation and the importance of the particular

Throughout the empirical chapters, there has been one key emerging theme: the role of local contingency when using a VALS in practice. Contingencies include the local culture; economic, political, and institutional issues; education, infrastructure and media to name a few. This section reviews the implications of local contingency on the ability of users to understand a warning, and the information that different users require.

7.1.1 Decoding warnings and the role of different expertise

The standardised VALS was developed with the aim of providing a universal warning to the range of users, so that once an alert level is issued, all users are able to understand it, no matter where they are from within the U.S. (see chapter 4). But, was this successful? There are both theoretical reasons and empirical evidence that suggest a standardised alert level system cannot have a singular meaning when users are both diverse and geographically distributed.

Empirically, research at the observatories, revealed numerous different interpretations of the meaning of VALS. One such example, recalled at both AVO and at HVO (HVO senior scientist 6, and AVO senior scientist 2), concerned a commercial Alaskan pilot flying from Alaska to Hawaii. The pilot, used to flying in Alaska and dealing with the aviation colour code frequently in place there, was concerned that the Kilauea volcano on the island of Hawaii was assigned an Orange alert level. Based on his experience with volcanoes in Alaska, he anticipated that the volcano would be exhibiting unrest with increased potential for eruption with ash. When the pilot arrived in Hawaiian airspace, he expected some form of diversion or information (such as a Volcanic Ash Advisory) regarding Kilauea, but received nothing and landed with no problems. He later discovered that Kilauea is erupting, but only emitting a small ash plume that prohibits low level flying within close proximity of the volcano. What he expected was based on his experience with volcanoes assigned alert level Orange in Alaska. Although alert level terms are standardised throughout the U.S., they mean different things to users, in different locations, demonstrating both flexibility and inconsistency in the meaning and interpretation of VALS by users. Often these interpretations build on an individual's local experiences and interactions with a VALS. In addition, the meanings of alert levels change between agencies. An Orange alert level does not affect the local VAAC or NWS in Hawaii as it does in Alaska. For the emergency services in Hawaii, an Orange / Watch alert level is meaningless due to the constant eruption of Kilauea yet, if the alert level for Long Valley caldera were raised to Yellow / Advisory this would trigger significant levels of response. Furthermore, locally developed VALS in place before the introduction of the standardised VALS may affect the meaning associated with each alert level.

Since the meaning of a VALS varies depending on the user, there is a need by users to have clarity over what the alert levels mean 'specifically', that is in their context, as by themselves the alert level 'can be vague' (LVO user – emergency manager 1). Users want to know why there was a change in alert level and seek further information that is specific; they are 'not just going to look at red and evacuate'. The following processes involved in decoding VALS (understanding a message) (Hall, 1980), highlight the importance of local context. First, scientists recognise the inescapable processes of interpretation and the importance of context in decoding, suggest 'it's impossible to have an alert level system where everybody […] is going to have the same understanding' (CVO senior scientist 2). Given its multiple and spatially distributed users, the interpretation of a standardised alert level will never be universal. Second, VALS are not a static tool, they change in purpose as the volcano goes from gearing up or down from an eruption, to during the eruption and its various phases of eruptive activity as it interchanges between a forecasting tool, to reporting the status of eruptive activity (Metzger et al., 1999). The message being encoded and decoded changes at different stages, thus both warning producer and receiver have to understand these temporal changes too. Third, there is a need for users to understand the characteristics of a volcano. An extended elevated alert level can become dangerous if no event occurs, as users tend to respond by thinking 'I don't need to be worried about it', particularly pilots, who may put the lives of passengers in danger if the volcano suddenly erupts, as per the Orange / Watch alert level (AVO user - FAA). Therefore, a number of users become more expert, learning about the history of the volcano and understanding what to watch out for so that once an alert level is issued they know how to respond (AVO user – NWS 2). Furthermore, scientists also acknowledge that they are able to communicate less information than they want. VALS do not reflect a number of volcanic hazards that can cause a lot of concern, therefore scientists have commented that the 'alert level itself is less important as to what they have to do in response to about it' (CVO scientist 6). What this means is that the users 'framework of knowledge' (Hall, 1980) may not be adequate to understand the warning, implying a disconnect in knowledge's between the different actors, as well as shifting patterns of expertise between scientists and users as they seek to redress these gaps. Finally, many users view alert levels as a form of 'calibration' for what they need to do, but as a user for Hawaii points out 'there is an intrinsic difference in a hazard that occurs every day versus somewhere like Mt. Rainier', where eruptions and activity occur every few hundred years (HVO scientist 1). All these issues illustrate that the standardised alert level is inserted into local systems where there are multiple users with differing levels of experience and expertise on volcanic hazards.

Given there is a need to integrate expertise on volcanic behaviour, with the expertise on how this activity may affect vulnerable populations and the environment (including critical infrastructure), it is clear there is no one expert involved. This was identified in chapter 6 as a 'gap' between the two groups. Users involved with VALS recognise that there is never going to be one expert who knows everything that needs to be known about a crisis; however with 'more experience, the more familiar you are' (HVO user - NPS), and over time, users are slowly becoming experts in understanding the volcanic knowledge they require to do their job. As Wynne et al. (1996) suggest, the role of expert, even in science, cannot be confined to the observatory scientists, particularly because they use the scientific information in different ways. Many users did suggest that 'the people in the science world must know, they must make an attempt to know of the response' that is needed (HVO user – emergency manager), presumably because they appreciate the influence this has on the decision-making of the alert level by the scientists (chapter 6). Therefore, it appears that all the involved actors work hard external to the VALS, to make sure that the decoding of a warning is accurate and meaningful. This is done through communicating with all the others involved using a number of communication products, and cooperating with one another via the coordination plans and meetings that give the opportunity for users to discuss what the hazards and potential risks are, and being prepared by developing a response plan, both of which are discussed further below.

From interviews with users, it has become apparent that they need clarity beyond that of an alert level to help them understand what the alert level means. An emergency manager in Hawaii stated that VALS cannot work alone as 'what is the good of all this if I don't have the follow up information on what to do when' (HVO user – emergency manager). The user needs additional information outside of the VALS to make a warning contextualised and therefore more effective. Emergency managers or those people in charge of making decisions about people's safety have difficult problems to deal with like 'should I evacuate or not?' (LVO user - emergency manager 1), 'where are people going to go / live?', 'will people actually pay attention or ignore the warnings?' (HVO user – emergency manager). The same emergency manager went on to state that 'I know this is insulting to scientists, but sometimes they don't listen very well, they are so entrenched with their science, but science is supposed to be for people, not science' (HVO user – emergency manager). Emergency managers need scientists to try to understand the problems they face and their situation and to help with their decision-making processes, and their limitations in knowledge. To address these issues, some locations hold 'desktop' simulation exercises where the scientists and emergency managers / stakeholders run through scenarios to establish what possible problems may emerge (CVO scientist 5).

The issues raised in this section of the disparity in meaning, expertise, and understanding of warning messages can be framed using theoretical exploration of the relationship between producers and consumers in any communication system. Here the point is made by reference to the theories introduced in chapter 2, but the conclusion is similar; what is intended by a communication is not necessarily what is received by audiences. As Hall (1980) explains, messages are both encoded and decoded, and there is no necessary correspondence between the processes of encoding and decoding. The prior empirical chapters focused on the processes involved in encoding a message, which incorporate the scientific and institutional commitments of the USGS within a VALS. This chapter demonstrates that the decoding of this message is equally important, returning to considerations of social risk and complexity. Hall (1980) draws attention to the importance of the social and institutional contexts for both producers and consumers, and their associated frameworks of knowledge, relations of production, and technical infrastructures. In theory, this suggests standardisation can only work if the hazards and local users are standardised too. Yet, in practice as one user suggests, ‘we are mixing up oranges and tangerines’ (HVO collaborator); currently an alert level at one volcano and used by a set of users may mean something quite different to another volcano and associated users.

7.1.2 Information requirements of the users

The legal mandate of the USGS is to provide a warning and make sure that the relevant people receive and understand it, but as the section above has indicated, this is not the only way the users of the VALS get the information they want. This section outlines what the users want from a VALS, and then reflects on how the standardisation has affected users’ ability to decode a message.

Prior to the standardisation of the VALS in 2006, users worked with the VALS relevant to their local volcano observatory. The initial rationale for developing VALS stemmed from the emergency managers in the Cascades during the 1980s. One of these emergency managers wanted the VALS to provide some scale of severity of information/warning:

> The scientific community is used to providing information and then having people react to that information. In the emergency response field, we are more attuned to reading that kind of information but at the end of it needing some guidance as to some sort of scale; how serious is this information you are providing us? So that was the difference, scientists were ‘capsulising ‘information on possible states of the volcano without really delineating on any kind of a scale how important this was; and first responders need that kind of references point, so that’s how we first began to talk about the alert levels (CVO user – emergency manager 1).

Interviews with users suggest that they regard the VALS as a scale to determine the importance of the information being distributed. This is in contradiction to the intention of the standardised VALS, which is to provide an indication of the eruptive activity of the volcano. Users tend to work in busy government agencies that are often already overwhelmed with other duties. For the users, VALS provide a method ‘to narrow our scope of view’ (VHP user - VAAC). With so many other duties, the alert level provides an important method of knowing which hazards are in a state of unrest and require more time and concentration in the course of other activities. In addition, VALS let the emergency managers know something is going on, as this emergency manager from the Cascades highlights:

> We need to prepare for something that could happen. When we get that first advisory we start dusting off plans because people do not read them every day, we get re-familiarised with the ‘what ifs’, that could happen and the lines of communication open up (CVO user – USFS 2)

Establishing the urgency of warning information is a key priority for the users to determine ‘where we are in terms of imminent danger’ (LVO user – Mammoth Lakes town 2). The VALS helps to ‘ramp up situational awareness’ that ‘dictates and drives our situation awareness and staffing’ (AVO user – NWS 3). So VALS not only provide information about the physical hazard, they are also used by the users for ‘planning purposes: what level we are at for planning; to determine whether open an Emergency Operation Centre (EOC) and start planning for an event’ (LVO user – emergency manager 1). Since U.S. emergency management protocols were standardised under the National Incident Management System (see chapter 4), all emergency managers are required to make the same preparatory decisions and follow standard protocols. For users, making sense of the VALS is just the first step to translating this warning into the subsequent stages of emergency planning, so instigating a whole new series of warnings encoded and decoded by other groups. The following emergency manager at the Cascades outlines the responsibilities of their job and provides an insight into how emergency managers conceptualise VALS as part of a chain or system of communications:

> For me as an emergency manager it [VALS] is a key tool in trying to arrive at public information statements and messages that we can give to the public that are understandable. And so it's got to be simple and understandable to us before we can craft a message that we then send to the public that they fully understand. [...] The key thing is not to create undue unnecessary panic in the messages, the public information statements that we send out, and to ensure that the messages coming from the scientific community are such that we can translate them for the elected officials, the public, whoever is going to use that information to make informed decisions as to what their actions should be, should they be faced with a threat (CVO user – emergency manager 2).

This quote highlights the responsibilities emergency managers and other users have during a crisis to protect the vulnerable public. In order to do this they need to understand the scientific information and warnings to make difficult but important decisions. Since it is important not to create any undue panic, there needs to be clarification between the scientists and users as to what precisely the risks are. The alert level is not decoded in isolation, but in consideration of scientists intentions in relation to potential public responses. Generally, if a user wants to know what is going on, then they are going to call directly the SIC or duty scientist (CVO user - USFS 1). In addition, whilst many of the emergency managers believe that the VALS are not really for public use, they are regarded as a useful 'yardstick that experts as well as general public can hopefully somewhat intuitively understand' (YVO collaborator).

For aviation clients, the issues are slightly different again: the high costs of diverting flight routes and carrying extra fuel for potential re-routing is unappealing, but equally they want to minimise the risks. Since pilots move at speed, they need relevant information quickly, in quite a different way than emergency managers on the ground as this scientist at LVO highlights:

> For ground response, [...] what is really important is that you have clear communication and understanding between the volcanologists and the officials responsible for emergency response. If you have that then the problem is solved, it really is. The aviation industry is different, the pilot is about to get into a plane, he looks through his NOTAMS and other sorts of guidance and warnings about hazards, be it weather or other things, and makes certain decision about how much fuel to load onboard, and talks to the dispatcher about routing. These things all have to happen fairly fast and they have to cover a range of hazards that might be spread over thousands of kilometres. It is a very different world. He is never likely to talk to a volcanologist, he has to have something simple and clear to react to (VHP manager 5).

As the previous chapter demonstrated, for the scientists, VALS are often a time consuming activity requiring discussion, deliberation and consensus building. The users of VALS, particularly of ground hazards, have expressed concern over the time lost during these discussions in getting what could be vital information to them. The users commonly portrayed VALS as a limited tool; and felt that if the scientists knew some information, but without any real certainty or clarity about what it means, it is still better to communicate this to the users as it is better to say something rather than ‘nothing at all’ (LVO scientist 2). The users regarded it ‘better to be ahead of the game rather than hide facts’ and consequently ‘not give very much warning time’ (LVO scientist 2). Unfortunately, a number of users felt that since the VALS is a formal expression under the USGS mandate to provide a warning, scientists are discouraged to issue alerts until there is greater certainty, which in turn puts pressure on the scientists to get the decision 'right' (AVO scientist 3). However, the users just want the information, and care little for formalities. Therefore, informal methods of warning and communication such as telephone calls are able to communicate information in a more interactive manner, especially if there is high uncertainty that is of interest to the users, without issuing any official warning information.

Although the standardisation committee took account of the requests by many users, a wide spectrum of users were not directly involved in the design process. Consequently, there appears to be a shortfall between what information the users want and what they actually get. Whilst in practice, elements of a post-normal science practice emerge from engaging with users during the standardisation process (Ravetz, 1999), a post-normal science approach is not as evident in the process of designing the standardised VALS. Yet, these extended peer communities seem even more important at the preplanning stage, where understanding local context and knowledge’s can provide enhancements to the design and use of VALS. During times of non-crisis, the actors involved can spend time deliberating plans and protocols, but during a crisis, they require information quickly, regardless of scientific uncertainties, and with more guidance on what the information means and how to act upon it.

7.2 Accommodating context and communicating a warning

The previous section outlined the importance of the particular when developing and communicating a warning. This section explores how local contexts and contingencies are communicated via the VALS and a number of other communication products that have developed outside the USGS. VALS are in essence a communication tool, but it has become clear that an alert level alone is not able to accommodate local contexts. For example by issuing ‘Orange / Watch’ it is not possible to know exactly what is going on at the volcano, or where or when activity or hazards may occur since the assigned descriptions for these levels are: ‘exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain’ or ‘eruption is underway but poses limited hazards’ (Gardner and Guffanti, 2006, p.2). To overcome these limitations, a number of communication products and protocols were established to provide more information and interaction for users to make sense of warnings in their own contexts. Consequently, many scientists and users regard VALS as providing a trigger point to initiate communication, as this scientist outlines:

> [An] alert level system is a shorthand, is the vehicle, it is the excuse to get into communications and dialogue, that gives you a justification and purpose […] that provides you the entry into having a discussion with very busy people who are otherwise occupied with other duties they have (VHP manager 4).

VALS can trigger a number of communication protocols and products (see below) that depend on the alert level, providing tools to alert different hierarchies of users, from the local level to the President of the U.S. The contexts of the users have influenced these products, as this scientist discusses:

> The aviation sector needs simple communication to make rapid decisions. On the ground first hand interaction with observatories is crucial. So as a result on the ground the uniform code is not that crucial in terms of guiding decision-making, but where it becomes more important is communicating the severity of the situation to Washington D.C., to the media, to the national and international public. That is where its real value is (VHP manager 5).

VALS are ‘some way of starting the communication process’ (CVO senior scientist 1), that also ‘help first responders to quickly grasp what is going on at the volcano and make rapid but informed decisions’ by providing a ‘shortcut towards long discussions with emergency managers’ (HVO senior scientist 5). Establishing communication products and protocols between the scientists and users also helps to establish contact, to maintain credibility, and to foster trust.

7.2.1 Communication products

As the Volcano Hazard Program (VHP) evolved throughout recent decades, as discussed in chapter 4, there has been an increase and diversification of users, and significant advances in technology in communications (i.e. the internet and mobile phones). Since the standardisation of the VALS a wide spectrum of communication products have developed, some also standardised, such as information statements, Volcano Activity Notices (VANs) and Volcano Observatory Notice for Aviation (VONAs), and the VHP website with alert levels assigned on a single map (see chapter 5). These products are uni-directional, in passing information from the scientists to the users as a final product. However, a majority of communication that occurs during a crisis is multi-directional, involving communication with several people, usually formalised via a number of protocols such as telephone call-down lists, and meetings between the relevant actors usually as part of a coordination plan, media talking points, and personal communication between the decision-makers. These two different types of communication products are reviewed in further depth to provide insights into how the VALS work in practice.

For the scientists, information statements provide a greater level of flexibility in communicating information than just issuing an alert level, although they follow a uni-directional format of information. Scientists tailor these messages to be relevant and of interest to the local users, however, these messages are still limited to text so there is no opportunity for dialogue or for users to add context. As a scientist states:

> I think info statements are really the key thing, I mean especially let’s look at Hawaii, the info statements about sulphur dioxide hazards and stuff like that brings a whole different thing that is not reflected in the alert level and that is what people need to be concerned about (VHP manager 6).

Together ‘the alert levels tell you how closely you should pay attention to the information statements’, and the information statement reassures the users and public that someone is ‘watching’ the volcano (CVO scientist 12). Information statements are ‘critical to explain what is happening and why’ but they are also the most ‘time consuming’ and ‘pressurised’ aspect of the warning (LVO senior scientist 1), since they need to be issued quickly. Since there is the strong desire by the scientists not to raise ‘undue alarm’, the decision to warn can become a ‘big time sink’ (LVO senior scientist 1). A scientist at CVO said that the rate in which the scientists ‘process and disseminate information is dependent of the alert level’ (CVO scientist 12) implying that at Red alert, information statements would be issued faster than at Yellow alert.

Therefore, the alert level issued provides a 'flag for users for how often the users should be looking for information' (CVO scientist 12). This implies that an alert level communicates a level of concern or sense of urgency. There is clearly a strong relationship between the VALS and the accompanying information statements, and many regard a VALS as a 'wrapper around the information statement' because it provides an instant way of identifying the importance of the information provided (HVO user - NPS). Therefore, an alert level without a message is unable to represent the complexities involved that relate to the volcanic crisis.

Although many users have become accustomed to the information statements they receive, including specific volcanic terminologies used, it is not always easy for the users to understand the information provided and they often have to 'keep reading the statements otherwise they are hard to make sense of' as this Hawaiian user states (HVO user - NPS). This is usually a consequence of technical information overwhelming the 'uninitiated geologist', although users do not have to understand everything to get the information they require (HVO user - NPS). Some users argued that 'to understand the colours [alert levels] you have to understand the paragraphs that the colours are based on, so why not give the paragraphs, why not give information?' (HVO senior scientist 5). This would give users the option of using the VALS if they wanted to, but not forcing it on them. In places like the Cascades where activity can be sporadic, emergency managers consider VALS as a useful tool to help gain their attention (as discussed in chapter 5). Therefore, where volcanic activity is infrequent, VALS play a more significant role in obtaining attention about new activity.

Differences in user groups also affect the type of information given in an information statement. A scientist said: 'I think from the words we put out with hazard notices or alert level changes; that is the real message, not necessarily the code itself, except for the aviation community' (VHP manager 6). For ground hazards there is a need to distinguish what is going on at the volcano and what potential hazards or activity may be occurring and where, but for the aviation sector they are only interested in just one aspect: is there ash in the air and where? The type of information these two user groups require is very different, which is why at AVO information statements have been standardised to form the VONAs and VANs that specifically accommodate each user's needs reflected in the two standardised VALS developed. VANs and VONAs have evolved as part of the standardisation process as reviewed in chapter 5 and the templates for each message is shown in Table 7.1. Originally developed at AVO, other VHP observatories are gradually adopting them.

AVO/USGS Volcanic Activity Notice (VAN)	(1) Volcano Observatory Notice For Aviation (VONA)
Volcano:	(2) Issued:
Current Volcano Alert Level:	(3) Volcano:
Previous Volcano Alert Level:	(4) Current Colour Code:
Current Aviation Colour Code:	(5) Previous Colour Code:
Previous Aviation Colour Code:	(6) Source:
Issued:	(7) Notice Number:
Source:	(8) Volcano Location:
Notice Number:	(9) Area:
Location:	(10) Summit Elevation:
Elevation:	(11) Volcanic Activity Summary:
Area:	(12) Volcanic cloud height:
Volcanic Activity Summary:	(13) Other volcanic cloud information:
Recent Observations:	(14) Remarks:
Remarks:	(15) Contacts:
Contacts:	(16) Next Notice:
Next Notice:	

Table 7.1 Details of a Volcanic Activity Notice (VAN) and a Volcano Observatory Notice For Aviation (VONA) (Observatory, 2010)

Since there is a complex relationship between the volcano, the social context, and the users involved in a volcanic crisis, different communication tools shape the way that VALS are encoded and decoded. Because this complex relationship is dependent on the crisis (what and when), VALS have in practice become locally adapted using a number of communication tools to make them useful to the key decision-makers and the local population, demonstrating the limitations in the standardised VALS and the creativity of local systems for circumnavigating this. To make encoding and decoding a message more effective, so that both groups understand the message and concerns of one another, local context is incorporated into a wide range of other more iterative communication processes, which are multi-directional.

Establishing contact to communicate effective warnings between the scientists and users is also essential and involves adopting multi-directional tools. During a crisis, each observatory follows a number of protocols, many of which are correlated to different alert levels, to facilitate these links. Once the scientist in charge makes the decision to change alert level or to issue new information, the first requirement is to do a call-down; a sequenced set of quick telephone calls to key agencies to notify them in person of the information, enabling 'discussion as to how you issue those levels' that is 'unique to that situation' (CVO scientist 13). For each observatory the sequence of the call-down is different depending on the users, 'who owns the land, the jurisdiction', the volcano's activity and the hazard characteristics (CVO scientist 13). Once the call-down is complete, an electronic form of the information is emailed to all the users, observatory mailing lists, and put on the website for the public to access, usually via a VAN / VONA. This whole process is incredibly fast, particularly following the introduction of the standardised message formats, which are set up as a database (primarily at AVO). It is through these processes that contact between the scientists and users is initially made, ensuring that those who really need to know the information are provided with this in person. In addition, the call-downs generate the opportunity for communication between the scientists and users, which may continue at greater length either by telephone or meeting in person to deal with the situation (discussed in section 7.2.2). This generates a personal feel to the message and facilitates multi-directional communication between both the encoders and decoders of the warning message to clarify the meaning and implications of the message.

Fostering trust is vital to make sure that once a crisis occurs, all actors are at least familiar with one another, and ideally have developed good relationships, so as to have enough mutual understanding to trust one another and the information provided. A number of users expressed the view that trying to get 'facts out of scientists' is difficult, but by 'building trust ahead of time' it was possible that they could trust each other and understand the others limitations, despite their institutionally 'different cultures' (CVO scientist 5). This requires a significant level of preparatory work and open communication commonly achieved by developing coordination plans between the volcano observatory and user agencies. The key purpose of this plan is to have 'recognised and standardised a system within an area of coverage, to promote communication of the hazard and management decisions' (CVO senior scientist 8). Plans such as these, have been implemented in Alaska, the Cascades, Mammoth Lakes and in Hawaii (Hill et al., 2002, Madden et al., 2008) and are vital to the success of communication because 'with the coordination plans, the communication is in place' (VHP manager 1). The plans are drawn up to provide background information about the volcano, its history and potential hazards, the different land owners, stakeholders and federal or state agencies involved with the land, and the plan for a crisis. The crisis plan typically outlines different roles and responsibilities of the different groups should a crisis happen, and are established following a number of meetings between the different actors, facilitating an opportunity to develop trust between the different actors involved.

Maintaining credibility is crucially important to the monitoring scientists. Without it, they fear, understandably, that users may not respond to warnings. The media and vulnerable populations may often request further information from the scientists, as seen by the overwhelming response to the Mt. St. Helens eruption, both in 1980 and 2004. Since the media are able to contact individual scientists rather than going through one central media representative at the observatory, it has been vital for scientists to develop ‘talking points’ about the crisis, so that all scientists give the same information, viewpoint and data (CVO manager). This reduces any confusion, prevents loss of credibility and generates a strong unified message from the observatory. Most users will only accept information relating to the crisis from the USGS, especially at HVO since it is the ‘only source that is responsible for hazard resources and identification. That is their job’ (HVO user - emergency manager). However, there are other academic scientists who may have different information relating to the crisis and if they do not collaborate with the observatory they can generate confusion within the media, which could be potentially dangerous. Users are equally wary of information from other so-called experts, who may have valid information but are not associated with the USGS. The observatory maintains credibility by following protocols to remain open 24 hours a day when at Orange / Watch alert levels or higher, providing the most up to date information for an on-going crisis (unless it is Kilauea under stable conditions, such as constantly erupting).

Users have differing capabilities and technologies to make sense of and act upon volcanic alerts. Communication has become more streamlined so that users can quickly access the information they need with the internet fast becoming a focal product for many users, especially at AVO where they are able to access live monitoring data themselves via the sophisticated public website. Although this is regarded by some scientists as dangerous, because you have 'non-experts' interpreting monitoring data, most users find it useful as it gives them a sense of ownership over the data and helps them identify with the difficulties the scientists have to face in interpreting the data (AVO - user NWS 2). One of the reasons this works particularly well at AVO may be because the agencies involved (mainly NWS, FAA, and VAAC) staff are used to looking at weather data and satellite images, which AVO also depends on strongly to identify ash at the remote volcanoes they monitor. In fact, one user stated that some of the users in Alaska ‘don’t want to know the code, they want to know what’s the data, what’s the monitoring data that is showing a change’ (AVO scientist 7). With improving technological capabilities, it will be interesting to see if the other observatories find internet tools as useful as AVO and their users have.

Interviews with numerous users have suggested that implementation of the standardised VALS at all the volcano observatories had little impact on the users. They are using protocols similar to those used before the standardised VALS, but with the new terminologies and using new standardised products, which may have occurred without the implementation of the standardised VALS. A user in Alaska stated that in many cases it is 'overkill' to change the system to a standardised VALS because what is in place seems to work well, and with modern technology providing many different ways to communicate, VALS may seem redundant (AVO scientist 7); they certainly were in Hawaii prior to the introduction of the standardised VALS, which previously consisted only of open communication.

7.2.2 Generating situational awareness

The existence of numerous communication products and tools indicate that observatories have to use them to make the VALS a meaningful tool to fulfil the user's needs. All actors involved in the VALS interviewed agreed that an alert level works well as a semaphore, but as a linear system it does not have the flexibility to communicate a full warning. Therefore, the large range of communication products and protocols provide compensation for this limitation, supporting it to prevent confusion and misinterpretation, and generate the desired response. Through open, multi-directional communication, the actors can develop mutual understanding that helps break down the boundaries that exist in both knowledge and expertise of each group, and their legal mandate, in order to make the best decision possible given the uncertainties involved and resources and capacity to respond in a crisis.

Only a few scientists defined VALS as 'a carefully crafted, consensus of appropriate communication, methods and communication protocols for describing the state of unrest at a volcano and depending on the acceptable laws of the culture, the reactions that should occur from that state of unrest' (CVO senior scientist 8). Feedback from all users showed that communication is the vital connection between all actors involved in the VALS. But, more than this, the relationships fostered during the communication of volcano information are a key aspect of the warning system. A scientist went as far to state that 'whatever system you have, as long as it is communicated to people, it is fine' (VHP manager 4). This implies that in practice, some of the users are not particular about the form of VALS used or its design. For users to manage the complexities involved in a VALS, communication over volcanic activity has to be multi-directional, open and discursive. This moves the understanding of how VALS work operate away from the focus on a single standardised alert level and towards the approaches suggested by post-normal science, in which deliberative processes bring together the expertise of scientists and users are encouraged, so that situational awareness can be generated.

Whether establishing contact, building trust or maintaining credibility, all these issues are addressed by having meetings, developing preparedness plans, and meeting frequently so as to get to know one another and generate some situational awareness between the different actors involved. In 2007, as part of this study, I attended such a meeting; the coordination team for the Mt. St. Helens Volcano Response Plan. During the meeting, it emerged that scientists were concerned that users tend to gear their response actions to specific alert levels, which consequently places pressure on the scientist when making the decision to assign an alert level (as discussed in chapter 6). Therefore, once the scientists communicate an alert level, the users know what to do as it is written into the plan, except it may be something unexpected. Consequently, there is a lot of 'situational awareness' that goes on around the volcano between the scientists and the users (CVO scientist 5), which also enables scientists to communicate to users 'so they [users] have some sense of our level of anxiety on escalating unrest on a volcano so they can understand the alert levels better' (LVO senior scientist 1). These coordination meetings provide the opportunity to clarify the nuances of the terms as understood by the users and scientists so each group are confident about what each alert level is likely to mean to each user for that specific volcano. All these activities follow the kinds of interactions suggested by a post-normal science, where different experts meet to establish and understand the complexities involved, much like advised in the Cynform model (Kurtz and Snowden, 2003).

Many of the communication tools used provide opportunities to educate different user groups about each other's roles and responsibilities, and learn more about volcanic activity and hazards. The observatory scientists work hard to educate users and the public about volcanic hazards and conduct many outreach and educational events to help prepare vulnerable populations against potential volcanic hazards. This long term preparatory approach is however, costly and time consuming, but rewarding by enabling risk communication (Fischhoff, 1995). Some scientists felt that obtaining people's attention during a crisis provides a more 'teachable moment where you can impart some information to them while you've got their attention, but the half-life of it is probably in terms of days or weeks' (CVO senior scientist 8). A key concern of the scientists is whether or not people will become complacent if there is a VALS in place; assuming they are safe because they will receive sufficient warning.

Communicating with the public can be a very powerful tool. In Hawaii, a scientist recalled an incident many years ago when scientists at HVO gave a talk to a local community telling them that following Kilauea's latest activity their community was highly likely to be overrun by lava. 'The strange thing was they applauded, they came up and talked to me and they said "we really appreciated it cause you treated us like grown-ups that can process the information, rather than just things to be told like what we are supposed to do like children" ' (HVO collaborator). This incident demonstrated that if you tell people what is going on using language they understand, people can understand and follow it. This openness stressed the importance of honest communication, whether good or bad news. It also indicates the importance of timing. Providing information in time for people to act on it is essential because during a crisis there is often little time to educate people and prevent panic reactions.

The media also plays an important role in educating and communicating to the public, but the alert levels themselves do not play a significant role as this journalist from a large newspaper in the Cascades details:

> It wasn't a big issue for the [x newspaper], because whatever the alert level is we're going to probably not get into that in depth, we are simply interested in what's happening at the mountain, what can you tell us about it, and we are interested in writing about it from more nuance point of view than just telling people an alert level and expecting them to know that some government agency ascribes to a level of risk (CVO user - media).

There is a need to learn from volcano crises around the world to prevent scientists and users repeating mistakes. Many scientists and users stressed the importance of the experiences of the VDAP team, and the need to access these experiences from this group of highly experienced scientists as 'these learning opportunities for people who have to face them [volcanic eruptions] are few and far between' (CVO user – emergency manager 3).

Although communication and trust are dependent on establishing coordination plans and effective interaction between all the actors, these factors are determined by the institutional and organisational contexts, time and resources available to the staff concerned, and staff remaining in their role for a number of years to provide a level of consistency. The role of the institution or organisation is critical in developing knowledge and protocols, as discussed by Vaughan (1999).

However, boundaries still exist between the institutional structures of the scientists and user's agencies or organisations, including their political agendas. To overcome these boundaries, policies / plans have been established using coordination meetings that facilitate communication between the different users.

7.3 Does the standardised VALS function effectively in communicating information about hazardous volcanic behaviour to a range of users?

The purpose of a VALS is to communicate and to aid the difficult decision-making processes that occur between the different actors. These actors have different values, institutional limitations and capacities, and operate within a context of uncertainty and unknown risk. In the course of this study, it has become clear that as these conditions change, whether it is the volcano's behaviour or social contexts, then the communication networks adapt to accommodate these changes. To some extent the communication between the actors becomes a self-organising process where protocols and procedure assist but do not necessarily dictate the frequency or type of communication that needs to occur. Whilst VALS are intended to be linear, in practice the process of issuing a volcanic warning is complex since there is multiplicity of legitimate perspectives, non-linearity, self-organisation, multiplicity of scales, and areas of continuing uncertainty. Therefore, the self-organising and adaptability of the communication networks provide the flexibility to accommodate the user's needs, requirements and capabilities in making decisions and communicating such information to their users. This is not achieved through the VALS. It seems reasonable to ask whether VALS fulfil their purpose of communicating warnings, or are they making this process more difficult by complicating the communication network? Or do they just act as a guide for concern or awareness?

It is because VALS operate within a number of complex systems, that it restricts the ability to integrate different experts, and investigate who is involved in decision-making and their measures of quality. Gallopin et al. (2001, p.226) state that 'knowledge in the sense of insight and understanding is absolutely not synonymous with capacity for prediction' and that 'equally, awareness of risks is not synonymous with capacity to intervene to reduce or control the risks', illustrating that there is a need for scientists to engage with other stakeholders in order to promote awareness and put into place plans to deal with potential volcanic hazards. This is something the USGS has been particularly successful at doing and demonstrates that when dealing with complexity in an open flexible fashion, is possible to effectively manage the complexities involved.

In order to manage the gaps between the science, uncertainty, and the risks posed in volcanic hazard warnings, multi-directional communication provides the key to facilitating open discussion between the scientists, users and other stakeholders or actors involved in the crisis. This communication occurs outside of the VALS because it is not a linear or top-down process. During a crisis, the communication that occurs becomes a complex network, or system, that generates feedback loops and enables the communication between the different actors to adapt and evolve as per the requirements of each of the actors involved. For every crisis, this system will be different, even if it is the same volcano, because the actors involved and the circumstances are constantly changing. By having a flexible and adaptive communications network, it is possible to accommodate the needs of the diverse range of users and varying hazards over time, unlike in the context of the VALS. Returning to communications theory, establishing open communication enables the producers and consumers of warnings to establish meaningful interpretations of the warning system, even if they are based in different contexts, rather than relying only on encoding and decoding the single alert level change. In addition, by using a standardised VALS, rather than one that is locally developed, it makes decoding even more complicated for the users. The wide scope of users with their own needs, geographies, and temporal relations to the hazard, makes decoding a generic message, such as a standardised alert level, challenging, hence the development of two different VALS to deal with ground and aviation based users.

This chapter has used information from both the scientists and the users of a VALS to conclude that in practice, the process of scientists generating a warning that is meaningful and useful to users, occurs as a sophisticated communication network. This network exists largely outside of the standardised VALS. Therefore, rather than conceptualising a VALS as the tool that communicates warning information, in practice VALS are only a small part of a very large and complex system of communication, already in place and working.

Chapter 8. Discussion and conclusions

This thesis sets out to understand better the volcano alert level system (VALS) concept and to evaluate how effective linear, standardised VALS are as warning tool for potentially hazardous volcanic behaviour, in the contexts of complexity, uncertainty and risk. Using the USGS, which standardised its VALS in 2006, as a case study, research conducted at the five Volcano Hazard Program (VHP) volcano observatories and at several user groups (U.S. federal agencies) during 2007 and 2008 has yielded data that has helped to answer the key research question. This study is important because there are increasing levels of standardisation nationally in both VALS and VEWS, as well as other natural hazard early warning system (EWS), globally. There is no known analytical study of the impact of standardisation on the ability for VALS and volcano early warning system (VEWS) to function effectively. Without this knowledge, it is not possible to establish what benefits or constraints standardisation can bring, and consequently policy-makers are unable to decide whether or not standardisation is appropriate for their jurisdiction, and if so, how best to standardise volcanic warnings to match their requirements. The UN endorses a globally comprehensive EWS, and therefore there is a concern that blindly following a current trend without understanding the full consequences may have severe repercussions. This study has provided the first investigation into VALS reviewing 'the first mile' in relation to how they work (unpacking the black box), reviewing the impact of standardisation, analysing them from an interdisciplinary perspective, and highlighting the importance of social science research and social contexts within the process.

8.1 Addressing the research aims

Through interviewing USGS and U.S. federal agency personnel, it has been possible to address the research aims and questions, using a large representative group, selected using the guidance of the scientist in charge at each volcano observatory. It is important to note, however, that the conclusions of this study only apply to the U.S. The country is a wealthy global power that adopts sophisticated emergency management practices and makes use of state-of-the-art scientific knowledge and technologies. Whilst the U.S. may not be representative of other nations that have to deal with volcanic hazards, notably those in the developing world, this thesis analyses arguably the most successful VALS in operation today. Therefore, it is possible to say with confidence, that given adequate funding, expertise and resources, the VALS addressed here provides an important benchmark for other VALS. It is likely that for developing countries, this same study would raise different issues such as lower levels of funding that result in limited monitoring capabilities, expertise, and resources for education and the communication of warnings. With less data on a volcano's activity uncertainties are likely to be higher, and with populations that may be difficult to access or communicate a warning, the risks involved may also be greater.

The field work conducted as part of this study provided the opportunity to observe how VALS work in practice and to obtain the views of USGS scientists on their interaction with the VALS both prior to, and post, the standardisation. An added advantage was gaining access to the users of the VALS to obtain some feedback on the application of VALS and the interactions between the different actors involved. Through interviews and ethnographic studies, it has been possible to address the three constituent research questions that each empirical chapter addressed. Throughout these chapters, the themes of managing complexity, decision-making, and communication recur, resulting from the problems of forecasting the hazard, the rigidity in the design of the VALS, the process of decision-making in issuing an alert level, and the standardisation of the VALS. These issues arise because of the difficult interactions between science, uncertainty and risk and the boundaries that are placed between them.

A review of relevant literature helped in understanding the constituent research questions from a theoretical standpoint, but the research conducted and presented in the empirical chapters provides a perspective based on actual application at the USGS. This next section summarises the main findings in the context of the three subsidiary questions introduced in chapter 1 and addressed in the empirically-focused chapters, before going on to provide an answer to the key research question and to relate the research findings to the body of literature analysed during this study.

1. **Why and with what implications did a <u>linear VALS</u> emerge as a tool for <u>managing complex</u> volcanic hazards?**

Chapter 5 reviewed the process of standardisation of the VALS at the USGS, viewing it as a socially constructed process, shaped by the demands of users and governmental policy developed following 9/11. The many complexities involved in VALS, such as the physical hazards and organisational issues, challenge the notion that a linear VALS can accommodate all these variabilities and complexities, despite the VALS already comprising of two different systems, one for ground hazards and the other for aviation hazards. This is possibly, why it took more time than expected to standardise. It is concluded, therefore, that a VALS is a limited tool since it is unable adequately to reflect the complexities involved. Consequently, it is proposed that VALS should be reconceptualised into a more flexible tool.

2. How are decisions made using the standardised VALS given contexts of complexity, uncertainty and risk?

Chapter 6 analysed the role of decision-making in VALS, showing that the complexities involved, both in relation to the volcanic behaviour and social contexts, lead to uncertainty, particularly scientific uncertainty. Because of these uncertainties decision-making becomes a difficult and subjective process. The data strongly indicate that scientists do not just assign alert levels based on the science or volcanic activity, but also consider the risks involved, which are dependent on the local social contexts. Establishing a sufficient body of knowledge and experience amongst the scientists and users of the VALS, so as to be able to make useful decisions that generate an effective warning, requires the actors involved to integrate closely to reduce the gaps between their respective levels of expertise and knowledge. Additionally it is identified that the standardised VALS in its linear form is actually complicating the warning process.

3. Does the standardised VALS function effectively in communicating information about hazardous volcanic behaviour to a range of users?

Chapter 7 demonstrated that communication is vitally important during the application of the VALS, enabling it to address the many complexities involved via a number of communication networks and protocols. In practice, the volcano warning system is an iterative, adaptive system that evolves like a complex adaptive system, facilitating the different actors involved to manage the volcanic crisis and establish the risks involved. This process is a negotiation within the communication networks that in practice work outside the standardised VALS framework. Consequently, it was concluded that the VALS are only a small part of a large communication network since a standardised VALS is limited in its ability to accommodate the important local contexts, local hazards, and local knowledge that has been identified throughout the empirical chapters. The real black box of the VALS is in fact, the nature and working of numerous communication processes and protocols that are already in place.

In summary, the empirical chapters concluded that standardisation is difficult to achieve for three reasons. Firstly, conceptually, natural hazard warning systems are complex and non-linear, and the VALS intervenes in an overall system characterised by emergent properties involved the interaction of many agents, for which forecasting and prediction are difficult. Secondly, pragmatically, the decision to move between alert levels is based upon more than volcanic activity and scientific data, with broader social and environmental risks playing a key role in changing alert levels. Thirdly, empirically, the geographical, social and political contexts of each volcano observatory results in the standardised VALS being applied in non-standard ways.

8.2 Research outcomes

From these findings it is possible to address the over-arching research question: **to what extent are standardised VALS an effective warning tool for volcanic hazards in different contexts of complexity, uncertainty and risk?** This section addresses this research question by first, reviewing whether the standardisation of the VALS works in practice; second, noting the fact that VALS cannot operate alone but only as part of a broader VEWS, and third, through evaluating whether or not VALS are useful tools, standardised or not, and if not, what could or does work?

8.2.1 Does standardisation of the USGS volcano alert level system work?

Given the pre-existence of separate VALS at three of the five observatories, and a different method of warning used in Hawaii, it is possible to review whether the standardisation of the VALS has proved to be an effective method for managing volcanic hazards as implemented at the USGS, by using the qualitative data presented.

It is difficult to establish precisely how effective the standardised VALS has been, primarily because it is a difficult metric to evaluate. For the aviation sector, it may be possible to determine how many aircraft may have avoided damage since the implementation of the standardised VALS, and how much this cost the aviation sector in flight diversions, although it is hard to obtain this data, since it is proprietary information held by the airline companies. However, the question remains; what metric do you use to evaluate the success of the standardised VALS? It is particularly hard to come up with such a metric when, in practice, the VALS are operated differently at each observatory:

> One of the main weaknesses is consistency and application across the observatories, we have not had enough practice yet among all the observatories to see how consistent we are; the answer is we are not, and how we going to get there? (AVO senior scientist 2)

This thesis has identified a number of advantages and disadvantages with respect to developing locally and nationally standardised VALS for local and national users, which are summarised in Table 8.1 below, so as to demonstrate the consistency and effectiveness of the standardised VALS. The three key categories reflect the information presented in the three empirical chapters.

Issues	**Locally developed VALS (individual USGS observatories)**	**Nationally Standardised VALS (new standardised system)**
Management	Local stakeholders develop close relationships	Streamlines communication within federal agencies, thereby reducing opportunities for confusion
Decision Making	Gears decision to local needs, circumstances and knowledge	Descriptions provide guidelines / criteria, but implications may vary
Communication	Provides flexibility for locally adapted warnings, consequently interpretation likely to be more effective	Provides familiar terminologies for use across different contexts, but associated meanings may be different

Table 8.1 This graphic compares pros and cons of local (left) and standardised (right) VALS.

Table 8.1 shows that there are benefits associated with both local and national systems. Using a local system provides greater flexibility to adapt to the local needs and integrate the VALS into the management processes of the crisis. However, local systems are becoming increasingly limited by nationally standardised disaster protocols such as the National Incident Management System (NIMS) and Common Alerting Protocol (CAP). Dependence on common terminology for each alert level may help streamline communications but equally can be misleading as a standardised VALS cannot provide specific information that a locally developed VALS can.

Limitations in the ability to provide diversity and pluralism suggest that there may not be enough flexibility in the design. It is clear that designing one standardised VALS (with two separate systems) to accommodate all the complexities involved is very difficult. The principle of 'one size fits all' does not apply to VALS; they need to adapt to reflect changes in volcanic behaviour and their impact on people, and this is better done when they are viewed from a holistic perspective to incorporate all the variables involved, many of which will be unknown prior to the crisis.

This study demonstrates that it is difficult for a VALS to be standardised, to maintain the benefits of a local system and, in addition, to be understood by users both local and global (e.g. aviators). This creates a problem as the more flexible a system becomes, the less standardised it is; this is the dichotomy of standardisation already identified in the standardisation literature (Fujimura, 1987). Although consistency is frequently identified as a key element of standardisation, in practice it does not seem to work. Currently the standardised VALS works around limitations in flexibility through the many communication products and networks developed between the scientists and the users. However, from the perspective of the USGS, most of the staff interviewed felt the standardised VALS has generally worked well resulting in a number of benefits, but also some drawbacks for the VHP team as outlined in Table 8.2.

Benefits	**Drawbacks**
Easy to use	The VALS cannot be tailored to local needs and local hazards, hence HVO uses an alert level system for SO_2 gas, and LVO could use one for CO_2 levels
Provides flexibility for staff to move from different observatories during a crisis to aid one another	The VALS has hardly been decoupled / split, and therefore it seems the purpose of having the two systems is redundant
Provides consistency across the organisation, which aids media and public response, also helps government and the president's office if there is a crisis	The VALS can be misinterpreted because of the double meanings in some of the levels and because users are used to what a particular alert level means within their local context

Table 8.2 Benefits and drawbacks of the use of the standardised VALS within the USGS

From a managerial or policy perspective, it could be argued that the standardised VALS works well in operation, since all the observatories use it to relay the status of volcanic activity, and no one has raised any serious concerns with its use (to the author's knowledge). However, this research has demonstrated that users develop different perceptions about what an alert level means, and that each volcano observatory has adapted the VALS to accommodate these different perceptions. There are significant cultural differences between Alaska, Hawaii, California and Washington States that affect the contextualisation of the VALS and the uses or role that they have. Therefore, it can argued that the standardised VALS is not actually standard as applied.

Yet there is a need for standardisation. There are a number of positive aspects of a standardised VALS that have already been identified for the USGS, users, policy makers and government to use. In addition, standardisation has made it easier for the aviation sector to use across the nation and territories, and for the emergency managers under standardised emergency procedures following the implementation of the NIMS. But there are limitations, for example tools such as national maps indicating alert levels for all volcanoes are useful but only reflect the volcano status, when in fact there are a lot of other associated hazards that could occur, posing significant threats.

The analysis of the standardisation of VALS, within the U.S. alone, highlights the complexities involved in using a national VALS, let alone an international one. There are more problems associated with ground hazard VALS, since populations and infrastructure are fixed and unable to avoid volcanic hazards unless areas are evacuated and critical infrastructure carefully planned. The volcano observatories have evolved in each location specifically to deal with the local aspects of the hazard, otherwise one could argue why is there not just one volcano observatory based in Menlo Park USGS Western Headquarters? In contrast, the aviation VALS is highly centralised and deals with users that are highly mobile and usually able to avoid ash hazards. Yet, even with the sophisticated and technologically advanced aviation sector, there have been real challenges in getting the ICAO aviation code adopted globally. It is still only used within the U.S. and, although on paper it has been accepted globally, in practice it has not been actively adopted outside of the U.S. Whether all countries will be pressured by ICAO in the future to comply remains to be seen, but such scales of policy implementation will generate some interesting questions. There is a unanimous agreement in the value of having a standardised VALS for the aviation sector by all interviewees, but this research suggests even this may have limitations, as subsequently seen during the Icelandic volcanic ash crisis in 2010.

It appears, therefore, that the ability of a VALS to satisfy local and global users needs remains problematical. The USGS case study highlights the fact that balancing the needs of local and global users when standardising a VALS is difficult and complex. From this insight alone it can be concluded that establishing a worldwide standardised VALS for ground hazards would only create further complications as there would be significantly larger differences in cultures, federal agency or civil defence management, and resources to manage volcanic crises. In addition, most volcano observatories already have VALS in place that their users know and understand, and which are designed to address local contexts.

The problems associated with the standardisation of VALS have been encountered many times within other contexts; complications in standardising procedures when the conditions they are operating in are changing (Fujimura, 1987), incorporating and extending old practices (Timmermans and Berg, 1997), fitting techniques to settings and methods (Knorr-Cetina et al., 1995), and defining boundaries about what should be left out of standardisation. Standardised practices may benefit policy makers but can lead to lower levels of compatibility and reduced standards (David and Greenstein, 1990). Most standardisation literature reviewed highlights the fact that there are levels of localisation for many standardised processes, and this is also revealed in the findings of this study, whereby local adaptations have evolved historically and continue to do so, despite implementation of the standardised VALS.

8.2.2 The need for an integrated volcano early warning system

Social contexts affect the use and success of VALS far more than previously acknowledged. There are still many scientific uncertainties within volcanology; scientists are continuously developing theories to understand the origin, processes and eruptive behaviour of volcanoes and the numerous associated hazards. However, this thesis indicates that it is not just scientific constraints involved in determining warnings, but also constraints from social and institutional contexts. Volcanic hazards become a problem in society because they generally occur on a longer time frame than political terms or human generations and therefore are not normally a priority. This generally results in limited funding and resources for monitoring volcanoes and conducting research on their past behaviours, and limited volcanic hazard awareness. From an institutional perspective, the wide ranging impact of volcanic hazards tends to result in the involvement of numerous institutions and agencies, and it is often difficult to maintain communication both within and external to each body involved. Increasing levels of bureaucracy and contending stakeholders mean that decisions can be complex and take a long time to make and implement. Decision-making is a highly pressured process, particularly for the scientists in charge and federal agency users who have a legal obligation to respond. To reduce this pressure emergency response plans are established prior to crisis to aid and generate communication and understanding; but this is not enough. Managing volcanic crises requires careful consideration and understanding of how to take action in the context of extreme uncertainty and complexity, both scientifically and socially. To do this successfully a VEWS should be fully integrated to cover everything from monitoring and detection, to analysis and interpretation of the data and understanding risk, to communication and generating an effective response. This requires planning, cooperation, the execution of drills, education, and discussion and communication, to name a few processes, between all actors so that during a crises effective decisions can be made quickly (see Fig. 8.1). VALS cannot operate without the foundation and support of a broader VEWS and it is possible to develop four key sub-systems, each one representing the complexities of a VEWS: the understanding and forecasting of volcanic hazards, volcano scientist management, volcanic crisis management, and the response (see Fig. 8.1). These sub-systems expand on those used by Mileti and Sorenson (1990), namely detection, management, and response, by distinguishing between management of the scientific activities and of the crisis, viewing each sub-system as a series of complex systems. Broader economic and social issues can limit or enhance the ability for the VALS and VEWS to fulfil its purpose. If the elements of a VEWS are in place, then a VALS is likely to function well. In reality, obtaining the staff, resources or funding to provide these capabilities are limited, for all agencies involved. To compensate, there needs to be feedback between the different groups and actors involved to make sure decisions are an iterative and collaborative process. Yet, all this activity occurs behind the scenes, and is not a formal part of VALS.

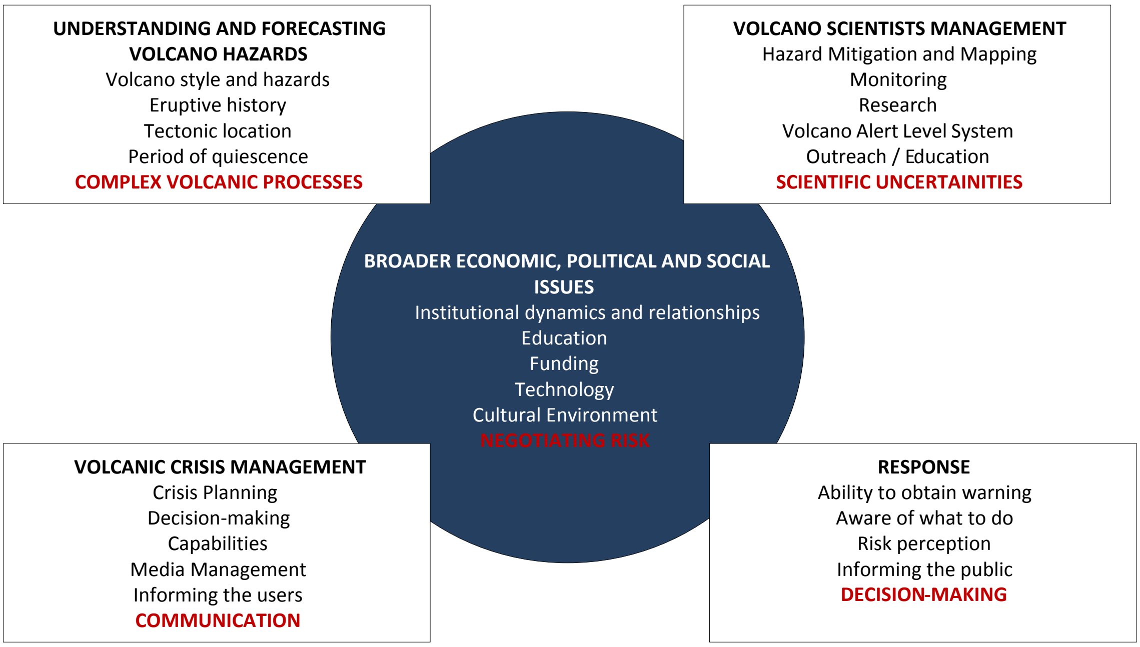

Figure 8.1 Model for how the volcano alert level system and volcano early warning system integrate

It is important to note that the sub-systems do not form a linear model, but are connected in such a manner as to influence one another in varying ways for every different context. The relationships between them are complex and this model aims only to raise awareness of the processes involved in EWS identified during this research. All of these sub-systems are part of the daily activities of the observatories, before, during, and after a crisis. Considering a VEWS as representing interactions between different complex systems consisting of different knowledge types and cultures of diverse user groups could provide some beneficial insights.

8.2.3 Are volcano alert level systems an effective warning tool?

The empirical chapters present not only the complexities involved in using a standardised VALS, but bring to attention the question of whether VALS are an effective tool to communicate volcanic hazards. This section explores whether VALS benefit or limit the warning process that the USGS has a mandate to fulfil.

Throughout the empirical chapters concerns are raised about using the standardised VALS. Yet chapter 4, which reviewed the VALS that existed prior to the standardisation, indicates there are some recurring problems. It seems that whichever VALS is used, similar questions arise, such as: what are the criteria for changing alert level? When is the decision made to change alert levels? How many alert levels should there be? Are colours or numbers better to use for the alert level? VALS old and new exclude many hazards and focus solely on the hazards on and within very close proximity of the volcano. Whilst it could be argued that the process of standardisation has helped raise awareness of different issues, it is clear that all VALS, standardised or not, have similar problems. The common theme is they are all linear tools managing complex situations, and although older VALS were designed for specific volcanoes or regions to address specific issues, they still have limitations.

The empirical chapters have demonstrated that VALS must be dynamic and adaptive in order to reflect the complexities involved. As circumstances change a VALS should be able to re-establish its normal state and have capacity to self-organise and self-stabilise, which may be difficult for institutions to accommodate. The current standardised USGS VALS, however, is unable to adapt to changes due to its linear design. If the descriptions of the alert levels were more flexible, it might be possible to develop a system that could reflect complexity as required. However, it is not just the design that is limited; as a crisis unfolds a VALS needs to evolve since it initially provides an indication of potential volcanic activity based on uncertainty, but once the volcano approaches eruption it transforms to a forecast tool, and once the volcano is in eruption the VALS is based on higher levels of certainty. Therefore, the VALS should adapt to these changes, or focus on a single specific function.

The most difficult aspect of a VALS involves coming to a decision about which alert level is most appropriate to assign. This decision is difficult because although it is supposed to be made solely on the basis of the volcano's behaviour, the associated hazards and their potential impact on society is also considered, as is the local culture, risk perception, and the political situation, amongst many others already discussed. Therefore, within this decision-making process there is a feedback loop, creating a circular causal relationship between the outputs and inputs, which helps to explain why it is so difficult for scientists to make decisions on alert levels. It is not possible to map the many different inputs and outputs involved in decision-making, or communication, or of the impact of the volcano, society or environment on the process, thereby indicating this is a complex system.

The standardised VALS now used by the USGS appears overcomplicated given that the idea of the system is simply to obtain attention. Valuable time is spent on deciding alert levels rather than initiating the necessary contacts to pass on written statements of scientific information. By establishing fixed descriptive criteria for each alert level, the VALS becomes a linear process, and therefore is unable to capture the complexities involved or to reflect any adaptation that occurs and express that in a suitable manner. The scientists have to negotiate complex phenomena with high levels of uncertainty and differing levels of potential risk. This exerts pressure to get the alert level right, making it very difficult to define the boundaries of each alert level. A certain element of 'gut feeling' is required and this is not reflected in the current VALS. In summary, the implication is that VALS are not sufficient, in their own right, to communicate the complexities involved in a volcanic crisis.

So why have a VALS at all if they are complicating the communication of potentially hazardous volcanic behaviour, which is occurring in any case via the complex communication networks that operate outside of the VALS? At HVO no VALS existed prior to the standardised version, and communication was, and still is, made directly between the scientists and users on a daily to weekly basis as required. Whilst this is appropriate for a constantly active volcano such Kilauea, it may not be appropriate for infrequently erupting volcanoes where, if a volcano became active, the close communication between the scientists and users is likely to take significant amounts of time to develop. Therefore there is an argument that in practice, a VALS is a communication initiation tool; an instrument to develop coordination plans, and provide a general awareness about the state of the volcano rather than about a specific hazard. This is most important in locations that do not deal with volcanic hazards frequently. If this communication occurs regularly then it may be surplus to requirement, as seen in Hawaii, although even here it might be of value to flag unexpected events. Users must communicate what information they need, and establish what to do in time of crisis. Effective outreach and education are the keys to this success, for both the decision-makers and the vulnerable public. A VALS therefore works a lot like a coat stand; it provides a frame from which to hang various protocols. If these protocols are in place (i.e. communication, coordination plans, education and outreach as identified in Fig. 8.1) then the VALS has completed its function and is surplus to requirements. However, if all the protocols are not in place then the VALS will still be needed to provide a framework to help communicate warnings. VALS could therefore be reconceptualised as a framework, rather than as a linear system. This raises the question of whether or not it should be the protocols that are standardised.

8.2.4 Hazard awareness levels

This study has shown that VALS are complex systems that are adaptive, have emergent properties and are self-organising. Rather than using linear models there may be more merit in applying models based on complexity to manage the complexities involved in issuing volcanic warnings. Approaches outlined by post-normal science (Ravetz, 1999) and the Cyneform model (Kurtz and Snowden, 2003) that are more deliberative and explore the values and knowledge required by the scientists and users, could help provide a more effective warning system with greater flexibility that encourages more stakeholder involvement. This research reveals that VALS currently exclude a number of processes within the communication network that are fundamental to the operationalisation of VALS. Therefore, it is the communication network that has been black boxed. The communication networks already exists, but it is not part of the linear VALS with four alert levels. Therefore, by removing the formality of the linear VALS it would enable the communication networks to operate more effectively as a flexible system that can manage the complexities involved.

Most interviewees expressed the notion that it was imperative that alert levels be accompanied with the appropriate information (i.e. information statement) since the VALS currently only represent the status of the volcano. So the key component of the warning, from the standpoint of scientists and users alike, is the detailed information issued that is adapted for the specific situation. So why have a description or meaning associated with the alert level when all it is trying to do is to raise awareness, to get people's attention? When a user gets a warning, they want to know how severe it is and how much attention they need to pay to it. This led to the idea that VALS need to reflect the awareness that users should have of the information being issued which can relate to the volcano (dormant or active) and the many associated hazards. It could be possible to establish a volcano awareness system, where a traffic light colour system indicates the level of awareness needed for the particular situation. This means that it could be tailored to any situation and any potentially hazardous volcanic behaviour, and would be, therefore far more flexible. It also encourages discussion as to what awareness is needed so that users can make decisions based on speedy information (even if uncertain), and the scientists can focus on providing this information and interpreting the science. Such an awareness system could potentially be standardised throughout the U.S. yet be locally operated and adapted for the local hazards and needs, and reflect temporal changes effectively. Nationally, an awareness level would indicate the level of awareness at each volcano and therefore the severity of a hazard such as a lahar, ash, or gas emissions. This way the system is able to be truly flexible, whilst maintaining the required broader government and congressional mandates. By removing the alert level descriptions and the focus on the eruptive activity only, it essentially frees the whole system to do its job, enabling the system to express awareness about the complex and different hazards and situations with less confusion in a simple design. Colours are selected rather than the NWS terms because they are more intuitive, as the data has indicated, and can be used by many different users without the association of probabilities and meteorological hazards that NWS imply.

Awareness Level	Meaning
Red	Urgent
Orange	Important
Green	Of Interest

Table 8.3 An example of what a hazard awareness system could look like

Currently VALS try to bridge the gap between the physical and social sciences using a simple linear tool. In fact, it is integration that is required. Awareness levels require discussion and consultation between scientists and the users, which already occurs, and enhance the broader integrated VEWS, making more transparent the decision-making and communication processes that already occur outside of the current VALS. So instead of trying to 'police' the gap between science and risk, they try and integrate it

.

It is also important to note that whilst large volcanic eruptions gain the attention of the media, many people who live around active volcanoes in the U.S. are affected by hazards that persist over long periods, such as noxious gases (e.g. Long Valley caldera), and low-level seismicity (e.g. Long Valley, Yellowstone, and Hawaii). It is such ever-present hazards that are not captured in the VALS that could provide most discomfort to local populations. An awareness system would additionally help accommodate these short to medium term changes.

8.2.5 Recommendations for volcano alert level system guidelines

Whether hazard awareness alert levels are tested and developed or VALS in their current form remain the standard, the lessons learnt as a result of this research could play a part in developing guidelines and suggested practices. It is possible to establish some common guidelines for the best practice in VALS. This could be reviewed and adopted by an International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) committee to distribute globally and aid monitoring scientists and users around the world in establishing their own VALS /

VEWS, or evaluating the effectiveness of their own system. The aim would not be to develop rigid frameworks for users, but to enable them to make more informed decisions when reviewing how to best manage hazard complexity within policy and in practice, based upon experiences, and lessons learned, at other volcanoes and observatories. Some provisional guidelines developed from this study are listed below, based on what has been effective for the USGS:

1) Have a VALS in place *prior* to a crisis
2) Design a VALS that can be easily used and be locally effective: no more than 3 or 4 levels and keep the design simple
3) Provide a clear description of what each alert level means or outline the role of each level
4) Organise coordination planning meetings so that stakeholders communicate face to face, develop relationships, and update the plan frequently
5) Provide educational and training opportunities aimed at key actors including drills and desktop exercises to understand one another's limitations and practices
6) Communicate a change in VALS by issuing a standardised report that provides details about what has happened i.e. information statement.

These recommendations reflect lessons learned within the U.S. In order to develop these guidelines for international use, further studies of comparable VALS in other developed and developing countries would provide invaluable input with respect to the importance of different economic and social circumstances. It would also be useful to evaluate whether or not there are if there any aspects of a VALS or VEWS that are shown to be most critical in providing effective warnings, so that countries with limited funding for VALS can focus their resources.

8.3 Contributions to theoretical frameworks

This chapter has reviewed the value of the research findings and their practical implications, but these findings can also be applied within a theoretical framework as outlined in the literature review. The conclusions drawn link back to the UN's review of EWS (UN ISDR PPEW, 2006). This study has demonstrated that although the role of science in EWS is important, it is not the element that is causing frequent failures in EWS. Gaps in the EWS have been identified by conceptualising VEWS as a series of complex-sub-systems that are connected by complex linking systems that bring these sub-systems together. These linking processes include aspects highlighted in Fig. 8.1, such as communication, decision-making, and negotiating risk that are, in themselves, complex issues. In addition, this study has shown the importance of local context in EWS. It is hoped this study can provide feedback to the UN's recommendations for EWS, and encourage further research into understanding how EWS operate in practice by comparing different case studies, as accomplished in this study through comparing the application of one system in five different locations.

This study has also highlighted the subjectivity of scientists when interpreting scientific data, and the limitations of their knowledge. Although models exist to provide statistical and theoretical frameworks in order to better understand volcanic processes or to aid in decision-making (Aspinall et al., 2006b, Sparks and Aspinall, 2004, Marzocchi et al., 2007), the complexities and uncertainties involved result in socially constructed knowledge. Integrating further insights from the sociology of scientific knowledge may help improve understanding of how scientists can, in practical terms, cope better with scientific uncertainties and the manufacture of knowledge within their own observatory, or even paradigm (Knorr-Cetina, 1981).

The difficulties of dealing with uncertainties, risk, ambiguities and ignorance are an integral part of understanding volcanic data and managing volcanic crises. In the literature review, Table 2.1 on p.77 provided an overview of all the different studies of these individual components, that Stirling regards as comprising 'incertitude' (Stirling, 2003). There is a need to understand better how incertitude can be considered in a more holistic way, enabling more consideration to the local context of not just scientists, but also of the users of the VALS. Research at the USGS has indicated that the scientists recognise risk is a social construct, and is not something easily quantifiable, hence they do not rely on the many risk models available (Newhall and Hoblitt, 2002, Marzocchi and Woo, 2007). In addition, risks are reviewed as 'reflective' in the way that Beck refers to in his 'Risk Society' (1992). This is because first, the decisions made during volcanic crises impact upon whether or not there is a risk, and second, successful land-use planning and coordination can help reduce the risk of populations to hazardous volcanic behaviour. Therefore, Beck's ‘Risk Society’ may have value when trying to understand how to better manage natural hazard risks.

There is a need to make sure that when warning information is encoded by the scientists, that users are able to usefully decode it so as to make the decisions they need to make as effectively as possible (Hall, 1980). This is made difficult by the different contexts of each actor involved in the VALS, and their individual and institutional knowledge's and values. It is possible to overcome the difficulties of pluralistic expertise and different values held between scientists, users and other stakeholders (including the public) by adopting approaches such as post-normal science, which intend to bring these groups together to develop a broader understanding that may be beneficial, helping to close the gap of knowledge between scientists and users (Ravetz, 2005). Methods commonly used within social science, such as deliberation and multi-criteria mapping, may help provide further levels of integration, beyond those already achieved between the USGS and their users (Burgess et al., 2007, Stirling, 1999). This could be implemented using progressive policy.

There is a clear dichotomy between bottom-up (locally adapted methods) and top-down approaches (government policy) which need to be integrated, but how can such a compromise be achieved? This research is unable to establish any solutions, other than suggesting the use of hazard awareness levels, but the standardisation of VALS has created a linear tool that is trying to manage complex issues, rather than using more flexible deliberative tools, which are increasingly being used to address complex problems such as health issues and climate change. There is growing momentum for a shift in the way that science is viewed, building on different levels of expertise and the realisation that science is a social construction that needs to be open to debate and discussion (Wynne, 1996). Given the wide range of volcanic eruption styles and hazards, the USGS is in the fortunate position of being able to learn from the range of volcanic crises within the U.S. and abroad through the VDAP team. Taking ideas from the social science literature it may be possible to reconceptualise VALS as a complex adaptive system of communication networks.

Standardisation is a tool used within policy development that aims to close down and simplify complex issues (Stirling, 2008). This study has shown that the simplification of the VALS has been difficult to achieve in practice because a number of other tools and systems have developed around the VALS to make it work, rather than questioning whether the system was fundamentally workable. This research however, has shown that VALS provide an important starting point for discussion between the different stakeholders in a VEWS, that facilitates an 'opening up' of complex issues. There is a need to open up rather than close down policy development of VALS that will facilitate approaches such as that of post-normal science. Opening up EWS policy for volcanoes encourages a precautionary approach, so that locations with infrequent volcanic activity can prepare for a crisis. This approach is adopted by the

USGS, but recognising it as a precautionary approach may help reconceptualise the role of VALS. Studies on the application of the precautionary principle to other complex, uncertain situations such as climate change, may provide insights into how VEWS and VALS could be more effective (Kriebel et al., 2001). Applying the framework outlined by Stirling in Fig. 2.12 (see p.86) would help articulate precaution and risk assessment in relation to a volcanic crisis (Stirling, 2007, p.313). The framework provides a method of determining whether precautionary appraisal, deliberative processes or risk assessment is needed to deal with the problem, providing a tool to evaluate the process, manage it and communicate it. Frameworks like this could be extremely valuable when looking at how best to provide warnings in a volcanic crisis.

The role of the organisation or institution in a VALS and VEWS has been somewhat overlooked within volcano literature. An institution's cultural approach to its work shapes the way that decisions are made and how the organisation communicates with other institutions (Vaughan, 1999). In addition, institutions have emergent effects in the way that complex information is transmitted between themselves and others, adding to the already complex systems operating during a volcanic crisis. This study has shown, however, that the cooperation and coordination required to make VEWS successful, as identified by Peterson and Tilling, is in practice critical (Peterson et al., 1993). The USGS have learnt from mistakes made in volcanic crises throughout the world, for example by adopting media 'talking points' so all scientists provide the same information, and therefore help maintain credibility and trust. One possible way to help facilitate scientific information into effective warnings decisions is to reorganise institutional practices to follow a mode 2 approach of science, which is context-driven, problem-focused and interdisciplinary (Gibbons, 1994).

Finally, this work supports the recent, but sparsely-numbered studies that demonstrate that complexity theory can provide a useful analytical or conceptual framework in disasters studies, and in particular, for warning systems (Paraskevas, 2006, Ramalingam et al., 2008). Reconceptualising EWS not as a linear system or a system full of feedback loops, but as a complex adaptive system that has to adapt to the changing nature of the complex systems within the EWS, enables a more open, transparent and comprehensive warning system, that embraces uncertainties and emergent properties, thereby changing the expectations of users, policy makers and the publics. As Wynne (1996) implies from his research, these groups are most likely fully capable of dealing with these complex factors. It seems somewhat regressive to think that science is a truth that is static and certain. By embracing science as a complex, uncertain and ever-changing body of knowledge, freedom is provided for users of this information to understand its limitations and determine, as a consequence, the risks involved.

In summary, this research contributes to the growing literature within the field of disaster management that deals with complexity; highlighting the difficulties encountered in adopting standardisation as a tool to manage the complexities associated with potentially hazardous volcanic behaviour, and demonstrating the need to accommodate social issues and local context in decision-making. By developing awareness levels and establishing guidelines for VALS it may be possible to make transparent the processes that are currently black boxed and fundamental to the effective operation of a VALS. This research suggests that the UN's drive to create a global platform for early warning systems across hazards requires further consideration since first, there are too many cultural issues between regions let alone countries; second, warning systems are locally adapted; third, there are many complexities involved in one hazard so making it a multi-hazard platform seems a further simplification of complex issues; and finally, there needs to be a review in the development of more holistic and effective methods in managing complexity where top-down and bottom-up approaches can work together in a constructive manner. It is also important to develop further knowledge about the processes that link sub-systems between VEWS and review how to better manage uncertainty and the considerations of risk in VEWS. It is possible that the sub-systems and suggested links between them, proposed in Fig. 8.1, could provide a form of basic criteria in evaluating VEWS, by providing a check-list of desired issues i.e. developing institutional dynamics and relationships. However, this research cannot determine which of these issues is more critical than others; additionally this model was developed in relation to VEWS and VALS in U.S. alone. Research of these systems in a developing country may identify different sub-systems and linking processes, although it is anticipated they would be similar, since many of the processes seem fundamental regardless of funding levels, monitoring capabilities, or technology.

In addition, this research has presented a different methodology for analysing large quantities of interview recordings within a multi-sited ethnography, using mind mapping. This method reflects the need to develop new ways of synthesising large quantities of qualitative data so as to understand interrelating issues that cut across many different contexts, in this example VALS, within different volcano observatories.

Notwithstanding the issues raised and the problems identified as a consequence of this study, it is unlikely the USGS will change the standardised VALS in the short term. Many scientists and users felt that after putting so much time and effort into the standardisation process, it was unlikely to change radically, if at all, in the near future. Some felt, however, that it would be worth revisiting in five years time, so as to evaluate how the effectively the systems was working, assuming the occurrence of one of more volcanic crises in the U.S. over this period. Most scientists agreed that VALS would also need to be reviewed by the various users to obtain feedback about how useful it is for them, how they are using them, and any problems they are having. The VALS system is likely to continue to evolve in the future as it has done in the past.

8.4 Recommendations for future work

This research has provided a foundation upon which a number of future research projects may be built. One such project could focus on the evaluation of VEWS within a developing country, in order to identify any differences in the operation of VALS and VEWS compared with the U.S. A developing country with a wide range of volcano observatories across different cultural regions, for example, the Philippines or Indonesia, could host informative comparative studies.

One of the most tangible products of this and future research could be the development of comprehensive guidance and guidelines in relation to VEWS and VALS, outlining best practices and the advantages and disadvantages of different aspects of VEWS and VALS so that those implementing or designing these systems are able to make more informed decisions and maximise relevance to local circumstances.

Another key area of exploration is to test the viability of hazard awareness levels or other complexity model approaches in order to provide a more flexible approach to VALS and hazard communication. This would involve a shift in the way a VALS works, and requires full evaluation by all actors to determine whether or not they can operate in practice and be more useful than the traditional linear formed VALS.

One of the more problematical issues addressed in this study has been the need to combine local requirements with those of a national government. It is suggested, therefore, that future research might focus on how early warning and disaster management policy may be better integrated so as to usefully incorporate both top-down and bottom-up approaches that can negotiate the different scales of needs better. It might be possible that the hazard awareness levels proposed in this thesis could provide the link. There is also a need to develop understanding of the processes that link different sub-systems within VEWS, so that they can be designed to be more effective. In addition, adopting a framework for articulating precaution and risk assessment (Stirling, 2007) within a disaster context may have some value and warrants further investigation.

In conclusion, this study demonstrates that the success of any VEWS and VALS lies in effective communication between the different actors to manage the complexities involved and to facilitate informed decisions. As demonstrated by the 2010 Eyjafjallajökull ash crisis, there are limitations to just how much standardisation is possible and desirable within VEWS and VALS, whilst at the same time retaining local meaning and contexts that ultimately appear to be critical in making warnings effective.

Appendix A: Interview structure

OVERVIEW

A: Introduction and Ethics Form

Individual Scene Setting

- Involvement with VALS
- What role does VALS play in work
- Their definition, and understanding of the purpose of VALS

To provide a context for the next section: Wish to review the changing nature of VALS given USGS new VALS. Is this something that has played a key role in your work?

B: What is your understanding of the process of standardisation coming about?

- When?
- Who – who was consulted? How consensus achieved? What roles were played?
- What –weather system?
- Why?
- Where?
- What was your involvement?

C: Implications

- What are protocols now? Procedures?
- How adopted within the organisation?
- What are implications for you and the others within the organisation
- What are implications for the users of the VALS?
- Problems (e.g. adoption of technology)

D: Uncertainty and Meaning

- Are the alert levels defined by specific criteria? If so what?
- How does the decision making work?
- How is uncertainty and risk factored in?

E: Ask for two examples

Talk through an example of how VALS work

a) Before standardisation

b) After

Provide prompts that link to theory: communication, roles, risk / uncertainty, knowledge / science

F: Opening out: to talk about change and future

- How far has your practice re VALS changed? For others?
- Where do you see the new VALS going now?
- What future challenges?
- What future opportunities?
- If you were going to standardise what would you have done?

Appendix A: Detailed interview schedule

A: Introduction and Ethics Form

Before we start, I've a few admin issues...hand over ethics review leaflet.

- Firstly, hope it is okay to digitally **record**.
- Second I need you to **sign something** to say you consent to this interview – all pretty straightforward – mention **data archive**
- **Summary of interview**: This interview aims to review how the VALS standardisation came to about, and what your experiences are of using it now.

The interview will take approximately one to one and a half hours.

Individual Scene Setting

I would like to start asking a few questions about your personal interactions with VALS…

- What has been your involvement with VALS?
- What role does has VALS played in your work?
- What is your definition, and understanding of the purpose of VALS?

I am interested in reviewing how the new VALS standardisation came about and the changing nature of VALS given USGS new volcano alert notification system. Is this something that has played a key role in your work?

B: What is your understanding of the process of standardisation coming about?

I would like to understand the process of standardisation by reviewing firstly what the driving forces of change were, and then how the new system came about.

1) What were the driving forces of change?

- **When** was standardisation first discussed, when did it actually change? *Try to develop a chronology*
- **What** was seen as the problem with the previous VALS in place?
- **Why** was standardisation selected as a tool to cope with volcanic hazard communication?

- **Who** wanted to make the change?
  Who implemented the changes and were these people involved in the decision making, and how were they selected?
  Were other actors involved in this process such as the end users i.e. EM, the media, public etc.?

2) How did the new system come about?

- **What** was seen as the best solution and why?
  Were other systems considered?
  What were the considerations – scientific, political, technological?
  How was it designed?
  What assumptions were made during standardisation?
  How was flexibility considered?

- **Who** was consulted?
  How was consensus achieved?
  What roles were played?

- **Where** were discussions held physically?
  Where within the hierarchy of the organisation?
  Were there pressures within the organization for such changes?

- **How** can the old and the new work together – for VALS and also technology / knowledge specific
- **What** were the problems encountered when discussing standardisation?
  What were identified as problems the new VALS would present? *Between roles, communication between stakeholders*

C: Implications

I would now like to understand the implications of the new VALS within the USGS (or agency), and if there were any problems?

- What are the protocols now? *What happened, who and how?*
  How have procedures changed?

- How has the VALS been adopted within the organisation?
  How far has your practice re VALS changed? For others within the organisation?
  How has the VALS affected use and compatibility within the different observatories?
  What are implications for other users of the VALS?

- What do you consider as the main changes in adopting the VALS *(e.g. adoption of technology, good or bad?)*
  Are the procedures and the language used more effective for users now? How can you test this?
  Has the new VALS improved early warning capacity and practice?
  Are people safer as a result?

D: Uncertainty and Meaning

One of the things that interest me is the management of risk and uncertainty within a standardised VALS.

- Are the alert levels defined by specific criteria?
  If so what are they?
  Are the criteria different for each volcano / observatory? What do they mean?
  Are the warnings a forecast or to provide current information?

- How does the decision making process work?
  Is the accuracy of the warning and ease of assigning a level dependent on the availability and quality of data?
  Has NVEWS helped to provide more accurate alerts?
  Do different observatories have different approached to decision making? *i.e. cultural issues*

- How is uncertainty and risk factored into the VALS?
  Is there flexibility within the current system to cope with uncertainties? Does it
    - Accommodate the various sizes, styles and durations of volcanic activity i.e. *hazards, ability to forecast*
    - Work equally well during escalating and deescalating activity
    - Be equally useful to both those on the ground and those in aviation
    - Retain and improve effective existing alert-notification protocols

  What new risks do you think the new VALS now poses to ability to provide an effective warning?

E: Ask for two examples

I would like to understand how VALS work in practice and your experiences using them, could you talk me through a brief example of how VALS worked before the standardisation, and now with the new VALS?
Provide prompts that link to theory: communication, roles, risk / uncertainty, knowledge / science

F: Opening out: to talk about change and future

In the last section of the interview I would like to discuss your thoughts relating to changes

- Where do you see the new VALS going now?
- Where else has the system been used?
- What do you think future challenges are?
- If you were going to standardise what would you have done?

G: Thanks, closing questions / feedback

- Is there anything which I haven't talked about which you would like to mention?
- Any recommendations for further people to talk to?
- Any final questions?
- Thank you for your time!

Appendix B: Ethics form

Projects participants

I am keen to involve a wide range of relevant views in this research project including discussions with a wide range of USGS Volcano Hazard Program staff, partner organisation staff, and emergency managers. Approximately forty interviews will be conducted over the five observatories and related organisations.

The research will involve interviews about how people experience and manage volcano alert level systems as part of their day to day roles, and to reflect on why and how standardisation occurred; no further specialist knowledge is required. Interviews are likely to take around 60 minutes and take place at your place of work, unless you would prefer another venue. Research data will be treated confidentially and what you say will be fully anonymised (for further information see *Promise to Participants*).

RESEARCH USERS

Activities and outputs of value to users in academic and policy communities will include:

- Academic publications in international refereed journals
- A web site disseminating results, executive summary, academic publications and other relevant links
- Presentations at international and national conferences

Refining the value of this research for participants and developing appropriate and useful outputs for users are important to me. Please do not hesitate to get in touch with further suggestions.

Personal Details

My name is Carina Fearnley, and I am a second year PhD student at Benfield UCL Hazard Research Centre, in the Department of Earth Sciences, UCL.

My research interests are focused on volcano early warning systems and understanding the standardisation processes that are occurring both within the USGS and globally. This study encompasses the disciplines of volcanology, science and technology studies, science communication, disaster management, and uncertainty.

I have been an active participant of the UK Science and Policy Interface for Disaster Reduction (SPIDER) network that reviews the gap between the physical and social sciences within volcanology.

Some recent publications include:

Barclay, J., Haynes, K., Mitchell, T., Solana, C., Teeuw, R., Darnell, A., Crosweller, H. S., Cole, P., Pyle, D., Lowe, C. J., Fearnley, C., Kelman, I., Framing volcanic risk communication within disaster risk reduction: finding ways for the social and physical sciences to work together. Special publication for Journal of the Geological Society (London) 2008. In Review

FEARNLEY, C., DAVIES, G., McGUIRE, W., TWIGG, J., 'Volcano Alert Notification Systems (VANS); opening the Black Box', Volcanic and Magmatic Studies Group Winter Meeting, January 2008 (abstract)

FEARNLEY, C., DAVIES, G., McGUIRE, W., TWIGG, J., 'Developing an Alternative Conceptual and Methodological Approach to Interpreting and Utilizing Volcanic Forecasting within Early Warning Systems', Cities on Volcanoes 5, Shimabara, Japan, November 2007 (abstract)

FEARNLEY, C., DAVIES, G., McGUIRE, W., TWIGG, J., 'Understanding Volcano Early Warning Systems' SPIDER Network Meeting, University of Coventry, England, March 2007 (abstract)

ESRC / ESRC Interdisciplinary Funded Studentship:

The Standardisation of Volcano Alert Level Systems

This research explores the issues associated with the recent standardisation of Volcano Alert Level Systems within the volcano hazard program of the USGS. Yet whilst this process is increasingly adopted by other countries, there is little understanding of the experiences of standardisation for volcano observatories and its impact on the ability to provide an effective warning to different groups.

The research seeks to establish:

- Why the volcano alert level system was standardised?
- How was it standardised, and what was changed within the volcano alert level system?
- For whom has standardisation benefitted?

And to explore:

- The experiences of standardisation for observatories and its impact on the ability to provide an effective warning to users.
- The influence of standardisation on the technology, practices and knowledge's of the volcano observatory

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Web: www.es.ucl.ac.uk/people/fearnley

Projects details

Volcano Alert Systems (VALS) have been adopted in many volcanically-active countries as a form of communication between scientists and other stakeholders, designed to ensure the safety of the at-risk population and minimisation of economic impact, through definition of the level of potential danger from volcano hazards.

A number of volcano crises have highlighted weaknesses within the VALS prior to and during the announcement of an alert level, yet there is minimal understanding of the operation of the processes involved in issuing alerts. VALS, in their current form, must therefore be regarded as 'black boxes'. Better understanding of this 'black box' should aid the development of robust VALS in different geographical, institutional and cultural contexts.

In recent years a number of volcano alert level systems have become standardised for different volcano hazards or styles of volcanic activity. Using insights into the process of standardisation from the sociology of scientific knowledge, this research argues that the motivations for, and experiences of, standardisation, may be used as a way to open up and understand the processes influencing the operation of a VALS and to reflect on its implications.

Prior to standardisation, VALS may have been locally based, focusing on an individual volcano or area and incorporating some aspects of the local society and culture, thereby serving the needs and understanding of the vulnerable population. Standardisation involves complex drivers that have the potential to reveal the cultural, institutional and scientific priorities influencing the construction of the VALS.

Web: www.es.ucl.ac.uk/people/fearnley

Promise to participants

This research project has been developed with reference to the ESRC Research Ethics Framework, the UK 1998 Data Protection Act and codes of conduct developed by the British Sociological Society. These guidelines are designed to protect all participants in a research project.

My promise to research participants includes the below:

- All participants will be **fully informed** about the nature of the research.
- **Written consent** will be obtained from all participants prior to the conduct of any interviews.
- All participants are **free to withdraw** from the study at any time without penalty.
- Permission will be requested from participants to record discussions using a digital voice recorder.
- All transcripts will be made **anonymous**, by removing names and identifying characteristics for individuals and organisations, unless otherwise agreed.
- A copy of your interview transcript will be provided on request.
- **If a** specialist transcription service will be used to produce transcripts for this research, a confidentiality agreement will be signed.
- All data will be collected and stored securely in accordance with the **UK Data Protection Act 1998**.
- The anonymised results of the research will be used for **academic publications and policy reports only**. These will be posted on the project website and as hard copies to participants on request.
- The ESRC requests that researchers consider making their anonymised data available to the UK Data Archive (http://www.data-archive.ac.uk/). This will be discussed with individuals.

You are welcome to raise any other issues or concerns with me.

Research agreement

Thank you very much for considering taking part in this research. Prior to carrying out interviews I am required to obtain the written consent of the participants. I would be grateful if you could fill in and sign the declaration below.

Name:

Role:

Email: (optional)

I can confirm that:

1. I have read and understood this project information leaflet
2. I have had the opportunity to request further information about this research project
3. I agree to take part in this research project

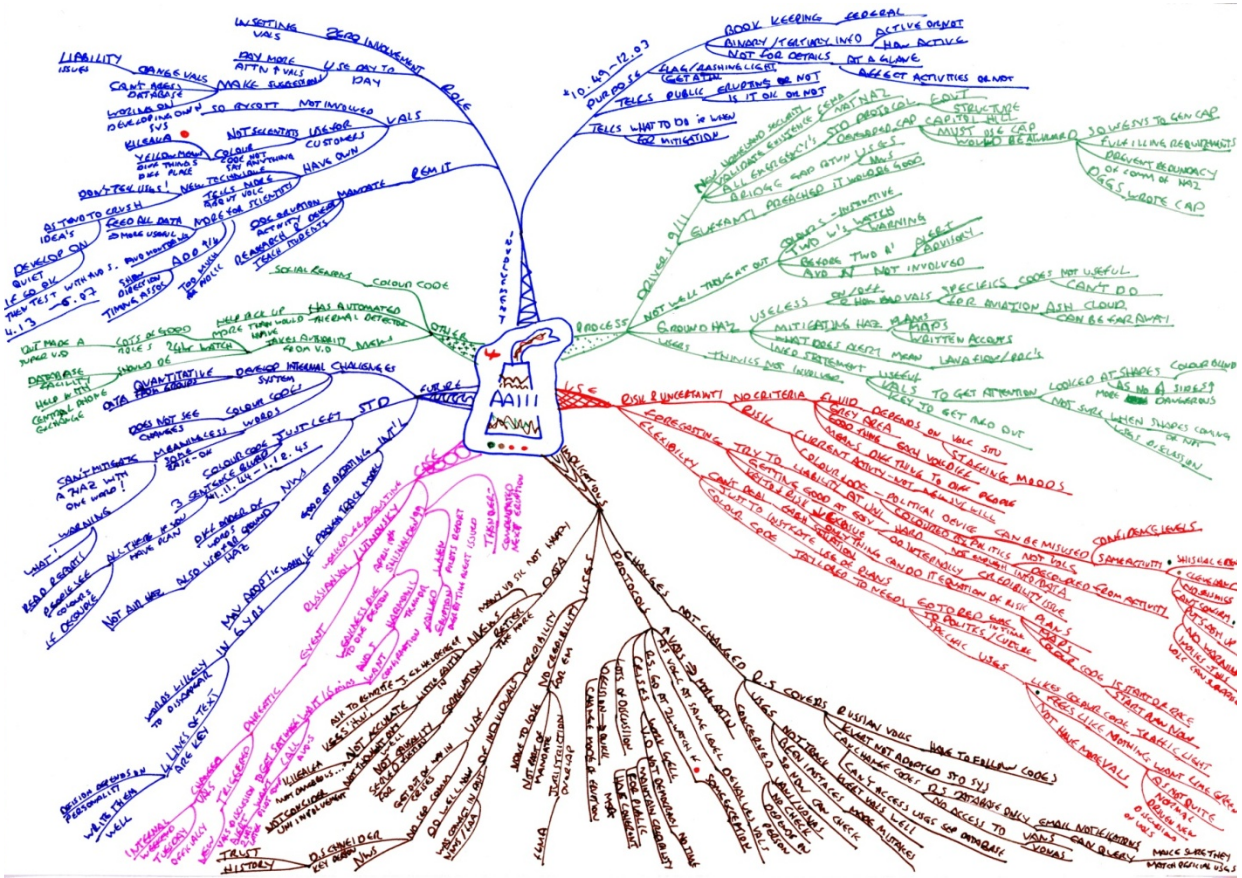
Please delete as appropriate:

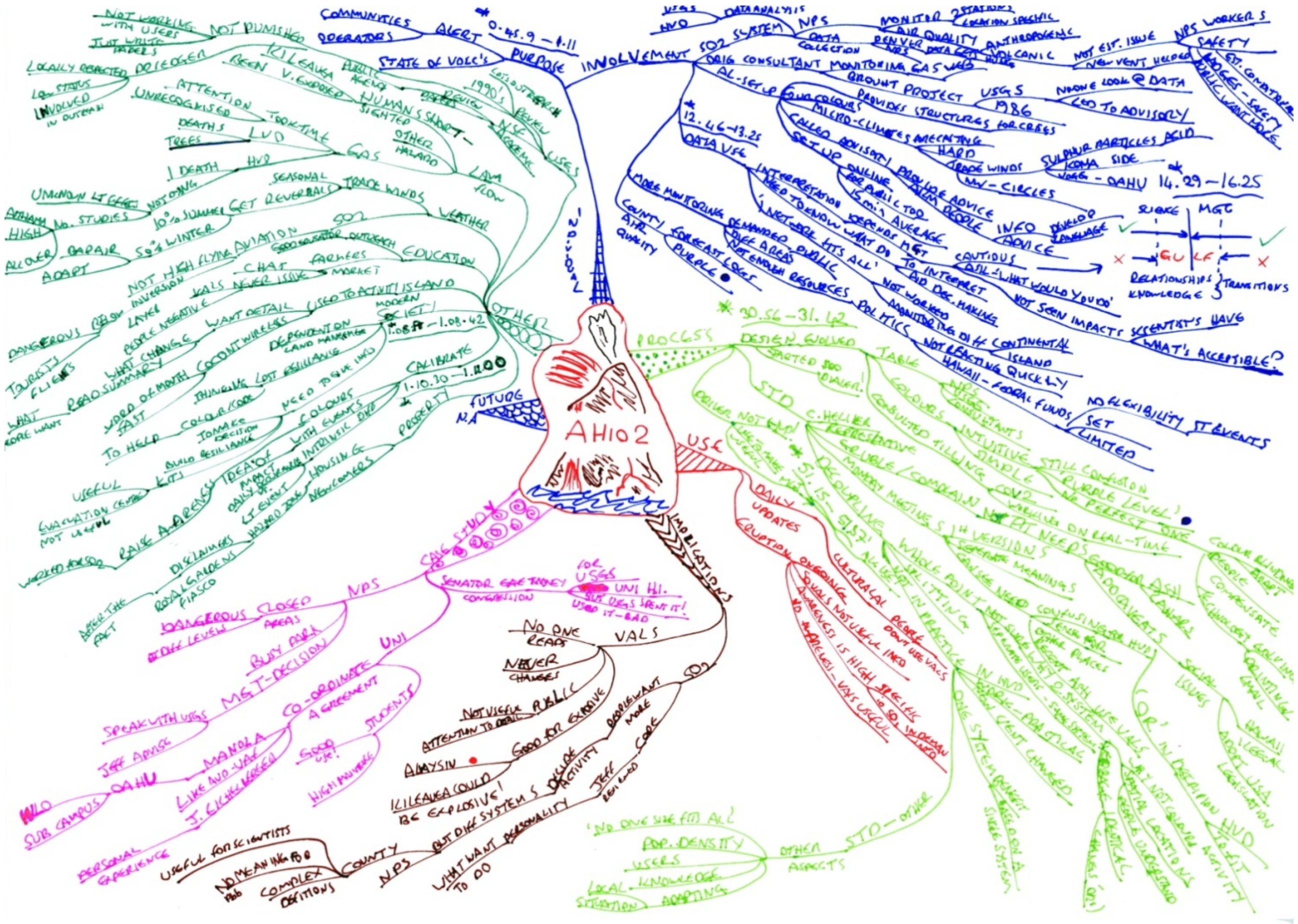
4. I **would/would not** like to be added to the project mailing list informing me about future research outputs.
5. **I agree/do not** agree for my anonymised interview transcript to be archived with the UK data archive

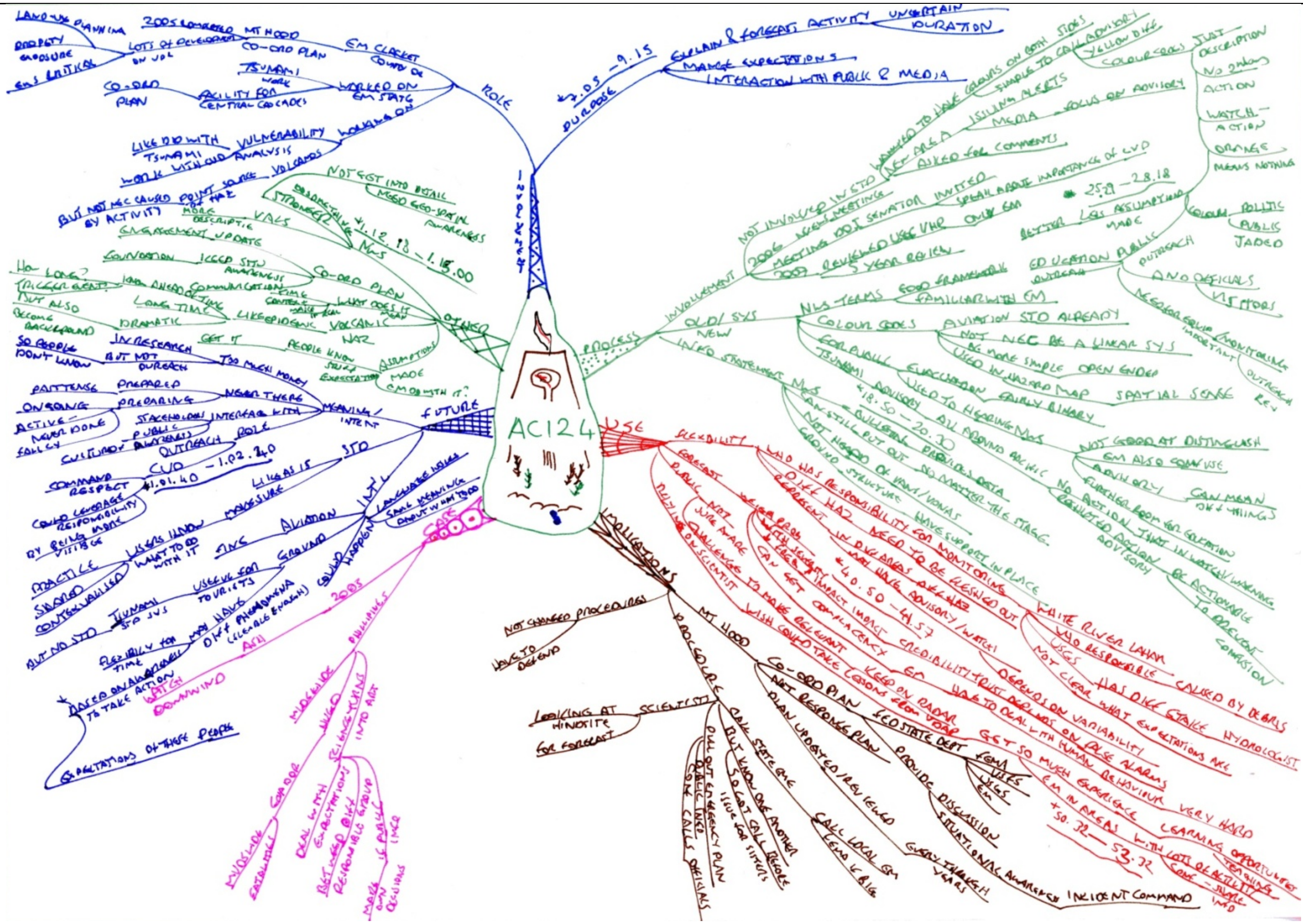
Signature:

Date:

Appendix C: Mind maps




AHI02
INVOLVEMENT
PURPOSE
PROCESS
USE
IMPLICATIONS
OTHER
CASE STUDY
FUTURE


AC124
ROLE
PURPOSE
PROCESS
USE
FUTURE
INCIDENT COMMAND

A403
INVOLVEMENT
PURPOSE
USES VALS
INDIVIDUAL
FUTURE
IMPLICATIONS
USG

Appendix D: Long Valley Colour Code

Table C1.—Criteria for deformation and strain rates for Color-Code conditions under table 2.

Condition Code	Strain and/or tilt rates [1]			Displacement rates [2]		
	24-hr (ppm/d)	weekly (ppm/w)	annual (ppm/y)	24-hr (mm/d)	weekly (mm/w)	annual (mm/y)
GREEN Quiescence & Weak unrest	<0.01	<0.1	<5	NA**	NA	<5
Minor unrest	>0.01	>0.1	>5	NA	NA	>5
Moderate-to-strong unrest	>0.1	>1	>50	NA	>5	>20
YELLOW	>1	>10	>500	>5	>50	>2,000
ORANGE	>10	>100	>5,000	>50	>500	>20,000

[1] Strain and tilt rates based on corresponding displacement rates over a 5-km baseline.
[2] Displacements below 1 mm and not resolvable by the 2-color EDM and GPS systems.

Notes:

- Read >5 mm/d as several millimeters per day, >10 mm/w as tens of millimeters per week (or centimeters per week), etc.
- Approximate annual rates indicate corresponding long-term cumulative displacements and strains: (1) Read >500 mm/y a few meters per year (this long-term rate includes, for example, the ~1-meter uplifts accumulated over one year (1983) in Campi Flegrei caldera, Italy, and Rabaul caldera, Papua New Guinea (see Figure 1 of Battaglia and others, 1999). (2) Read >5,000 mm/y as many meters to tens of meters per year.

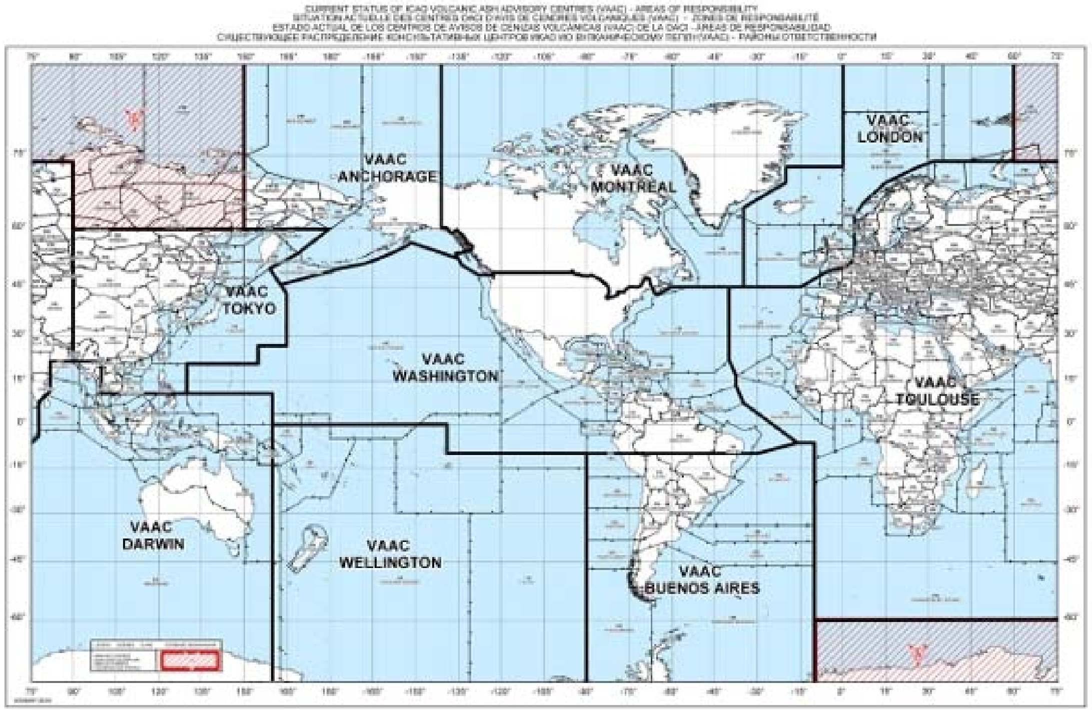
Table C1. Criteria for deformation and strain rates for Colour-Code conditions at LVO (Hill et al., 2002, p.42)

CONDITION	EXPIRES AFTER*	SUBSEQUENT CONDITION
GREEN (No immediate risk) Weak Unrest Minor Unrest Moderate-to-Strong Unrest	 1 day 2 days 3 days	GREEN Background Weak Unrest Minor Unrest
YELLOW (Watch)	14 days	GREEN (to appropriate Unrest level under green)
ORANGE (Warning)	7 days	YELLOW
RED (Alert: Eruption in progress)	1 day	ORANGE

*Number of days after the activity level falls below the threshold for a given **CONDITION.**

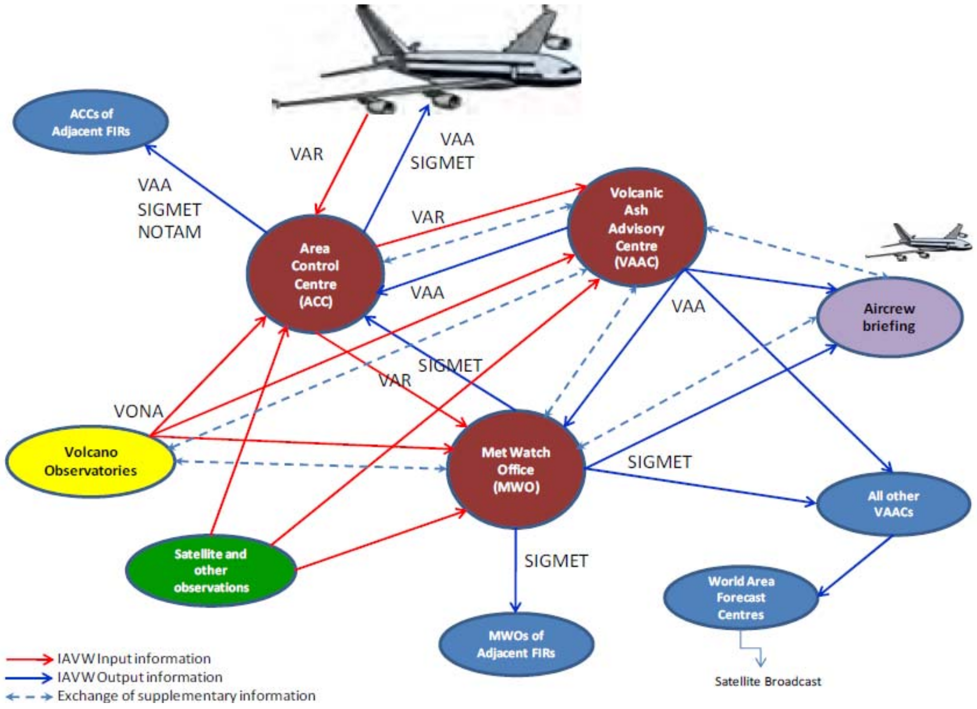
Table 3. Stand-down rules for Colour-Code conduction under declining activity levels (Hill et al., 2002, p.9)

Appendix E: Volcanic Ash Advisory Centres



Map of the Nine Volcanic Ash Advisory Centres around the world and their responsbile areas for advising international aviation of the location and movement of clouds of volcanic ash (Volcanic Ash Advisory Centre, 2010)

Appendix F: The International Airways Volcano Watch



A simplified diagram of the International Airways Volcano Watch (IAVW) (Lechner et al., 2009, p.14).
SIGMETS, VAA, NOTAM, VONA and VAR are all forms of notifications used for different purposes such as meteorological (SIGMET) or volcanic ash hazards (VAA) to communicate between the different actors involved within the IAVW

Reference list

ADAM, B., BECK, U. & LOON, J. V. 2000. *The risk society and beyond : critical issues for social theory,* London, SAGE.

ADLEMAN, J. N., CAMERON, C. E., SNEDIGAR, S. F., NEAL, C. A. & WALLACE, K. L. Unpublished. Outreach and Public Communications Strategies at the Alaska Volcano Observatory during the 2005-2006 Eruption of Augustine Volcano, Cook Inlet, Alaska. USGS.

AIRPORT-TECHNOLOGY.COM. 2010. *The World's Top Ten Cargo Hub Airports* [Online]. Available: http://www.airport-technology.com/features/feature78850/ [Accessed 07/09/2010].

ALDER, K. 1998. Making things the same: representation, tolerance and the end of the Ancien Regime in France. *Social Studies of Science,* 28**,** 499-545.

ALEXANDER, D. 2005. Towards the development of a standard in emergency planning. *Disaster Prevention and Management,* 14**,** 158-175.

ALEXANDER, G. 1982. Mammoth Area Tremors Hint at Volcanism. *Los Angeles Times*.

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE RESEARCH COMPETITIVENESS PROGRAM 2007. Review of the United States Geological Survey Volcano Hazards Program.

ARNOLDI, J. 2009. *Risk : an introduction,* Cambridge, Polity.

ASPINALL, W. & COOKE, R. M. Year. Expert judgement and the Montserrat Volcano eruption. *In:* MOSLEH, A. & BARI, R. A., eds. Proceedings of the 4th International Conference on Probabilistic Safety Assessment and Management PSAM4, 13th-18th 1998 New York City, USA. 2113-2118.

ASPINALL, W. P., CARNIEL, R., JAQUET, O., WOO, G. & HINCKS, T. 2006a. Using hidden multi-state Markov models with multi-parameter volcanic data to provide empirical evidence for alert level decision-support. *Journal of Volcanology and Geothermal Research,* 153**,** 112-124.

ASPINALL, W. P., LOUGHLIN, F., MICHAEL, A. V., MILLER, A. D., NORTON, G. E., ROWLEY, K. C., SPARKS, R. S. J. & YOUNG, S. R. 2002. The Montserrat Volcano Observatory: its evolution, organization, role and activities. *In:* DRUITT, T. H. &

KOKELARR, B. P. (eds.) *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999.* Geological Society London.

ASPINALL, W. P., LYNCH, L. L., ROBERTSON, R. E. A., ROWLEY, K., SPARKS, R. S. J., VOIGHT, B. & YOUNG, S. R. 1998. The Soufriere Hills eruption, Montserrat, British West Indies: Introduction to special section, part 1. *Geophysical Research Letters,* 25**,** 3387-3387.

ASPINALL, W. P., MADER, H. M., COLES, S. G., CONNOR, C. B. & CONNOR, L. J. 2006b. Structured elicitation of expert judgement for probabilistic hazard and risk assessment in volcanic eruptions. *Statistics in Volcanology.* London: Special Publication of IAVCEI, Geological Society.

ASPINALL, W. P., WOO, G., VOIGHT, B. & BAXTER, P. J. 2003. Evidence-based volcanology: application to eruption crises. *Journal of Volcanology and Geothermal Research,* 128**,** 273-285.

AVEN, T. 2003. *Foundations of risk analysis : a knowledge and decision-oriented perspective,* Chichester, Wiley.

AXELROD, R. & COHEN, M. D. 1999. *Harnessing complexity : organizational implications of a scientific frontier,* New York ; London, Free Press.

BAILEY, R. A. & USGS 1983. *The Volcano Hazards Program: objectives and long-range plans,* Reston, Virginia, U.S. Geological Survey.

BAK, P. 1996. *How nature works : the science of self-organized criticality,* New York, Copernicus.

BAKUN, W. H. 1987. Parkfield earthquake prediction scenarios and response plans. *Open-File Report 87-192.* Menlo Park, CA: U.S. Geological Survey.

BAKUN, W. H. 1988. Parkfield Earthquake Alert Levels. *California Geology,* 41**,** 61-62.

BANKOFF, G. 2007. Dangers to going it alone: Social capital and the origins of community resilience in the Philippines. *Continuity and Change,* 22**,** 327-355.

BANKOFF, G., FRERKS, G. & HILHORST, T. 2004. *Mapping vulnerability: disasters, development, and people,* London; Sterling, Va., Earthscan Publications.

BARBERI, F., CARAPEZZA, M. L., VALENZA, M. & VILLARI, L. 1993. The control of lava flow during the 1991-1992 eruption of Mt. Etna. *Journal of Volcanology and Geothermal Research,* 56**,** 1-34.

BARBERI, F., MARTINI, M. & ROSI, M. 1990. Nevado del Ruiz volcano (Colombia): pre-eruption observations and the November 13, 1985 catastrophic event. *Journal of Volcanology and Geothermal Research,* 42**,** 1-12.

BARTON, A. H. 1969. *Communities in disaster : a sociological analysis of collective stress situations,* Garden City, N.Y., Doubleday.

BASHER, R. 2006. Global early warning systems for natural hazards: systematic and people-centred. *Phil.Trans.R.Soc.,* 364**,** 2167-2182.

BATTAGLIA, M. & SEGALL, P. 2004. The Interpretation of Gravity Changes and Crustal Deformation in Active Volcanic Areas. *Pure and Applied Geophysics,* 161**,** 1453-1467.

BAXTER, J. & EYLES, J. 1997. Evaluating qualitative research in social geography: establishing 'rigour' in interview analysis. *Transactions of the Institute of British Geographers,* 22**,** 505-525.

BAXTER, J. & EYLES, J. 1999. The utility of in-depth interviews for studying the meaning of environmental risk. *Professional Geographer,* 51**,** 307-320.

BAXTER, P. 2004. Medical effects of volcanic eruptions. *Bulletin of Volcanology,* 52**,** 532-544.

BAXTER, P. J., ASPINALL, W. P., NERI, A., ZUCCARO, G., SPENCE, R. J. S., CIONI, R. & WOO, G. 2008. Emergency planning and mitigation at Vesuvius: a new evidence-based approach. *Journal of Volcanology and Geothermal Research,* 178**,** 454-473.

BECK, U. 1992. *Risk Society: Towards a New Modernity,* London, Sage.

BECK, U. 1997. The Relations of Definitions: Cultural and Legal Contexts of Media Constructions of Risk. *In:* UNPUBLISHED (ed.) *Media, Risk and the Environment.* University of Wales, Cardiff.

BECK, U., GIDDENS, A. & LASH, S. 1994. *Reflexive modernization : politics, tradition and aesthetics in the modern social order,* Cambridge, Polity Press.

BENSON, C. 2005. Volcanoes and the economy. *In:* MARTI, J. & ERNST, G. (eds.) *Volcanoes and the environment.* New York: Cambridge University Press.

BERTALANFFY, L. V. 1975. *Perspectives on general system theory : scientific-philosophical studies,* New York, G. Braziller.

BERTALANFFY, L. V. & WOODGER, J. H. 1933. *[Kritische Theorie der Formbildung.] Modern Theories of Development. An introduction to theoretical biology ... Translated and adapted by J. H. Woodger*, pp. x. 204. Oxford University Press: London.

BERTOLASO, G., DE BERNARDINIS, B., BOSI, V., CARDACI, C., CIOLLI, S., COLOZZA, R., CRISTIANI, C., MANGIONE, D., RICCIARDI, A., ROSI, M., SCALZO, A. & SODDU, P. 2009. Civil protection preparedness and response to the 2007 eruptive crisis of Stromboli volcano, Italy. *Journal of Volcanology and Geothermal Research,* 182**,** 269-277.

BIJKER, W. E., HUGHES, T. P. & PINCH, T. J. 1987. *The social construction of technological systems new directions in the sociology and history of technology,* Cambridge, Mass, MIT Press.

BIRKMANN, J. 2006. *Measuring vulnerability to natural hazards : towards disaster resilient societies,* Tokyo, United Nations University.

BLUMER, H. 1969. *Symbolic Interactionism: Perspective and Method,* Berkeley, University of California Press.

BRANTLEY, S. R., CASADEVALL, T. J. & GEOLOGICAL SURVEY (U.S.) 1990. The Eruption of Redoubt Volcano, Alaska, December 14, 1989-August 31, 1990. *USGS Circular 1061.* Washington, Denver, CO: US GPO.

BRANTLEY, S. R., MCGIMSEY, R. G. & NEAL, C. A. 2004. The Alaska Volcano Observatory - Expanded Monitoring of Volcanoes Yields Results. *Fact Sheet 2004-3084.* USGS.

BURGESS, J., STIRLING, A., CLARK, J., DAVIES, G., EAMES, M., STALEY, K. & WILLIAMSON, S. 2007. Deliberative mapping: a novel analytic-deliberative methodology to support contested science-policy decisions. *Public Understanding of Science,* 16**,** 299-322.

BUZAN, T. & BUZAN, B. 2006. *The mind map book*. Harlow: BBC Active.

CAA. 2010a. *Rationale for the introduction of a 'time limited zone' for operations in volumes of airspace forecast to contain levels of volcanic ash* [Online]. Available: http://www.caa.co.uk/docs/7/Rationale%20for%20the%20move%20to%20the%20TLZ%20system%20v1%200.pdf [Accessed 07/08/2010].

CAA. 2010b. *Rationale for the removal of the currently volcanic ash buffer zone* [Online]. Available: http://www.caa.co.uk/docs/7/Rationale%20for%20the%20Removal%20of%20the%20Current%20Ash%20Buffer%20Zone.pdf [Accessed 07/08/2010].

CAA. 2010c. *Volcanic Ash* [Online]. Available: http://www.caa.co.uk/docs/2011/VolcanicAshBriefing.pdf [Accessed 07/08/2010].

CAPRA, F. 1996. *The web of life : a new synthesis of mind and matter,* London, Flamingo, 1997.

CARDONA, O. D. 1997. Management of the volcanic crises of Galeras volcano: Social, economic and institutional aspects. *Journal of Volcanology and Geothermal Research,* 77**,** 313-324.

CASADEVALL, T. J. 1994. The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. *Journal of Volcanology and Geothermal Research,* 62**,** 301-316.

CASADEVALL, T. J., AIR LINE PILOTS ASSOCIATION, AEROSPACE INDUSTRIES ASSOCIATION OF AMERICA & USGS 1991. First international symposium on volcanic ash and aviation safety : program and abstracts : Seattle, Washington, July 8-12, 1991. *U.S. Geological Survey circular.* Reston, Va., Denver, CO: U.S. Dept. of the Interior

CASADEVALL, T. J., ASSOCIATION.;, A. L. P. & AMERICA., A. I. A. O. 1994. *Volcanic ash and aviation safety : proceedings of the First International Symposium on Volcanic Ash and Aviation Safety,* Washington

Denver, CO, U.S. G.P.O. ;

For sale by U.S. Geological Survey, Map Distribution.

CHALMERS, A. F. 1999. *What is this thing called science?,* Buckingham, Open University Press.

CHAMBERS, R. 1997. *Whose reality counts? : putting the first last,* London, Intermediate Technology.

CHESTER, D. K. 1993. *Volcanoes and society,* London, E. Arnold.

CHESTER, D. K., DEGG, M., DUNCAN, A. M. & GUEST, J. E. 2000. The increasing exposure of cities to the effects of volcanic eruptions: A global survey. *Environmental Hazards,* 2**,** 89-103.

CHESTER, D. K., MARTI, J. & ERNST, G. G. 2005. Volcanoes, society, and culture. *Volcanoes and the Environment.* Cambridge University Press.

CHRISTIANSEN, R. L., LOWENSTERN, J. B., SMITH, R. B., HEASLER, H., MORGAN, L. A., NATHENSON, M., MASTIN, L. G., MUFFLER, P. L. J. & J.E, R. 2007. Preliminary Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National Park and Vicinity. . *Open-File Report 2007-1071.* USGS.

CILLIERS, P. 1998. *Complexity and postmodernism : understanding complex systems,* London, Routledge.

CLAPPERTON, C. M. 1977. Volcanoes in space and time. *Progress in Physical Geography,* 1**,** 375-411

COLLINS, H. M. 1981. What Is TRASP - the Radical Program as a methodological imperative. *Philosophy of the Social Sciences,* 11**,** 215-224.

COLLINS, H. M. 1990. *Social Knowledge and Intelligent Machines*, Cambridge, Mass: MIT press.

CRANDELL, D. R. 1971. Postglacial Lahars From Mount Rainier Volcano, Washington. *In:* SURVEY, U. S. G. (ed.) *Professional Paper 677.* USGS.

CRANDELL, D. R. & MULLINEAUX, D. R. 1978. *Potential hazards from future eruptions of Mount St. Helens volcano, Washington,* Washington, U.S. Govt.

CURD, M. A. C., J.A 1998. *Philosophy of Science: the Central Issues,* New York: Norton.

CVO 2004. Alert Levels for Cascade Range Volcanoes, unpublished internal document. Accessed: 28/04/2008.

CYRANSKI, J. 1986. The probability of probability. *Justice*.

DAVID, P. A. & GREENSTEIN, S. 1990. The economics of compatibility standards: an introduction to recent research. *Economics of Innovation and New Technology,* 1.

DE LA CRUZ-REYNA, S. & TILLING, R. I. 2008. Scientific and public responses to the ongoing volcanic crisis at Popocatépetl Volcano, Mexico: Importance of an effective hazards-warning system. *Journal of Volcanology and Geothermal Research,* 170**,** 121-134.

DE MARCHI, B. & RAVETZ, J. R. 1999. Risk management and governance: a post-normal science approach. *Futures,* 31**,** 743-757.

DENIS, H. 1995. Scientists and disaster management *Disaster Prevention and Management,* 4**,** 14-19.

DENZIN, N. K. 1997. *Interpretive ethnography ethnographic practices for the 21st century,* Thousand Oaks, Sage Publications.

DEPARTMENT OF HOMELAND SECURITY 2008. National Incident Management System.

DORAVA, J. M. & MEYER, D. F. 1994. Hydrologic hazards in the lower Drift River basin associated with the 1989-1990 eruptions of Redoubt Volcano, Alaska. *Journal of Volcanology and Geothermal Research,* 62**,** 387-407.

DOUGLAS, M. 1984. *Purity and Danger,* London, Routlege & Kegan Paul.

DOUGLAS, M. & WILDAVSKY, A. B. 1983. *Risk and culture : an essay on the selection of technical and environmental dangers*, Berkeley ; London : University of California Press, 1982

DRIEDGER, C. L. N., C.A.; KNAPPENBERGER, T.A.; NEEDHAM, D. H.; HARPER, R. B.; STEELE, W.P 2008. Hazard Information Management During the Autumn 2004 Reawakening of Mount St. Helens Volcano, Washington. *A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006. Professional Paper 1750.* U.S. Geological Survey.

DRUITT, T. H. & KOKELAAR, B. P. 2002. *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999*, Geological Society London.

DZURISIN, D. 2007. *Volcano deformation geodetic monitoring techniques,* Berlin, Springer.

EDEN, L. 2004. *Whole world on fire organizations, knowledge, and nuclear weapons devastation,* Ithaca, N.Y, Cornell University Press.

EDMONDS, M. 2008. New geochemical insights into volcanic degassing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 366**,** 4559-4579.

EM-DAT 2008. Disaster Profile for Volcanoes. August 2008 ed.: The OFDA/CRED International Disaster Database.

EMERSON, R. M., FRETZ, R. I. & SHAW, L. L. 1995. *Writing ethnographic fieldnotes,* Chicago, University of Chicago Press.

EWERT, J. W., GUFFANTI, M., CERVELLI, P. & QUICK, J. 2006. The National Volcano Early Warning System (NVEWS). *U.S. Geological Survey Fact Sheet 2006-3142.* Reston, Virginia: U.S. Geological Survey.

EWERT, J. W., GUFFANTI, M. & MURRAY, T. L. 2005. An assessment of volcanic threat and monitoring capabilities in the United States framework for a National Volcano Early Warning System NVEWS. *U.S. Geological Survey Open-File Report 2005-1164.* Reston, Virginia: U.S. Geological Survey.

EWERT, J. W., MILLER, C. D., II, J. W. H. & STAUFFER, P. H. 2007. Mobile Response Team Saves Lives in Volcano Crises. *In:* PROGRAM, U. V. D. A. (ed.) *US Geological Survey Fact Sheet 064-97.* U.S. Geological Survey.

FEMA 2007. Robert T. Stafford Disaster Relief and Emergency Assistance Act, as amended, and Related Authorities.

FISCHHOFF, B. 1995. Risk Perception and Communication Unplugged: Twenty Years of Process. *Risk Analysis,* 15**,** 137-145.

FISKE, R. S. 1984. Volcanologists, journalists, and the concerned local public: a tale of two citites in the Eastern Caribbean. *Studies in Geophysics. Explosive Volcanism: Inception, Evolution, and Hazards.* Washington, D. C: National Academy Press.

FORM, W. & NOSTOW, S. 1958. *Community in Disaster,* New York, Harper & Row.

FOSTER, H. D. 1980. *Disaster planning: the preservation of life and property,* New York, Springer.

FOXWORTHY, B. & HILL, M. 1982. Volcanic Eruptions of 1980 at Mount St. Helens: The First 100 Days. *Geological Survey Profesional Paper 1249.* U.S. Geological Survey.

FRANCIS, P. & OPPENHEIMER, C. 2004. *Volcanoes,* Oxford, Oxford University Press.

FRENZEN, P. M. M., M.T 2008. Managing Public and Media Response to a Reawakening Volcano: Lessons from the 2004 Eruptive Activity of Mount St. Helens. *A Volcano*

Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006. U.S. Geological Survey.

FUJIMURA, J. H. 1987. Constructing 'Do-Able' Problems in Cancer Research: Articulating Alignment. *Social Studies of Science,* 17**,** 257-293.

FUNTOWICZ, S. & RAVETZ, J. R. 1994. Emergent complex systems. *Futures,* 26**,** 568-582.

FUNTOWICZ, S. O. & RAVETZ, J. R. 1993. Science for the post-normal age. *Futures,* 25**,** 739-755.

GAILLARD, J. C. & DIBBEN, C. J. L. 2008. Volcanic risk perception and beyond. *Journal of Volcanology and Geothermal Research,* 172**,** 163-169.

GALLE, B., OPPENHEIMER, C., GEYER, A., MCGONIGLE, A. J. S., EDMONDS, M. & HORROCKS, L. 2003. A miniaturised ultraviolet spectrometer for remote sensing of SO2 fluxes: a new tool for volcano surveillance. *Journal of Volcanology and Geothermal Research,* 119**,** 241-254.

GALLOPIN, G. C., FUNTOWICZ, S., O'CONNOR, M. & RAVETZ, J. 2001. Science for the twenty-first century: From social contract to the scientific core. *International Social Science Journal,* 53**,** 219-229.

GARCIA, C. & FEARNLEY, C. 2011. Evaluating Critical Links in Early Warning Systems for Natural Hazards. *Natural Hazards Review,* 12.

GARDNER, C., GUFFANTI, M., HELIKER, C., HILL, D., LOWENSTERN, J. & MURRAY, T. 2004a. White Paper: Volcano alert-level notification within the Volcano Hazards Program: a report to look at the feasibility of a single unified system for all U.S. volcanoes.

GARDNER, C. A., GUFFANTI, M., HELICKER, C. C., HILL, D. P., LOWENSTERN, J. B. & MURRAY, T. L. 2004b. A proposed alert-level notification scheme for aviation and ground based hazards at U.S. Volcanoes. *2nd International Conference on Volcanic Ash and Aviation Safety.* USA: US Geological Survey VHP.

GARDNER, C. A. & GUFFANTI, M. C. 2006. U.S. Geological Survey's Alert Notification System for Volcanic Activity. *Fact Sheet 2006-3139.* U.S. Geological Survey.

GARLAND, D. 2003. The Rise of Risk. *In:* ERICSON, R. V. & DOYLE, D. (eds.) *Risk and morality.* Toronto, ON: University of Toronto Press.

GEIS, D. 2000. By design: the disaster resistant and quality-of-life community. *Natural Hazards Review,* 1**,** 151-160.

GIBBONS, M. 1994. *The new production of knowledge the dynamics of science and research in contemporary societies,* London, SAGE Publications.

GIERYN, T. F. 1983. Boundary-Work and the Demarcation of Science from Non-Science - Strains and Interests in Professional Ideologies of Scientists. *American Sociological Review,* 48**,** 781-795.

GILLESPIE, D. F. & PERRY, R. W. 1976. An integrated systems and emergent norm approach to mass emergencies. *Mass Emergencies,* 1.

GILLESPIE, D. F., ROBARDS, K. J. & CHO, S. 2004. Designing safe systems: using system dynamics to understand complexity. *Natural Hazards Review,* 5**,** 82-88.

GILLIES, D. 1998. The Duhem Thesis and the Quine Thesis. *In:* CURD, M. & COVER, J. A. (eds.) *Philosophy of Science: The Central Issues.* New York: Norton.

GLADWIN, H., LAZO, J. K., MORROW, B. H., PEACOCK, W. G. & WILLOUGHBY, H. E. 2009. Social science research needs for the hurricane forecast and warning system. *Bulletin of the American Meteorological Society,* 90**,** 25-29.

GLANTZ, M. H. 2004. Usable Science 8: Early Warning Systems: Do's and Don'ts. . *Report of Workshop 20-23 October, 2003. Shanghai, China.*

GLANTZ, M. H. 2009. *Heads Up! Early Warning Systems for Climate, Water and Weather-Related Hazards*, United Nations University Press.

GLEICK, J. 1987. *Chaos: making a new science,* New York, NY, Viking.

GLOVER, D. & STRAWBRIDGE, S. 1985. *The sociology of knowledge,* Ormskirk, Causeway.

GNS. 2010. *Volcano alert levels explained* [Online]. Available: http://www.gns.cri.nz/what/earthact/volcanoes/alertl_1.html [Accessed 05/01/2010 2010].

GOULD, P. & WHITE, R. 1986. *Mental maps*. London: Allen & Unwin.

GUFFANTI, G., BRANTLEY, S. R., CERVELLI, P., NYE, C., SERAFINE, G., SIEBERT, L., VENEZKY, D. & WALD, L. 2007. Technical-information products for a National Volcano Early Warning System. *USGS Open File Report 2007 - 1250.* Reston, Virginia.

HAAG, D. & KAUPENJOHANN, M. 2001. Parameters, prediction, post-normal science and the precautionary principle - a roadmap for modelling for decision-making. *Ecological Modelling,* 144**,** 45-60.

HALL, M. L. 1990. Chronology of the Principal Scientific and Governmental Actions Leading Up to the November 13, 1985 Eruption of Nevado-Del-Ruiz, Colombia. *Journal of Volcanology and Geothermal Research,* 42**,** 101-115.

HALL, P. H. 2007. Early Warning Systems: Reframing the Discussion. *The Australian Journal of Emergency Management,* Vol. 22**,** 32-36.

HALL, S. 1980. Encoding / decoding. *In:* HALL, S. H., DOROTHY.; LOWE, ANDREW.; WILLIS, PAUL. (ed.) *Culture, media, language : working papers in cultural studies, 1972-79.* London: Hutchinson in association with the Centre for Contemporary Cultural Studies, University of Birmingham.

HAMMERSLEY, M. 1991. *Reading ethnographic research : a critical guide,* London, Longman.

HANSETH, O., MONTEIRO, E. & HATLING, M. 1996. Developing Information Infrastructure: the Tension between Standardization and Flexibility. *Science, Technology, & Human Values,* 21**,** 407-426.

HAWAII STATE DEPT. OF HEALTH AND COUNTY CIVIL DEFENSE. 2008. *Emissions from Kilauea Volcano: brief summary of hazards and protective measures* [Online]. Hilo, Hawaii. Available: http://www.uhh.hawaii.edu/~nat_haz/volcanoes/SO2Brochure.pdf [Accessed 25/06/2008].

HAWAII VOLCANOES NATIONAL PARK. 2008. *Hawaii Volcanoes National Park sulfur dioxide advisory program* [Online]. Available: http://www.nature.nps.gov/air/WebCams/parks/havoso2alert/havoadvisories.cfm [Accessed 25/06/2008 2008].

HAWKING, S. W. & MLODINOW, L. 2010. *The grand design,* London, Bantam Press.

HAYNES, K. 2008. Volcanic island in crises: investigating environmental uncertainty and the complexities it brings. *The Australian Journal of Emergency Management,* 21**,** 21-28.

HAYNES, K., BARCLAY, J. & PIDGEON, N. 2008a. The issue of trust and its influence on risk communication during a volcanic crisis. *Bulletin of Volcanology,* 70**,** 605-621.

HAYNES, K., BARCLAY, J. & PIDGEON, N. F. 2008b. Whose reality counts? Factors affecting the perception of volcanic risk. *Journal of Volcanology and Geothermal Research,* 172**,** pp259-272.

HELIKER, C., GRIGG, J. D., TAKASHASHI, T. J. & WRIGHT, T. L. 1968. Volcano monitoring at the U.S Geological Survey's Hawaiian Volcano Observatory. *Earthquakes and volcanoes,* 18**,** 1-72.

HEMASPAANDRA, L. A. & OGIHARA, M. 2001. *The complexity theory companion,* New York, Springer.

HEWITT, K. 1983. *Interpretations of calamity from the viewpoint of human ecology*, Allen & Unwin.

HILL, D. P. 1998. 1998 SSA Meeting - Presidential Address: Science, Geologic Hazards, and the Public in a Large, Restless Caldera. *Seismological Research Letters,* 69.

HILL, D. P., DZURISIN, D., ELLSWORTH, W. L., ENDO, E. T., GALLOWAY, D. L., GERLACH, T. M., JOHNSTON, M. J. S., LANGBEIN, J., MCGEE, K., MILLER, C. D., OPPENHEIMER, D. & SOREY, M. L. 2002. Response plan for volcano hazards in the Long Valley Caldera and Mono Craters region, California. *U.S. Geological Survey bulletin 2185.* Menlo Park, Calif, Denver, Colo.: U.S. Dept. of the Interior.

HILL, D. P. J., M.J.S; LANGBEIN, J.O; MCNUTT, S.R; MILLER, C.D; MORTENSEN, C.E; PITT, A.M; ROJSTACZER, S. 1991. Reponse plans for Volcanic Hazards in the Long Valley Caldera and Mono Craters Area, California. *Open File Report 91-270.* U.S. Department of the Interior, U.S. Geolgogical Survey.

HINE, C. 2007. Multi-sited ethnography as a middle range methodology for contemporary STS. *Science Technology and Human Values,* 32**,** 652-671.

HOGLE, L. F. 1995. Standardization across Non-Standard Domains: The Case of Organ Procurement. *Science, Technology, & Human Values,* 20**,** 482-500.

HOYOIS, P., SCHEUREN, J. M., BELOW, R. & GUHA-SAPIR, D. 2007. Annual Disaster Statistical Review: Numbers and Trends 2006. Brussels: CRED.

IATA. 2010. *Volcano Crisis Cost Airlines $1.7 Billion in Revenue - IATA Urges Measures to Mitigate Impact* [Online]. Available: http://www.iata.org/pressroom/pr/Pages/2010-04-21-01.aspx [Accessed 06/08/2010].

ICAO 2004. Handbook on the International Airways Volcano Watch (IAVW) and Annex 15.

ICAO. Year. Second Meeting of The International Airways Volcano Watch Operations Group (IAVWOPSG). *In*, 26 to 30 September 2005 2005 Lima, Peru.

IFRC 2009. World Disasters Report 2009 - Focus on early warning, early action. *In:* KNIGHT, L. (ed.). Geneva: International Federation of Red Cross and Red Crescent Societies.

IKEYA, H. 2008. The Heisei Eruption of Mt. Unzen-Fugendake and Measures Against Volcanic Disasters. *Journal of Disaster Research,* Vol.3**,** pp. 276-283.

IRWIN, A. & WYNNE, B. 1996. *Misunderstanding science? the public reconstruction of science and technology,* Cambridge, Cambridge University Press.

JAMIESON, D. 1996. Scientific uncertainty and the political process. *Annals of the American Academy of Political and Social Science***,** 35-42.

JAPAN METEOROLOGICAL AGENCY. 2010. *Volcanic Warnings and Volcanic Alert Levels* [Online]. Available: http://www.seisvol.kishou.go.jp/tokyo/STOCK/kaisetsu/English/level.html [Accessed 06/01/2010 2010].

JAQUET, O., CARNIEL, R., SPARKS, S., THOMPSON, G., NAMAR, R. & DI CECCA, M. 2006. DEVIN: A forecasting approach using stochastic methods applied to the Soufriere Hills Volcano. *Journal of Volcanology and Geothermal Research,* 153**,** 97-111.

JASANOFF, S. 1987. Contested Boundaries in Policy-Relevant Science. *Social Studies of Science,* 17**,** 195-230.

JASANOFF, S. 2005. *Designs on nature : science and democracy in Europe and the United States,* Princeton, N.J., Princeton University Press.

JASANOFF, S. & MARTELLO, M. L. 2004. *Earthly politics : local and global in environmental governance,* Cambridge, Mass., MIT Press.

JOHNSON, J. B., ASTER, R. C., RUIZ, M. C., MALONE, S. D., MCCHESNEY, P. J., LEES, J. M. & KYLE, P. R. 2008. Interpretation and utility of infrasonic records from erupting volcanoes. *Journal of Volcanology and Geothermal Research,* 121**,** 15-63.

JORDAN, K. & LYNCH, M. 1998. The Dissemination, Standardization and Routinization of a Molecular Biological Technique. *Social Studies of Science,* 28**,** 773-800.

KAY, J. J., REGIER, H. A., BOYLE, M. & FRANCIS, G. 1999. An ecosystem approach for sustainability: Addressing the challenge of complexity. *Futures,* 31**,** 721-742.

KEITH, T. E. C. 1995. *The 1992 eruptions of Crater Peak vent, Mount Spurr volcano, Alaska,* Washington

Denver, CO, US GPO; U.S. Dept. of the Interior

KELMAN, I. & MATHER, T. A. 2008. Living with volcanoes: The sustainable livelihoods approach for volcano-related opportunities. *Journal of Volcanology and Geothermal Research,* 172**,** 189-198.

KEYS, H. J. R. 2007. Lahars of Ruapehu Volcano, New Zealand: risk mitigation. *Annals of Glaciology,* 45**,** 155-162.

KILBURN, C. R. J. 2003. Multiscale fracturing as a key to forecasting volcanic eruptions. *Journal of Volcanology and Geothermal Research,* 125**,** 271-289.

KILBURN, C. R. J. 2004. Fracturing as a quantitative indicator of lava flow dynamics. *Journal of Volcanology and Geothermal Research,* 132**,** 209-224.

KILBURN, C. R. J. & SAMMONDS, P. R. 2005. Maximum warning times for imminent volcanic eruptions. *Geophysical Research Letters,* 32**,** 1-4.

KIM, D. H. 1994. *Systems thinking tools : a user's reference guide,* Cambridge, Mass., Pegasus Communications.

KIRIANOV, V. Y., NEAL, C. A., GORDEEV, E. I. & MILLER, T. P. 2002. The Kamchatkan Volcanic Eruption Response Team (KVERT). *Fact Sheet 064-02.* U.S Geological Survey.

KITCHIN, R. & TATE, N. 2000. Analysing and interpreting qualitative data. *In:* KITCHIN, R. & TATE, N. (eds.) *Conducting research in human geography : theory, methodology and practice.* Harlow: Prentice Hall.

KNIGHT, F. 1921. *Risk, Uncertainty and Profit,* Chicago, Houghton Mifflin Company.

KNORR-CETINA, K. 1981. *The manufacture of knowledge an essay on the constructivist and contextual nature of science,* Oxford, Pergamon.

KNORR-CETINA, K. 1999. *Epistemic cultures how the sciences make knowledge,* Cambridge, Mass, Harvard University Press.

KNORR-CETINA, K., JASANOFF, S., MARKLE, G. E., PETERSEN, J. C. & PINCH, T. J. 1995. Laboratory Studies - The Cultural Approach to the Study of Science. *Handbook of Science and Technology Studies.* Sage Publications.

KNORR-CETINA, K. & MULKAY, M. J. 1983. *Science observed : perspectives on the social study of science,* London, Sage.

KOEHLER, G. A. Year. What Disaster Response Management Can Learn from Chaos Theory : Conference Proceedings. *In:* KOEHLER, G. A., ed. What disaster response management can learn from chaos theory, 2001 1995. California Research Bureau, California State Library (Sacramento, Calif) 293-308

KRIEBEL, D., TICKNER, J., EPSTEIN, P., LEMONS, J., LEVINS, R., LOECHLER, E. L., QUINN, M., RUDEL, R., SCHETTLER, T. & STOTO, M. 2001. The precautionary principle in environmental science. *Environmental Health Perspectives,* 109**,** 871-876.

KUHN, T. S. 1962. *The structure of scientific revolutions,* Chicago, University of Chicago Press.

KUHN, T. S. 1977. *The essential tension selected studies in scientific tradition and change,* Chicago, University of Chicago Press.

KUPPERS, A. N. & ZSCHAU, J. 2002. *Early Warning Systems for Natural Disaster Reduction*, Springer.

KURTZ, C. F. & SNOWDEN, D. J. 2003. The new dynamics of strategy: Sense-making in a complex and complicated world. *IBM Syst. J.,* 42**,** 462-483.

LASH, S., SZERSZYNSKI, B. & WYNNE, B. 1996. *Risk, environment and modernity : towards a new ecology,* London, Sage.

LATOUR, B. 1987. *Science in action how to follow scientists and engineers through society,* Cambridge, Mass, Harvard University Press.

LATOUR, B. 1999. *Pandora's hope essays on the reality of science studies,* Cambridge, Mass, Harvard University Press.

LATOUR, B. 2005. *Reassembling the social an introduction to actor-network-theory,* Oxford, Oxford University Press.

LATOUR, B. & WOOLGAR, S. 1979. *Laboratory life the social construction of scientific facts,* Beverly Hills, Sage.

LECHNER, P., MACKERSY, K., TUPPER, A., PATRICK, R., RUGLYS, M., GUFFANTI, G. & ROMERO, R. 2009. Guidance for State Volcano Observatories: The International Airways Volcano Watch. WOVO.

LEONARD, G. S., JOHNSTON, D. M., PATON, D., CHRISTIANSON, A., BECKER, J. & KEYS, H. 2008. Developing effective warning systems: Ongoing research at Ruapehu volcano, New Zealand. *Journal of Volcanology and Geothermal Research,* 172**,** 199-215.

LIPMAN, P. W. & MULLINEAUX, D. R. 1982. The 1980 eruptions of Mount St. Helens, Washington. *Geological Survey professional paper 1250.* Washington: US GPO.

LOCKHART, A. B. & MURRAY, T. L. 2004. The Puyallup River vally Pilot Lahar Detection System. *Open File Report 2004-1028.* Reston, Virginia: USGS.

LOWENSTERN, J. B., SMITH, R. B. & HILL, D. P. 2006. Monitoring super-volcanoes: geophysical and geochemical signals at Yellowstone and other large caldera systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 364**,** 2055-2072.

LUHMANN, N. 1993. *Risk : a sociological theory*, Walter de Gruyter.

LUHMANN, N. 1998. *Observations on modernity,* Stanford, Calif., Stanford University Press.

LYNCH, M. 1993. *Scientific practice and ordinary action ethnomethodology and social studies of science,* Cambridge, Cambridge University Press.

LYNCH, M. & JASANOFF, S. 1998. *Contested identities : science, law and forensic practice,* London, Sage.

MADDEN, J., MURRAY, T. L., CARLE, W. J., CIRILLO, M. A., FURGIONE, L. K., TRIMPERT, M. T. & HARTIG, L. 2008. Alaska interagency operating plan for volcanic ash episodes

MADER, G. G., BLAIR, M. L., OLSON, R. A., ASSOCIATES, W. S. A. & ASSOCIATES, V. 1987. *Living with a volcanic threat : response to volcanic hazards, Long Valley, California,* Portola Valley, CA, W. Spangle and Associates.

MADER, H. M. 2006. *Statistics in volcanology,* London, Geological Society.

MALONE, S. 2008. A Warning about Early Warning. *Seismological Research Letters,* 79**,** 603-604.

MARCUS, G. E. 1995. Ethnography in / of the World System: The Emergence of Multi-Sited Ethnography. *Annual Review of Anthropology,* 24**,** 95-117.

MARSHALL, C. & ROSSMAN, G. B. 2006. *Designing qualitative research,* London, SAGE.

MARTIN, B., RICHARDS, E. & JASANOFF, S. 1995a. Scienctific Knowledge, controversy, and public decision making. *In:* JASANOFF, S. & SOCIETY FOR SOCIAL STUDIES OF SCIENCE (eds.) *Handbook of science and technology studies.* Thousand Oaks, California: Sage.

MARTIN, B., RICHARDS, E., JASANOFF, S. & SOCIETY FOR SOCIAL STUDIES OF, S. 1995b. Scienctific Knowledge, controversy, and public decision making. *Handbook of science and technology studies.* Thousand Oaks, Calif: Sage.

MARZOCCHI, W., SANDRI, L., FURLAN, C. A., MADER, H. M., COLES, S. G., CONNOR, C. B. & CONNOR, L. J. 2006. A quantitative model for volcano hazard assessment. *Statistics in Volcanology.* London: Special Publication of IAVCEI, Geological Society.

MARZOCCHI, W., SANDRI, L. & SELVA, J. 2007. BET_EF: a probabilistic tool for long- and short-term eruption forecasting. *Bulletin of Volcanology,* 70**,** 623-632.

MARZOCCHI, W. & WOO, G. 2007. Probabilistic eruption forecasting and the call for an evacuation. *Geophysical Research Letters,* 34.

MASTIN, L. G., GUFFANTI, M., SERVRANCKX, R., WEBLEY, P., BARSOTTI, S., DEAN, K., DURANT, A., EWERT, J. W., NERI, A., ROSE, W. I., SCHNEIDER, D., SIEBERT, L., STUNDER, B., SWANSON, G., TUPPER, A., VOLENTIK, A. & WAYTHOMAS, C. F. 2009. A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *Journal of Volcanology and Geothermal Research,* 186**,** 10-21.

MCCRACKEN, G. D. 1988. *The long interview,* Newbury Park, Calif., Sage Publications.

MCENTIRE, D. A. 2004. The status of emergency management theory: issues, barriers, and recommendations for improved scholarship. *FEMA Higher Education Conference.* Emmitsburg, MD.

MCENTIRE, D. A. & FULLER, C. 2002. The need for a holistic theoretical approach: An examination from the El NinÌƒo disasters in Peru. *Disaster Prevention and Management,* 11**,** 128-140.

MCGUIRE, B. 2002. *Natural hazards and environmental change,* London, Arnold.

MCGUIRE, B., KILBURN, C. R. J. & MURRAY, J. B. 1995. *Monitoring active volcanoes strategies, procedures and techniques,* London, UCL Press.

MCGUIRE, W. J. & KILBURN, C. R. J. 1997. Forecasting volcanic events: Some contemporary issues. *International Journal of Earth Sciences,* 86**,** 439-445.

MCNUTT, S. R. 2000. Volcanic Seismicity. *In:* SIGURDSSON, H., HOUGHTON, B., MCNUTT, S., RYMER, H. & STIX, J. (eds.) *Encyclopedia of Volcanoes.* San Diego, CA: Academic Press.

MELNICK, O. & SPARKS, R. S. J. 1999. Non-linear dynamics of lava dome extrusion. *Nature* 402**,** 37-41.

MERTON, R. K. & STORER, N. W. 1973. *The sociology of science theoretical and empirical investigations,* Chicago, University of Chicago Press.

METZGER, P., D'ERCOLE, R. & SIERRA, A. 1999. Political and scientific uncertainties in volcanic risk management: The yellow alert in Quito in October 1998. *GeoJournal,* 49**,** 213-221.

MILETI, D. 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States,* Washington DC, Joseph Henry Press.

MILETI, D. S. & SORENSON, J. H. 1990. Communication of Emergency Public Warnings: A Social Science Perspective and State-of-the-Art Assessment. Oak Ridge National Laboratory.

MILLER, C. 2001. Hybrid Management: Boundary Organizations, Science Policy, and Environmental Governance in the Climate Regime. *Science, Technology, & Human Values,* 26**,** 478-500.

MILLER, T. D. & CASADEVALL, T. J. 2000. Volcanic Ash Hazards to Aviation. *In:* SIGURDSSON, H. & HOUGHTON, B. F. (eds.) *Encyclopaedia of volcanoes.* San Diego: Academic Press.

MITCHELL, M. 2009. *Complexity : a guided tour,* Oxford ; New York, Oxford University Press.

MITCHELL, T. C. 2006. *Building a disaster resilient future : lessons from participatory research in St. Kitts and Montserrat.* PhD, University College London.

MOGI, K. 1958. Relation between the eruptions of various volcanoes and deformations of the ground surfaces around them. *Bull. Earth. Res. Inst.,* 36**,** 99134.

MOTHES, P. A., HALL, M. L. & JANDA, R. J. 1998. The enormous Chillos Valley Lahar: an ash-flow-generated debris flow from Cotopaxi Volcano, Ecuador. *Bulletin of Volcanology,* 59**,** 233-244.

NATIONAL RESEARCH COUNCIL 2000. *Review of the U.S. Geological Survey's Volcano Hazard Program,* Washington D.C.

NEAL, C., CASADEVALL, T. J., MILLER, T. P., HENDLEY II, J. W. & H., S. P. 1997. Volcanic Ash-Danger to Aircraft in the North Pacific. *U.S. Geological Survey Fact Sheet 030-97.* U.S. Geological Survey.

NEAL, C., WALLACE, K., ALBANESE, S., FISH, A. & CAHILL, C. 2006. Communicating Ash-Fall Hazard to the Public During Eruptions: A Proposed Scheme to Streamline Ash-Fall Warning Messages in the U.S. Based on the Recent Activity at Augustine Volcano, Alaska. *American Geophysical Union, Fall Meeting* San Francisco.

NEUBERG, J., MADER, H. M., COLES, S. G., CONNOR, C. B. & CONNOR, L. J. 2006. Multi-paramter monitoring and modelling of volcanic processes. *Statistics in Volcanology.* London: Special Publication of IAVCEI, Geological Society.

NEWHALL, C., ARAMAKI, S., BARBERI, F., BLONG, R., CALVACHE, M., CHEMINEE, J. L., PUNONGBAYAN, R., SIEBE, C., SIMKIN, T., SPARKS, S. & TJETJEP, W. 1999. Professional conduct of scientists during volcanic crises. *Bulletin of Volcanology,* 60**,** 323-334.

NEWHALL, C. & PUNONGBAYAN, R. S. 1997. *Fire and Mud - Eruptions and Lahars of Mount Pinatubo, Philippines,* Seattle, London, University of Washington Press.

NEWHALL, C. G. & DZURISIN, D. 1988. Historical unrest at large calderas of the World. *U.S. Geological Survey bulletin 1855.* Washington, D.C.: US GPO.

NEWHALL, C. G. & HOBLITT, R. P. 2002. Constructing event trees for volcanic crises. *Bulletin of Volcanology,* 64**,** 3-20.

NEYLAND, D. 2008. *Organizational Ethnography*, Sage Publications.

NOAA NWS. 2010. *Pacific Tsunami Warning Centre: Tsunami messages* [Online]. Available: http://www.weather.gov/ptwc/ [Accessed 06/08/2010 2010].

NOWOTNY, H. 1996. Umwelt, Zeit, Komplexizität: Auf dem Weg zur Endosoziologie. *In:* DIEKMANN, A., JAEGER, C. (ed.) *Sonderheft der Kölner Zeitschrift für Soziologie und Sozialpsychologie hrsg.* .

NOWOTNY, H. 1999. The place of people in our knowledge: towards local objectivity and socailly robust knowledge. *Eur. Rev,* 2**,** 247-262.

NOWOTNY, H. 2005. The increase of complexity and its reduction: Emergent interfaces between the natural sciences, humanities and social sciences. *Theory, Culture and Society,* 22**,** 15-31+269.

NOWOTNY, H., SCOTT, P. & GIBBONS, M. 2001. *Re-thinking science : knowledge and the public in an age of uncertainty,* Cambridge, Polity Press.

O'BRIEN, G. 2008. UK emergency preparedness: A holistic response? *Disaster Prevention and Management,* 17**,** 232-243.

O'BRIEN, G. & READ, P. 2005. Future UK emergency management: New wine, old skin? *Disaster Prevention and Management,* 14**,** 353-361.

OASIS. 2008. *Common Alerting Protocol, v. 1.1* [Online]. Available: http://www.oasis-open.org/committees/download.php/15135/emergency-CAPv1.1-Corrected_DOM.pdf [Accessed 06/06/2009].

OBSERVATORY, A. V. 2010. *Volcano Activity Notifications* [Online]. Available: http://www.avo.alaska.edu/activity/avoreport.php?view=info [Accessed 08/07/2010 2010].

OFCM. Year. Proceeding of the 2nd International Conference on Volcanic Ash and Aviation Safety. *In*, June 21-24, 2004 2004 Alexandra, Virginia USA. U.S. Department of Commerce / National Oceanic and Atmospheric Administration.

ORLIKOWSKI, W. J. & BAROUDI, J. J. 1991. Studying Information Technology in Organizations: Research Approaches and Assumptions. *Information Systems Research,* 2**,** 1-28.

PARASKEVAS, A. 2006. Crisis management or crisis response system?: A complexity science approach to organizational crises. *Management Decision,* 44**,** 892-907.

PARESCHI, M. T., CAVARRA, L., FAVALLI, M., GIANNINI, F. & MERIGGI, A. 2000. GIS and volcanic risk management. *Natural Hazards,* 21**,** 361-379.

PARTNERSHIP FOR PUBLIC WARNING. 2003. A National Strategy for Integrated Public Warning Policy and Capability. Available: http://www.partnershipforpublicwarning.org/ppw/docs/nationalstrategyfinal.pdf [Accessed 16/05/2003].

PATON, D., JOHNSTON, D. & HOUGHTON, B. F. 1998. Organisational response to a volcanic eruption. *Disaster Prevention and Management,* 7**,** 5-13.

PETERSON, D. W. 1988. Volcano hazards and public response. *Journal of Geophysical Research,* 93**,** 4161-4170.

PETERSON, D. W., TILLING, R. I., KILBURN, C. R. J. & LUONGO, G. 1993. Interactions between scientists, civil authorities and the public at hazardous volcanoes. *Active Lavas.* London: UCL Press.

PIEPERS, I. 2006. The International System: at the Edge of Chaos. Available: http://arxiv.org/ftp/nlin/papers/0611/0611062.pdf.

POPPER, K. R. 1968. *The logic of scientific discovery,* London, Hutchinson.

PRATA, A. J. & TUPPER, A. 2009. Aviation hazards from volcanoes: The state of the science. *Natural Hazards,* 51**,** 239-244.

PROCTER, J. 2004. *Stuart Hall,* London ; New York, Routledge.

PYLE, M. 1998. Forecasting sizes and repose times of future extreme volcanic events. *Geology,* 26**,** 367-370.

QUARANTELLI, E. L. 1995. What is a disaster? *International Journal of Mass Emergencies and Disasters,* 13**,** 221-229.

RABBITT, M. C. 1989. The United States Geological Survey: 1879-1989. *U.S. Geological Survey Circular 1050.*

RAMALINGAM, B., JONES, H., REBA, T. & YOUNG, J. 2008. Exploring the science of complexity: Ideas and implications for development and humanitarian efforts. Working Paper 285. London: Overseas Development Institute (ODI).

RAVETZ, J. 2004. The post-normal science of precaution. *Futures,* 36**,** 347-357.

RAVETZ, J. 2005. The post-normal sciences of precaution. *Water Science and Technology,* 52**,** 11-17.

RAVETZ, J. R. 1999. What is Post-Normal Science. *Futures,* 31**,** 647-653.

RONAN, K. R., PATON, D., JOHNSTON, D. M. & HOUGHTON, B. F. 2000. Managing societal uncertainty in volcanic hazards: a multidisciplinary approach. *Disaster Prevention and Management,* 9**,** pp.339 - 349.

RUEGG, J. C., RUDLOFF, A., VIGNY, C., MADARIAGA, R., DE CHABALIER, J. B., CAMPOS, J., KAUSEL, E., BARRIENTOS, S. & DIMITROV, D. 2009. Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile. *Physics of the Earth and Planetary Interiors,* 175**,** 78-85.

SAARINEN, T. F. & MCPHERSON, H. J. 1981. Notices, Watches and Warning: An appraisal of the USGS's warning system with a case study from Kodiak, Alaska. *Natural Hazard Research working paper 42*

SAARINEN, T. F. & SELL, J. L. 1985. *Warning and Response to the Mount St-Helens Eruption,* Albany, State University of New York Press.

SANDIN, P. 1999. Dimensions of the precautionary principle. *Human and Ecological Risk Assessment (HERA),* 5**,** 889-907.

SARDAR, Z. & RAVETZ, J. R. 1994. Complexity: Fad or future? *Futures,* 26**,** 563-567.

SCARPA, R. & TILLING, R. 1996. *Monitoring and Mitigation of Volcano Hazards,* Berlin, Springer.

SCARTH, A. 1994. *Volcanoes : an introduction,* London, UCL Press.

SCARTH, A. 2002. *La catastrophe Mount Pele and the destruction of Saint-Pierre, Martinique,* Harpenden, Herts, Terra Publishing.

SCHILLING, S. P. 1998. LAHARZ: GIS Programs for Automated Mapping of Lahar-inundation Hazard Zones. *Open-File Report 98-638.* Reston, Virginia: U.S. Geological Survey

SCOTT, B. Year. Volcano Alert Systems: Is there a generic one? *In:* Citites on Volcanoes 5, November 19 -23, 2007 2007 Shimabara, Japan.

SCOTT, K. M., MACÍAS, J. L., NARANJO, J. A., RODRIGUEZ, S. & MCGEEHIN, J. P. 2001. Catastrophic Debris Flows Transformed from Landslides in Volcanic Terrains: Mobility, Hazard Assessment and Mitigation Strategies. *Professional Paper 1630* Reston, Virginia: USGS.

SCOTT, W. E. & TILLING, R. I. 1989. Volcanic-hazards zonation and long-term forecasts. *Volcanic Hazards.* American Geophysical Union.

SELECT BIPARTISAN COMMITTEE 2006. A Failure of Initiative: Final Report of the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina. *In:* US HOUSE OF REPRESENTATIVES (ed.). Washington D.C.: Government Printing Office.

SENGE, P. M. 1990. *The fifth discipline: the art and practice of the learning organization,* New York, Doubleday / Currency.

SHERROD, D. R. S., W. E.; STAUFFER, P. H. 2008. A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004-2006. *Professional Paper 1750.* U.S. Geological Survey.

SIGURDSSON, H. & HOUGHTON, B. F. 2000. *Encyclopaedia of volcanoes,* San Diego, Academic Press.

SIMKIN, T. & SIEBERT, L. 1994. *Volcanoes of the world : a regional directory, gazatteer, and chronology of volcanism during the last 10,000 years,* Tucson, Arizona, Geoscience Press published in association with the Smithsonian Institution.

SINHA, A. K. & AVRANI, S. U. 1984. The disaster warning process: A study of the 1981 Gujarat cyclone. *Disasters,* 8**,** 67-73.

SLOVIC, P. 1999. Trust, emotion, sex, politics, and science: Surveying the risk- assessment battlefield. *Risk Analysis,* 19**,** 689-701.

SLOVIC, P. 2000. *The perception of risk,* London, Earthscan Pub.

SLOVIC, P., FISCHHOFF, B. & LICHTENSTEIN, S. 2007. Why study risk perception? *Risk Analysis,* 2**,** 83-93.

SNOWDEN, D. 2005. Strategy in the context of uncertainty. *Handbook of Business Strategy,* 6**,** 47-54.

SOKAL, A. D. & BRICMONT, J. 1998. *Intellectual impostures : postmodern philosophers' abuse of science*, London : Profile.

SOLANA, M. C., KILBURN, C. R. J. & ROLANDI, G. 2008. Communicating eruption and hazard forecasts on Vesuvius, Southern Italy. *Journal of Volcanology and Geothermal Research,* 172**,** 308-314.

SORENSEN, J. H. 2000. Hazard warning systems: Review of 20 years of progress. *Natural Hazards Review,* 1**,** 119-125.

SOREY, M. L., FARRAR, C. D., GERLACH, T. M., MCGEE, K. A., EVANS, W. C., COLVARD, E. M., HILL, D. P., BAILEY, R., ROGIE, J. D., HENDLEY II, J. W. & STAUFFER, P. H. 1996. Invisible CO2 Gas Killing Trees at Mammoth Mountain, California. *U.S. Geological Survey Fact Sheet 172-96.* Reston, Virginia: U.S Geological Survey.

SORNETTE, A., DUBOIS, J., CHEMINÉE, J. L. & SORNETTE, D. 1991. Are Sequences of Volcanic Eruptions Deterministically Chaotic? *J. Geophys. Res,* 97**,** 11,931-11,945.

SORRELL, J. M. & REDMOND, G. M. 1995. Interviews in qualitative nursing research: differing approaches for ethnographic and phenomenological studies. *Journal of Advanced Nursing,* 21**,** 1117-1122.

SPARKS, R. S. J. 2003. Forecasting volcanic eruptions. *Earth and Planetary Science Letters,* 210**,** 1-15.

SPARKS, R. S. J. & ASPINALL, W. 2004. Volcanic activity; frontiers and challenges in forecasting, prediction and risk assessment. *In:* SPARKS, R. S. J. & HAWKESWORTH, C. J. (eds.) *The State of the Planet: frontiers and challenges* Washington DC: American Geophysical Union.

STACEY, R. D. 1996. *Complexity and creativity in organizations,* San Francisco, Berrett-Koehler.

STEENBLIK, J. W. 1990. Volcanic Ash: A rain of terra. *Airline Pilot June / July.*

STIRLING, A. 1999. On Science and Precaution in the Management of Technological Risk (A synthesis report of case studies). Seville.: Institute for Prospective Technological Studies (European Commission Joint Research Centre).

STIRLING, A. 2003. Risk, uncertainty and precaution: some instrumental implications from the social sciences. *In:* BERKHOUT, F., LEACH, M., AND SCOONES, I. (ed.) *Negotiating Environmental Change.* Aldershot, UK: Edward Elgar.

STIRLING, A. 2007. Risk, precaution and science: towards a more constructive policy debate. *European Molecular Biology Organization,* 8**,** 309-315.

STIRLING, A. 2008. "Opening up" and "closing down": Power, participation, and pluralism in the social appraisal of technology. *Science Technology and Human Values,* 33**,** 262-294.

SUSMAN, P., O'KEEFE, P. & WISNER, B. 1983. Global disasters, a radical interpretation. *In:* HEWITT, K. (ed.) *Interpretations of calamity : from the viewpoint of human ecology.* London: Allen & Unwin.

SWANSON, D. A., CASADEVALL, T. J., DZURISIN, D., HOLCOMB, R. T., NEWHALL, C. G., MALONE, S. D. & WEAVER, C. S. 1985. Forecasts and predictions of eruptive activity at Mount St. Helens, USA: 1975-1984. *J. Geodynamics,* 3**,** 397-423.

SWANSON, D. A., CASADEVALL, T. J., DZURISIN, D., MALONE, S. D., NEWHALL, C. G. & WEAVER, C. S. 1983. Predicting Eruptions at Mount St-Helens, June 1980 Through December 1982. *Science,* 221**,** 1369-1376.

TAKAHASHI, T. 2007. *Debris flow : mechanics, prediction and countermeasures,* London, Taylor & Francis.

TALEB, N. 2007. *The black swan : the impact of the highly improbable,* New York, Random House.

TATTERSALL, C., WATTS, A. & VERNON, S. 2007. Mind mapping as a tool in qualitative research. *Nursing Times* [Online], 103. Available: http://www.nursingtimes.net/nursing-practice-clinical-research/mind-mapping-as-a-tool-in-qualitative-research/199503.article.

TAYAG, J., INSAURIGA, S., RINGOR, A., BELO, M., NEWHALL, C. G. & PUNONGBAYAN, R. S. 1996. People's Reposnse to Eruption Warning: The Pinatubo Expereince, 1991-92. *Fire and mud: Eruptions and lahars of Mount Pinatubo, Phillippines.* Seattle and London: University of Washington Press.

TELFORD, J. & COSGROVE, J. 2006. Joint Evaluation of the International Response to the Indian Ocean Tsunami: Synthesis Report. Tsunami Evaluation Coalition.

THIEREN, M. 2005. Asian tsunami: death-toll addiction and its downside. Bulletin of the World Health Organization (BLT)

THOMPSON, D. 2000. *Volcano cowboys : the rocky evolution of a dangerous science,* New York, St. Martin's Press.

TIERNEY, K. J. & DYNES, R. R. 1994. *Disasters, collective behavior, and social organization / edited by Russell R. Dynes and Kathleen J. Tierney,* Newark: London; Cranbury, NJ, University of Delaware Press; Associated University Presses.

TILLING, R. 1989. Volcanic Hazards and the Mitigation: Progress and Problems. *Reviews of Geophysics,* 27**,** 237-269.

TILLING, R. & LIPMAN, R. W. 1993. Lessons in reducing volcanic risk. *Nature,* 364**,** 277-280.

TILLING, R. I. 2002. Volcano Monitoring and Eruption Warnings. *In:* ZSCHAU, J. & KUPPERS, A. N. (eds.) *Early Warning Systems for Natural Disaster Reduction.* Springer.

TILLING, R. I., HELIKER, C. C. & WRIGHT, T. L. 1987. *Eruptions of Hawaiian volcanoes : past, present, and future,* Denver, CO, Dept. of the Interior, U.S. Geological Survey.

TILLING, R. I., TOPINKA, L. J., SWANSON, D. A. & GEOLOGICAL SURVEY (U.S.) 1990. *Eruptions of Mount St. Helens : past, present, and future,* Washington, D.C., U.S. Dept. of the Interior. .

TILLING, R. I., ZSCHAU, J. & KŠUPPERS, A. N. 2003. Volcano monitoring and eruption warnings. *Early warning systems for natural disaster reduction.* Berlin: Springer.

TILLING, R. T. 2001. Development of a universal scheme of volcano-status levels. *Cities on Volcanoes 2 Workshop.* Auckland, New Zealand.

TIMMERMANS, S. & BERG, M. 1997. Standardization in Action: Achieving Local Universality through Medical Protocols. *Social Studies of Science,* 27**,** 273-305.

TOBIN, G. A. & WHITEFORD, L. M. 2002. Community resilience and volcano hazard: The eruption of Tungurahua and evacuation of the Faldas in Ecuador. *Disasters,* 26**,** 28-48.

TROISE, C., DE NATALE, G. & KILBURN, C. R. J. 2006. *Mechanisms of activity and unrest at large calderas,* London, Geological Society.

TWIGG, J. 2004. *Disaster Risk Reduction: Mitigation and Preparedness in Development and Emergency Programming*, Humanitarian Practice Network (HPN).

U.S. CONGRESS 1879. Organic Act of the U.S. Geological Survey. 20 Stat. L., 394.

UN ISDR. 2003. *Terminology: Basic Terms of Disaster Risk Reduction* [Online]. Available: www.unisdr.org/eng/library/lib-terminology-eng%20home.htm [Accessed 25/08/2009].

UN ISDR. Year. Yokohama Strategy and Plan of Action for a Safer World: Guidelines for Natural Disaster Prevention, Preparedness and Mitigation. *In:* World Conference on Disaster Reduction, 23-27 May 1994 2004 Yokohama, Japan.

UN ISDR 2005. Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters.

UN ISDR. Year. Early Warning - From Concept to Action - The Conclusions. *In:* Third International Conference on Early Warning: From Concept to Action, 27–29 March 2006 2006a Bonn, Germany.

UN ISDR. Year. Early warning - from concept to action: the conclusions of the third international conference on early warning (EWC III). *In*, 27-29 March 2006 2006b Bonn, Germany. 32.

UN ISDR PPEW 2006. Global Survey of Early Warning Systems: An assessment of capacities, gaps and opportunities toward building a comprehensive global early warning system for all natural hazards. *In:* PLATFORM FOR THE PROMOTION OF EARLY WARNING (UNISDR - PPEW) (ed.). UN.

UNDHA 1992. Internationally Agreed Glossary of Basic Terms Related to Disaster Management. Geneva: UN.

UNDRO 1985. Volcanic Emergency Management. Geneva.

UNDRO 1990. Mitigating Natural Disasters: Phenomena, effects and options. *In:* OFFICE OF THE UNITED NATIONS DISASTERS RELIEF CO-ORDINATOR (ed.) *A manual for policy makers and planners.* Geneva: United Nations

URRY, J. 2005a. The complexities of the global. *Theory, Culture and Society,* 22**,** 235-254+273.

URRY, J. 2005b. The complexity turn. *Theory, Culture and Society,* 22**,** 1-14.

US DEPARTMENT OF HOMELAND SECURITY. 2010. *Department of Homeland Security Advisory System* [Online]. Available: http://www.dhs.gov/files/programs/Copy_of_press_release_0046.shtm#5 [Accessed 06/05/2010].

US FOREST SERVICE 1992. Mt St Helens Contingency Plan.

USGS 2004. Understanding Volcano Hazards and Preventing Volcanic Disasters, A Science Strategy for the Volcano Hazards Program. *U.S. Geological Survey, 2004-2008.*

USGS. 2009a. *About USGS: our mission and vision* [Online]. Available: http://www.usgs.gov/aboutusgs [Accessed 07/05/2010].

USGS. 2009b. *Eruption Warning and Real-Time Notifications* [Online]. Available: http://volcanoes.usgs.gov/Products/Warn/warn.html [Accessed 07/08/2009 2008].

USGS. 2009c. *USGS Science Areas* [Online]. USGS. Available: http://www.usgs.gov/programs.asp [Accessed 07/08/2010].

USGS NEWSROOM 2010. USGS Awards $2.7 Million in Stimulus Funding to Improve the Detection of Changes in the Earth's Crust.

USGS VHP 2007. Volcano hazard notification for volcanic activity: towards a more uniform approach. USGS.

USGS VHP WEBSITE. 2008. *The Consortium of U.S. Volcano Observatories* [Online]. Available: http://volcanoes.usgs.gov/vhp/cusvo.php [Accessed 13/08/2010 2010].

VAN DER SLUIJS, J. 2005. Uncertainty as a monster in the science-policy interface: four coping strategies. *Water Science and Technology,* 52**,** 87-92.

VARLEY, N., JOHNSON, J., RUIZ, M., REYES, G., MARTIN, K., MADER, H. M., COLES, S. G., CONNOR, C. B. & CONNOR, L. J. 2006. Applying statistical analysis to understanding the dynamics of volcanic eruptions. *Statistics in Volcanology.* London: Special Publication of IAVCEI, Geological Society.

VAUGHAN, D. 1996. *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*, University of Chicago and Chicago Press.

VAUGHAN, D. 1999. The role of the organization in the production of techno-scientific knowledge. *Social Studies of Science,* 29**,** 913-943.

VELASCO, M. L. C. 2000. Mt Galeras: activities and lessons to be learned. *Philosophical Transactions of the Royal Society of London Series A-Mathematical Physical and Engineering Sciences,* 358**,** 1607-1617.

VHP USGS. 2003. *A Science Strategy for the Volcano Hazards Program,* [Online]. Available: http://volcanoes.usgs.gov/publications/pdf/5yrplan0408.pdf [Accessed 06/09/2010].

VHP WEBSITE. 2009a. *Icons for USGS Volcanic Activity Alert-Notification System* [Online]. U.S. Geological Survey Volcano Hazard Program. Available: http://volcanoes.usgs.gov/activity/alertsystem/icons.php [Accessed 20/04/2009].

VHP WEBSITE. 2009b. *Volcano Status Map* [Online]. Available: http://volcanoes.usgs.gov/activity/ [Accessed 02/04/2009].

VOIGHT, B. 1990. The 1985 Nevado-Del-Ruiz Volcano Catastrophe - Anatomy and Retrospection. *Journal of Volcanology and Geothermal Research,* 42**,** 151-188.

VOLCANIC ASH ADVISORY CENTRE. 2010. *VAAC's around the world* [Online]. NOAA. Available: http://vaac.arh.noaa.gov/info/index.php [Accessed 07/09/2010].

VON KRAUSS, M. K., VAN ASSELT, M. B. A., HENZE, M., RAVETZ, J. & BECK, M. B. 2005. Uncertainty and precaution in environmental management. *Water Science and Technology,* 52**,** 1-9.

WAYTHOMAS, C. F., POWER, J. A., RICHTER, D. H. & MCGIMSEY, R. G. 1998. Preliminary volcano-hazard assessment for Akutan Volcano east-central Aleutian Islands, Alaska. *Open-File Report 98-0360.* Anchorage, Alaska; Denver, CO: Alaska Volcano Observatory, USGS.

WEBLEY, P. & MASTIN, L. 2009. Improved prediction and tracking of volcanic ash clouds. *Journal of Volcanology and Geothermal Research,* 186**,** 1-9.

WEBLEY, P. W., DEHN, J., LOVICK, J., DEAN, K. G., BAILEY, J. E. & VALCIC, L. 2009. Near-real-time volcanic ash cloud detection: Experiences from the Alaska Volcano Observatory. *Journal of Volcanology and Geothermal Research,* 186**,** 79-90.

WEBSTER, A. 2004. Health technology assessment: A sociological commentary on reflexive innovation. *International Journal of Technology Assessment in Health Care,* 20**,** 61-66.

WEEKS, J. 2004. *Unpopular culture the ritual of complaint in a British bank,* Chicago, University of Chicago Press.

WHITE, D. 1995. Application of systems thinking to risk management : a review of the literature. *Management Decision,* 33**,** 35-45.

WHITE, G. F. & HAAS, J. E. 1975. *Assessment of research on natural hazards*, MIT Press.

WILLIAMS, R. S. & MOORE, J. G. 1983. *Man Against Volcano: The Eruption on Heimaey, Vestmannaeyjar, Iceland*, USGS.

WISNER, B. 2004. *At risk : natural hazards, people's vulnerability, and disasters,* London ; New York, Routledge.

WMO 2007. ICAO Annex 3 - Meteorological Service for International Air Navigation / WMO Technical Regulations (C.3.1).

WOVO. 2008. *Volcano Alert Levels* [Online]. Available: http://www.wovo.org/volcanic-alert-levels.html [Accessed 06/09/2008 2008].

WOVO. 2010. *The World Organization of Volcano Observatories (WOVO) Database of Volcanic Unrest (WOVOdat).* [Online]. Available: http://www.wovodat.org/ [Accessed 06/07/2010 2010].

WRIGHT, T. L. & PIERSON, T. C. 1992. Living with volcanos : The U.S. Geological Survey's Volcano Hazards Program. *U.S. Geological Survey circular 1073.* Washington, D.C.: United States Government Printing Office.

WYNNE, B. 1982. *Rationality and ritual : the Windscale inquiry and nuclear decisions in Britain,* Chalfont St Giles, The British Society for the History of Science.

WYNNE, B. 1996. May the sheep safely graze? A reflexive view of the expert-lay knowledge divide. *In:* LASH, S., SZERSZYNSKI, B. & WYNNE, B. (eds.) *Risk, environment and modernity : towards a new ecology.* London: Sage.

WYNNE, B. 2005. Reflexing complexity: Post-genomic knowledge and reductionist returns in public science. *Theory, Culture and Society,* 22**,** 67-94+270.

YEARLEY, S. 2005. *Making sense of science understanding the social study of science,* London, SAGE.

YIN, R. K. 2003. *Applications of case study research,* Thousand Oaks, Sage Publications.

YOUNG, P. C., MADER, H. M., COLES, S. G., CONNOR, C. B. & CONNOR, L. J. 2006. New approaches to volcanic time-series analysis. *Statistics in Volcanology.* London: Special Publication of IAVCEI, Geological Society.

YOUNG, S. R., VOIGHT, B., SPARKS, R. S. J., ROWLEY, K., ROBERTSON, R. E. A., LYNCH, L. L. & ASPINALL, W. P. 1998. The Soufriere Hills eruption, Montserrat, British West Indies: Introduction to special section, part 2. *Geophysical Research Letters,* 25**,** 3651-3651.

ZHONG, Y. & LOW, S. P. 2009. Managing crisis response communication in construction projects - from a complexity perspective. *Disaster Prevention and Management,* 18**,** 270-282.