Global volcanic hazards and risk

Summary background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015

A report by Global Volcano Model[1] and the
International Association of Volcanology and Chemistry of the Earth's Interior[2]

GVM GLOBAL VOLCANO MODEL

IAVCEI

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1. The Global Volcano Model (GVM; http://globalvolcanomodel.org/) was launched in 2011 and has grown to include 31 partner institutes collaborating from across the globe representing scientists from disciplines including volcanology, engineering and social science as well as private sector institutions. GVM is an international collaborative platform to integrate information on volcanoes from the perspective of forecasting, hazard assessment and risk mapping. The network aims to provide open access systematic evidence, data and analysis of volcanic hazards and risk on global and regional scales, and to support Volcano Observatories at a local scale.
2. The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI; http://www.iavcei.org/) is an association of the International Union of Geodesy and Geophysics (IUGG). IAVCEI is the international association for volcanology with about 2000 members. The Association represents the primary international focus for: (1) research in volcanology, (2) efforts to mitigate volcanic disasters, and (3) research into closely related disciplines. There are 22 topic focussed Commissions of IAVCEI covering all aspects of volcanology, including hazards and risk.

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This is Section I of IV of the GVM/IAVCEI contribution to the UN ISDR GAR-15. This is a summary report to accompany a longer Technical Report (Section II of IV). Information sources referred to in this summary can be found in the Technical Report.

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Cover image: The incandescent lava dome at the summit of Soufriere Hills Volcano, Montserrat. Photograph by Paul Cole.

Contents

1 Introduction

Volcanic hazard and risk have not been considered in previous GAR reports. This summary report for GAR15 is supported by a technical report, a series of background papers and case studies, and thus comprises the first global assessment of volcanic hazard and risk. This documentation is a joint effort of the Global Volcano Model (GVM) network and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). The Volcanoes of the World database of the Smithsonian Institution (VOTW4) provides the source of most volcano data used in this study.

Approximately 800 million people live within 100 km of a volcano that has the potential to erupt. These volcanoes are located in 86 countries and additional overseas territories worldwide [see CS1 and Section IV: Country Profile report][*]. Volcanic eruptions can cause loss of life and livelihoods in exposed communities, damage critical infrastructure, displace populations, disrupt business and add stress to already fragile environments[1]. The total loss of life from volcanic eruptions has been modest compared to other natural hazards (~280,000 documented since 1600 AD)[2]. However, a small number of eruptions are responsible for a large proportion of these fatalities, demonstrating the potential for devastating mass casualties in a single event (Figure 1). Importantly, these eruptions are not all large and the impacts are not all proximal to the volcano. For example, the modest eruption of Nevado del Ruiz, Colombia, in 1985 triggered lahars (volcanic mudflows) which resulted in the deaths of more than 23,000 people tens of kilometres from the volcano[3].

There is often a lack of awareness of volcanic risk in areas beyond the immediate proximity of a volcano and indeed the risk may not have been assessed at all[4]. Understanding the risks posed by a volcano requires a thorough understanding of the eruptive history of that volcano, ideally through both geological and historical research[5]. There is still significant uncertainty about the eruption history at many of the world's volcanoes. For example, before the 2008 eruption of Chaitén volcano, Chile, the few studies available suggested that the last eruption occurred thousands of years ago. The threat appeared low and so the closest monitoring station operated by the Volcano Observatory was more than 200 km away It was only after the 2008 eruption, which resulted in the evacuation of Chaitén town, that new dating was undertaken which showed that in fact Chaitén volcano has been more active than previously thought. Had the research been done first, an eruption may have been anticipated[6]. The inequalities in monitoring capacity worldwide and the lack of basic geological information at some volcanoes is demonstrated in the report of country and regional profiles [Section IV].

Volcanic eruptions are almost always preceded by 'unrest'[7,8] including volcanic earthquakes and ground movements, which can allow scientists at Volcano Observatories to provide early warnings if there is a good monitoring network[9] [CS12, CS15]. Increasingly, effective monitoring from both the ground and space is enabling Volcano Observatories to provide good short-term forecasts of the onset of eruptions or changing hazards situations[10,11]. Such forecasts and early warnings can support timely decision-making and risk mitigation measures by civil authorities[4,12]. For example, nearly 400,000 people were evacuated during the November 2010 eruption of Merapi, Indonesia and it is estimated that 10,000 to 20,000 thousand lives were saved as a result[13] . There were 386 fatalities

[*] This report is supported by case studies with the label CS and these are located as appendices: summaries are provided as an appendix to this section and full case studies are provided in Section II.

and estimated losses of US$300 million[14][CS6, CS7]. Many Volcano Observatories are active in the vulnerable communities, helping to build awareness of, and resilience to, volcanic hazards and risk.

The economic impact of volcanic eruptions has recently become more apparent at local, regional and global scales. The 2010 eruption of the Eyjafjallajökull volcano in Iceland caused serious disruption to air traffic in the north Atlantic and Europe as fine volcanic ash in the atmosphere drifted thousands of kilometres from the volcano[15]. The resulting global economic losses from this modest-sized eruption accumulated to about US $ 5 billion[16] as global businesses and supply chains were affected.

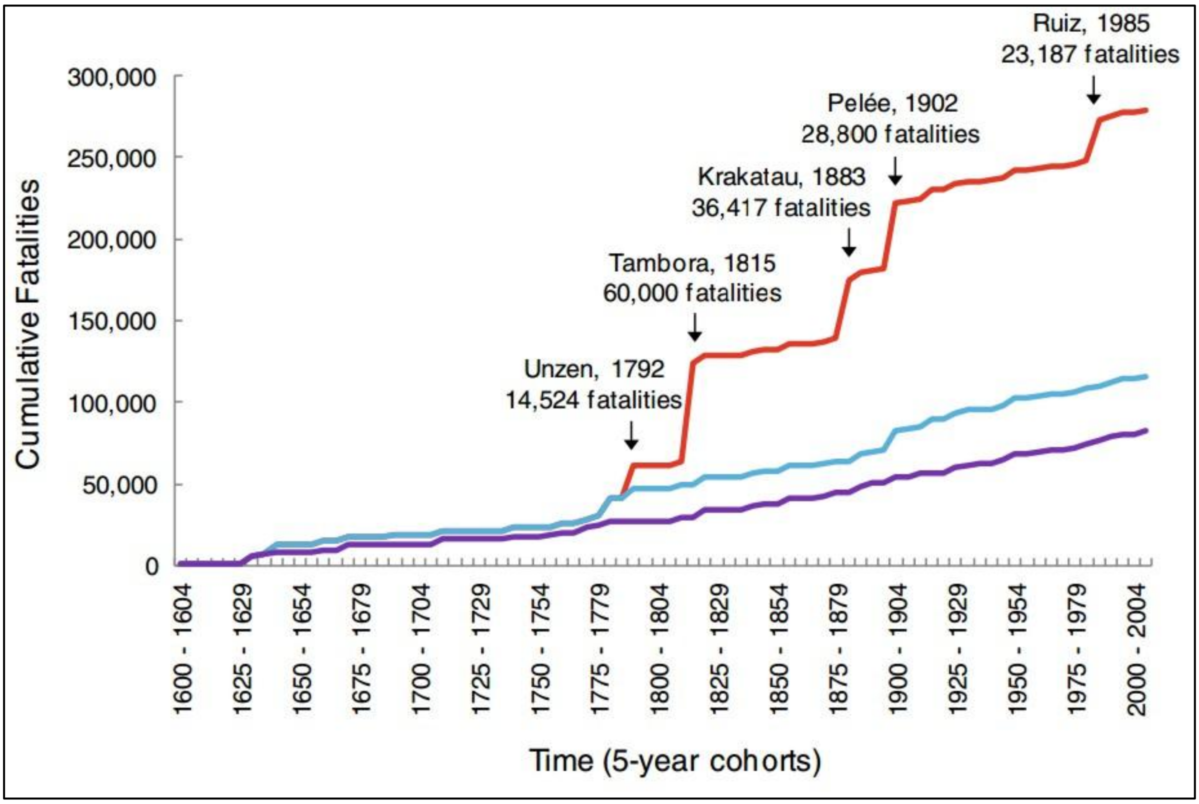

Figure 1: Cumulative number of fatalities directly resulting from volcanic eruptions[2]. Shown using all 533 fatal volcanic incidents (red line), with the five largest disasters removed (blue line), and with the largest ten disasters removed (purple line). The largest five disasters are: Tambora, Indonesia in 1815 (60,000 fatalities); Krakatau, Indonesia in 1883 (36,417 fatalities); Pelée, Martinique in 1902 (28,800 fatalities); Nevado del Ruiz, Colombia in 1985 (23,187 fatalities); Unzen, Japan in 1792 (14,524 fatalities). The sixth to tenth largest disasters are: Grímsvötn, Iceland, in 1783 (9,350 fatalities); Santa María, Guatemala, in 1902 (8,700 fatalities); Kilauea, Hawaii, in 1790 (5,405 fatalities); Kelut, Indonesia, in 1919 (5,099 fatalities); Tungurahua, Ecuador, in 1640 (5,000 fatalities). Counts are calculated in five-year cohorts.

The median duration of historical volcanic eruptions has been about 7 weeks, but eruptions may be as short as one day or may last for decades[17]. The size and frequency of eruptions is also highly variable. Volcanic eruptions produce a variety of different hazards, including pyroclastic flows, lahars, lava flows, ballistics, ash fall, lightning, gases and aerosols. These hazards may occur in different combinations at different times[1,18]. Long-lived or frequent eruptions pose particular challenges for communities and there are good examples of social adaptation in response to these difficult situations[19]. For example, Soufrière Hills Volcano in Montserrat (Lesser Antilles), erupted frequently between 1995-2010. These eruptions caused 19 fatalities on 25 June 1997[20], and the loss of the capital, port and airport, social and economic distress, and the progressive off-island evacuation of more than 7,500 people (two thirds of the pre-eruption population), leaving a population of less than 3,000 in 1998[21]. A strong cultural identity has helped islanders to cope and a state-of-the-art Volcano Observatory has become established that continues to support development of new methodologies in hazard and risk assessment [CS18]. Tungurahua in Ecuador has erupted since 1999 and innovative incentives to encourage rapid evacuation have been developed. A system of community 'vigías' (watchers) support scientists, civil defence and their communities by observing the volcano and organising evacuations of their communities if necessary[22]. Some of the farmers at highest risk have been allocated additional fields away from the volcano, providing options for retreat in times of threat and uncertainty [CS23]. The preservation or rebuilding of livelihoods, critical infrastructure systems and social capital is essential to successful adaptation under these conditions.

Despite exponential population growth, the number of fatalities per eruption has declined markedly in the last few decades, suggesting that risk reduction measures are working to some extent[2]. There has been an increase in volcano monitoring and resultant improvements in hazard assessments, early warnings, short-term forecasts, hazard awareness, communication and preparedness around specific volcanoes[23-28]. It is conservatively estimated that at least 50,000 lives have been saved over the last century as a consequence of these improvements[2]. Unfortunately, many volcanoes worldwide are either unmonitored or not sufficiently monitored to result in effective risk mitigation (Country Profiles, Secion IV) and therefore when they re-awaken the losses may be considerable.

Although volcanoes do present hazards during unrest and eruption, they also provide benefits to society during their much longer periods of repose[29-32]. Volcanoes commonly provide favourable environments: soils are often fertile; elevated topography provides good living and agricultural conditions, especially in the equatorial regions[33]; water resources are commonly plentiful; volcano tourism can be lucrative; and some volcanoes have geothermal systems, making them a target for exploration and potential energy resources[32]. These benefits mean many individuals and communities choose to live in volcanic areas, but they may not be aware of volcanic risks.

2 Volcanoes in space and time

Most active volcanoes occur at the boundaries between tectonic plates[34,35] (Figure 2) where the Earth's crust is either created in rift zones (where tectonic plates move slowly apart) or destroyed in subduction zones (where plates collide and one is pushed below the other). Most volcanoes along rift zones are deep in the oceans along mid-ocean ridges. Some rift zones extend from the oceans and seas onto land, for example in Iceland and the East African Rift valley. The Pacific 'ring of fire' comprises chains of island volcanoes (e.g. Aleutians, Indonesia, Philippines) and continental volcanoes (e.g. in the Andes) that have formed above subduction zones. These volcanoes have the potential to be highly explosive. Other notable subduction zone volcanic chains include the Lesser Antilles in the Caribbean and the South Sandwich Islands in the Southern Atlantic. Some active volcanoes occur in the interiors of tectonic plates above mantle 'hot spots', the Hawaiian volcanic chain and Yellowstone in the USA being the best-known examples.

There are many different types of volcanoes in each of these settings, some are typical steep-sided cones, some are broad shields, some of the larger caldera volcanoes are almost indistinguishable on the ground and can only be seen clearly from space[17,35]. Each volcano may demonstrate diverse eruption styles from large explosions that send buoyant plumes of ash high into the atmosphere to flowing lavas. Each eruption evolves over time resulting in a variety of different hazards and a wide range of consequent impacts. This variety in behaviours arises because of the complex and non-linear processes involved in the generation and supply of magma to the Earth's surface[36]. The subsequent interaction of erupting magma with surface environments such as water or ice may further alter the characteristics of eruptions and thus their impacts. This great diversity of behaviours and consequent hazards means that each volcano needs to be assessed and monitored individually. For this reason a critical aspect of living with an active volcano is to have a dedicated Volcano Observatory.

There are two main measures of volcanic eruptions, namely magnitude and intensity, neither of which is easy to measure. The magnitude of an eruption is defined as total erupted mass (kg), while intensity is defined as the rate of eruption or mass flux (kg per second). A widely used index to characterise the size of purely explosive eruptions is the *Volcanic Explosivity Index* (VEI) which comprises a scale from 0 to 8 (Figure 3). The VEI is usually based on the volume of explosive ejecta (which can be estimated based on fieldwork after an eruption) and also the height of the erupting column of ash[37]. The height of an ash column generated in an explosive eruption can be measured relatively easily and is related to intensity[38,39] .

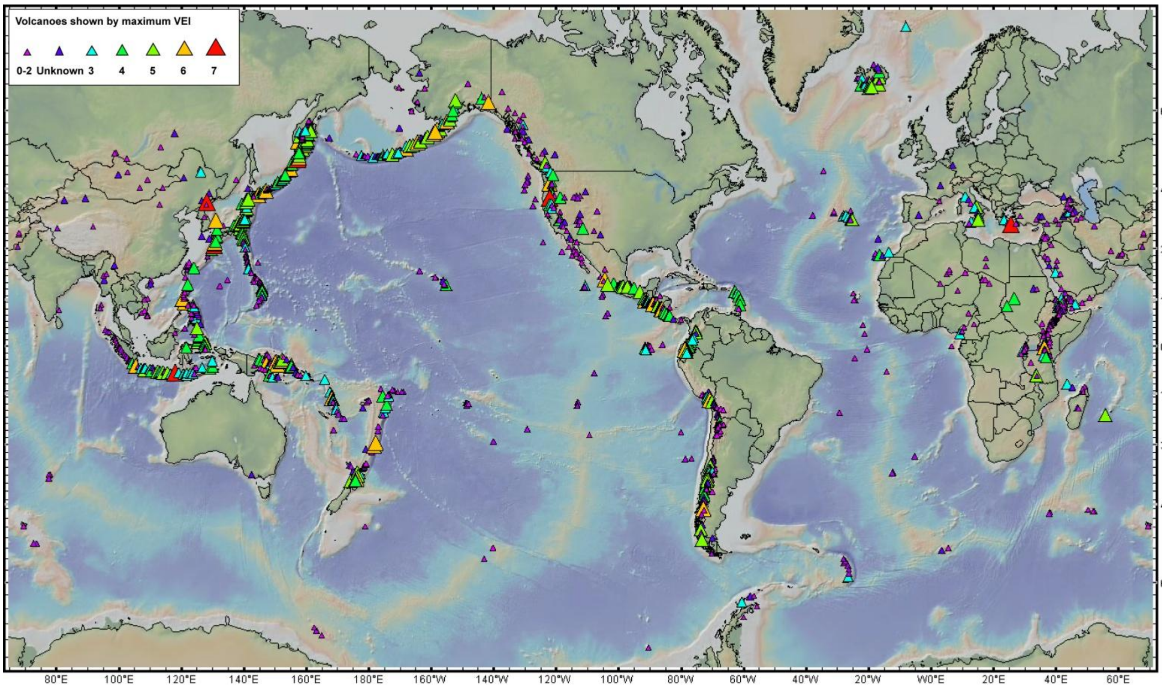

Figure 2: Potentially hazardous volcanoes are shown with their maximum recorded VEI during the Holocene. Eruptions of unknown size and VEI 1-2 are shown in purple and dark blue. The warming of the colours and the increase in size of the triangles represents increasing VEI. Volcanoes mostly occur along plate boundaries with a few exceptions. There may be thousands of additional active submarine volcanoes along mid-ocean ridges but they don't threaten populated areas.

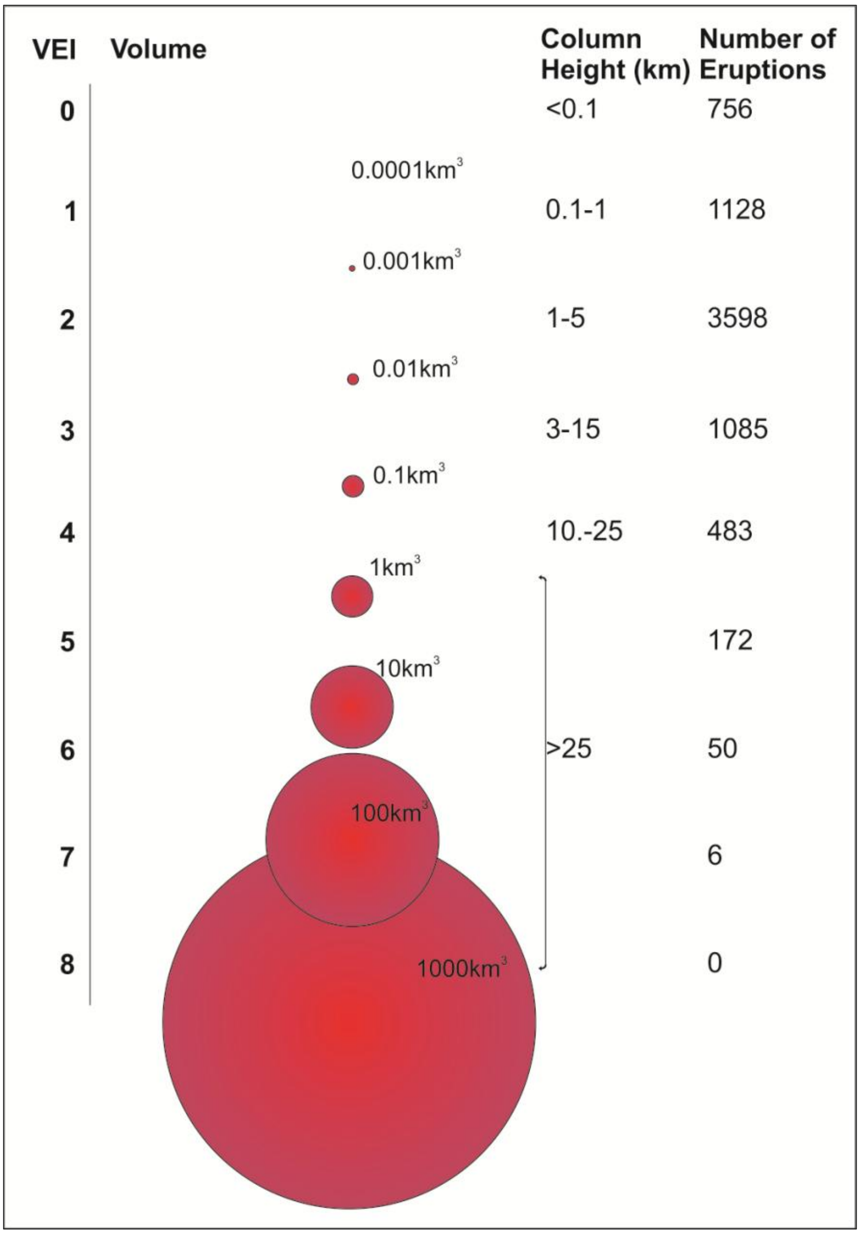

Figure 3: VEI is best estimated from erupted volumes of ash but can also be estimated from column height. The typical column heights and number of confirmed Holocene eruptions with an attributed VEI in VOTW4.22 are shown[17].

In general, there is an increasing probability of fatalities with increasing eruption magnitude, for example, all recorded VEI 6 and 7 eruptions have caused fatalities[2]. Five major disasters dominate the historical dataset on fatalities accounting for 58% of all recorded fatalities since 4350 BC (Figure 1). The two largest disasters in terms of fatalities were caused by the largest eruptions (Tambora 1850; Krakatau 1883). Nevertheless, small eruptions can be devastating, the modest eruption of Nevado del Ruiz (VEI 3) and the subsequent 23,000+ fatalities being a case in point[3]. A statistical analysis of all volcanic incidents (any volcanic event that has caused human fatalities), excluding the five dominant major disasters, highlights the fact that VEI 2-3 eruptions are most likely to cause a fatal volcanic incident of any scale and VEI 3-4 eruptions are most likely to have the highest numbers of fatalities[2].

The Smithsonian Institution collates the Volcanoes of the World database[17,40] (VOTW4.0) which is regarded as the authoritative source of information on Earth's volcanism and is the main resource for this study (data cited in this report are from VOTW4.22).

In total there are 1,551 volcanoes in VOTW4.0 of which 866 are known to have erupted in the last 10,000 years (Holocene). Over the same time period there are 9,444 known volcanic eruptions in the database. Since 1500 AD, there are 596 volcanoes that are known to have erupted. Only about 30% of the world's Holocene volcanoes have any published information about eruptions before 1500 AD, while 38% have no records earlier than 1900 AD. Statistical studies of the available records[41-43] suggest that only about 40% of explosive eruptions are known between 1500 and 1900 AD, while only 15% of large Holocene explosive eruptions are known prior to 1 AD.

The record since 1950 is believed to be almost complete with 2,208 eruptions recorded from 347 volcanoes. The average number of eruptions ongoing per year since 1950 is 63, with a minimum of 46 and maximum of 85 eruptions recorded per year. On average 34 of these are new eruptions beginning each year.

Going further back in time, the LaMEVE database[44] lists 3,130 volcanoes that have been active in the last 2.58 million years (Quaternary period), and some of these may well be dormant rather than extinct. Many of these volcanoes remain unstudied and much more information is needed to understand fully the threat posed by all of the world's volcanoes. There are also thousands of submarine volcanoes, but the great majority of these (with one or two exceptions) do not constitute a major threat.

Magnitude	**Return Period (years)**	**Uncertainty (years)**
≥4.0	2.5	0.9
≥4.5	4.1	1.3
≥5.0	7.8	2.5
≥5.5	24	5.0
≥6.0	72	10
≥6.5	380	18
≥7.0	2,925	190
≥7.5	39,500	2,500
≥8.0	133,350	16,000

Table 1: Global return periods for explosive eruptions of magnitude M, where $M = Log_{10}m - 7$ and m is the mass erupted in kilograms. The estimates are based on a statistical analysis of data from VOW4 and the Large Magnitude Explosive Volcanic Eruptions database (LaMEVE) version 2 (http://www.bgs.ac.uk/vogripa/)[44]. The analysis method takes account of the decrease of event reporting back in time [43]. Note that the data are for $M \geq 4$.

Estimating the global frequency and magnitude of volcanic eruptions requires under-recording to be taken into account[41-43]. Statistical analysis of global data for explosive eruptions (with under-recording accounted for) shows a decrease in the frequency of eruptions as magnitude increases (Table 1.1).

Volcanoes that erupt infrequently may have a high impact. For example, Pinatubo, Philippines[12] was dormant for a few hundred years before it erupted in 1991 [CS4], so populations, civil protection services and government authorities had no previous experience or even expectation of activity at the volcano. Conversely, some volcanoes are frequently active and local communities have learned to adapt (e.g. Sakurajima, Japan; Etna, Italy; Tungurahua, Ecuador [CS23]; Soufrière Hills volcano, Montserrat[23]. Very infrequent, extremely large volcanic eruptions (i.e. VEI 7-8+) have the potential for regional and global consequences and yet we have no experience of such events in recent historical time[45]. The super-eruptions that took place at Yellowstone (M=8 or more) have an estimated return period of about 130,000 years (Table 1), so are of very low probability in the context of human society.

3 Volcanic hazards and their impacts

Volcanoes produce multiple hazards[1,46] that must each be recognised and accounted for in order to mitigate their impacts. Depending upon volcano type, magma composition, eruption style and intensity at any given time, these hazards will have different characteristics. The major volcanic hazards that create risks for communities include:

Ballistics. Ballistics (also referred to as blocks or bombs) are rocks ejected by volcanic explosions. In most cases the range of ballistics is a few hundred metres to about two kilometres from the vent, but they can be thrown to distances of more than 5 kilometres in the most powerful explosions. Fatalities, injuries and structural damage result from direct impacts of ballistics, and those which are very hot on impact can start fires.

Volcanic ash and tephra. Explosive eruptions and pyroclastic density currents (see below) produce large quantities of intensely fragmented rock, referred to as tephra. The very finest fragments from 2 mm down to nanoparticles are known as 'volcanic ash' and can be produced in huge volumes. The physical and chemical properties of volcanic ash are highly variable and this has implications for impacts on health, environment and critical infrastructure [CS9; CS10], and also for the detection of ash in the atmosphere using remote sensing. Falling volcanic ash may cause darkness and very hazardous driving conditions, while concurrent rainfall leads to raining mud. Even relatively thin ash fall deposits (≥ 1 mm) may threaten public health[47,48] damage crops and vegetation, disrupt critical infrastructure systems[19,49,50], transport, primary production and other socio-economic activities over potentially very large areas. Ash fall creates major clean-up demands[1] [CS9], which need to be planned for (e.g. the availability of large volumes of water for hosing, trucks and sites to dump ash). The accumulation of ash on roofs can be hazardous especially if it is wet; for example, the collapse of roofs during the 1991 Mount Pinatubo eruption killed about 300 people [CS4]. Unfortunately, volcanic ash fall can also be persistent during long-lived eruptions, giving crops, the environment and impacted communities limited chance to recover[51]. Remobilisation of volcanic ash by wind can continue for many months after an eruption prolonging exposure[48,50].

Volcanic explosions inject volcanic ash into the stratosphere and ash may be transported by prevailing winds hundreds or even thousands of kilometres away from a volcano. Airborne ash is particularly dangerous for the aviation sector[52] [CS11]. For example, eruptions at Galunggung volcano, Indonesia, in 1982 and Redoubt volcano, Alaska, in 1989 caused engine failure of two airliners that encountered the drifting volcanic ash clouds. Forecasting the dispersal of volcanic ash in the atmosphere[39] (typically the role of Volcanic Ash Advisory Centres, see CS11) and forecasting how much ash will fall, where and with what characteristics (typically the role of Volcano Observatories, see CS12) are major challenges during eruptions [CS9].

The potentially wide geographic reach of volcanic ash, the relatively high frequency of explosive volcanic eruptions, and the variety of potential impacts make volcanic ash the hazard most likely to affect the greatest number of people. Section III on volcanic ash fall hazard and risk.

Pyroclastic flows and surges. These are hot, fast-moving avalanches of volcanic rocks, ash and gases that flow across the ground and may originate from explosive lateral blasts, the collapse of explosive eruption columns or the collapse of lava domes (Figure 4). *Pyroclastic flows* are concentrated flows of rocks, ash and gases that are typically confined to valleys, and *pyroclastic surges* are more dilute turbulent clouds of ash and gases that can rapidly spread across the landscape and even travel uphill or across water[53]. The spectrum of flow types are sometimes collectively referred to as *pyroclastic density currents.* They are the most lethal volcanic hazard accounting for one third of all known volcanic fatalities. They travel at velocities of tens to hundreds of kilometres per hour and have temperatures of hundreds of degrees centigrade.

Figure 4: Pyroclastic flow from the 1984 explosive eruption of Mayon, Philippines (C.Newhall).

A *volcanic blast* is a term commonly used to describe a very energetic kind of pyroclastic density current which is not controlled by topography and is characterised by very high velocities (more than 100 m/s in some cases) and dynamic pressures[54]. Volcanic blasts can destroy or cause severe damage to infrastructure, vegetation and agricultural land[1,54,55], and can even remove soil from the bedrock[23]. A volcanic blast from Mont Pelée volcano on the Caribbean island of Martinique destroyed the town of St. Pierre in 1902 with the loss of 29,000 lives[2]. This current took only three minutes to reach the edge of the town, which was about 5 kilometres from the volcano's summit.

There is no plausible protection from pyroclastic density currents and survival is very unlikely. Those who have survived in buildings at the margins of dilute currents have been very badly burned[20]. Thus the only appropriate response to the threat of an imminent pyroclastic density current is evacuation.

Lahars and floods. Lahars (volcanic mudflows) are a major cause of loss of life associated with volcanic eruptions, and account for 15% of all historical fatalities[2].

Figure 5: a) Only the roofs of 2-storey buildings are visible after repeated inundation by lahars following the 1991 eruption of Pinatubo, Philippines (C.Newhall).

b) Lahars during the 1991 eruption of Pinatubo in the Philippines caused the destruction of concrete bridges (USGS).

Lahars are fast-moving and destructive mixtures of volcanic debris and water that can destroy buildings, bridges, roads and cut off escape routes (Figure 5). Lahars can directly affect areas at distances of tens of kilometres from a volcano and may cause flooding hazards at even greater distances. They commonly occur when intense rain falls on unconsolidated volcanic debris, but they may also result from volcanic activity melting summit ice caps and glaciers or from eruptions in crater lakes. The moderate VEI 3 eruption of Nevado del Ruiz, Colombia, in 1985 produced pyroclastic density currents that melted some of the ice cap and generated lahars, causing ~23,000 fatalities in the town of Armero and village of Chinchina[3]. The potential for lahars during heavy rainfall can persist for years or even decades after an eruption if there are significant thicknesses of loose deposits, as was the case following the 1991 eruption of Pinatubo in the Philippines [CS4]. Geothermal activity beneath ice or the breaching of crater lakes and reservoirs can also trigger lahars between eruptions.

Debris avalanches, landslides and tsunamis. Many volcanoes are steep-sided mountains, partly built of poorly consolidated volcanic deposits which may be prone to instability, especially if there are active hydrothermal systems[56,57]. *Debris avalanches* can be large and remarkably mobile flows formed during the collapse of volcanic edifices and are commonly associated with volcanic eruptions or magmatic intrusions. Debris avalanches can lead to *lateral volcanic blasts* as the highly pressurised interior of a volcano is exposed (e.g. Mount St Helens, 1980). Volcanic landslides and debris avalanches can also be caused by hurricanes or regional tectonic earthquakes. Hurricane Mitch in 1998 triggered a major landslide on Casita volcano in Nicaragua, causing at least 3,800 fatalities. Debris avalanches that enter the sea displace large volumes of water and may cause tsunamis. In 1792 a debris avalanche from Mount Unzen, Japan, caused a tsunami resulting in over 32,000 fatalities. Most of the 36,417 fatalities reported during the 1883 eruption of Krakatau, Indonesia, were the result of lethal tsunamis generated from pyroclastic flows entering the sea[58]. Landslides are common on volcanoes, whether active or not.

Volcanic gases and aerosols. Volcanic gases can directly cause fatalities, health impacts, and damage to vegetation and property [CS7; CS8 and CS10]. Although the main component of gases released during most eruptions is water vapour, there are many other gas species and aerosols released, including carbon dioxide, sulfur dioxide, halogens (hydrogen fluoride and chloride) and trace metals such as mercury, arsenic and lead. The impact of volcanic gases on people depends on the concentrations present in the atmosphere and the duration of exposure. Volcanic gases tend to be denser than air and may accumulate in depressions or confined spaces (such as basements and work trenches), or flow along valleys. In 1986, a sudden overturn and release of carbon dioxide from Lake Nyos in Cameroon generated a silent and invisible gas cloud that flowed into surrounding villages, causing 1,800 fatalities as a result of asphyxiation[59]. Such lake overturns may occur without eruptive activity, for example following earthquakes or landslides into lakes (e.g. Lake Kivu[60] [CS8]).

Fluorine and chlorine-bearing gases can also be hazardous and may adhere to the surfaces of volcanic ash. People and animals can be affected by fluoride poisoning if they consume affected water, soil, vegetation or crops. Volcanic gases emitted by a volcano may combine with rainfall to produce acid rain which damages sensitive vegetation and ecosystems. Sulfur dioxide gas converts in the atmosphere to sulphate aerosols, a major cause of air pollution[61].

Lava. Lava flows usually advance sufficiently slowly to allow people and animals time to evacuate. However, anything in the path of a lava flow will be damaged or destroyed, including buildings, vegetation and infrastructure. Exceptional circumstances or unusual chemical compositions found at a small number of volcanoes can produce rapidly flowing lavas. For example, Nyiragongo in the Democratic Republic of Congo has a lake of very fluid lava at the summit. When the crater wall fractured in 1977 lava flowed downhill at speeds of more than 80 km/h killing an estimated 282 people. Another exceptionally mobile lava flow in 2002 [CS8] destroyed about 13% of Goma city, 80% of its economic assets, part of the international airport runway and the homes of 120,000 people[62], which combined with felt earthquakes and fear of death to cause severe psychological distress[60].

In contrast, very viscous lava will pile up to form a *lava dome* above a vent. These can be extremely hazardous with high pressure, gas-rich interiors and a tendency for partial or total collapse leading to pyroclastic flows and surges (pyroclastic density currents) [CS6].

Volcanic earthquakes. Earthquakes at volcanoes are typically small in magnitude (≤M5) but they may be felt and may cause structural damage. They may be particularly strong before a volcanic eruption as magma is forcing a path through the Earth's crust.

Lightning. Lightning occurs in volcanic ash clouds and has caused a number of fatalities[2].

Each volcanic hazard is a controlled by different physical and chemical processes that may occur at varying intensities and for different durations over time. Different hazards may occur concurrently (e.g. pyroclastic density currents and volcanic gas) or sequentially (ash fall followed by generation of lahars during intense rainfall). Some hazards are short-lived (e.g. ballistics associated with an explosion) or long-lived (e.g. repeated volcanic ash fall over weeks and months).

Secondary hazards such as disease or famine arising from evacuation, contaminated water, crop failure, loss of livestock, pollution and environmental degradation for example, can be widespread and account for over 65,000 fatalities since 1600 AD[2]. If a volcanic eruption is superimposed on an existing humanitarian crisis, as occurred in Goma in 2002, the likelihood of cascading impacts is much higher[60].

Consideration for the short and long term health consequences of various volcanic hazards has been a focus of attention for many years, resulting in a compilation of resources (including recommended sampling and analysis protocols) and a network of experts known as the International Volcanic Health Hazard Network [CS10]. Concentration thresholds and durations of exposure to volcanic gases, for example, are available to enable quantitative risk assessments to be developed for particular hazards scenarios [CS18, CS24].

4 Monitoring volcanic eruptions

Volcanic eruptions are usually preceded by days to months or even years of precursory activity or 'unrest'[9,17], unlike other natural hazards such as earthquakes. Detecting and recognising these signs provides the best means to anticipate, plan for and mitigate against potential disasters [CS15]. Unfortunately, only about 35% of Earth's active volcanoes are continuously monitored to identify such warning signs. Based on reports from Volcano Observatories summarised by the Global Volcanism Program of the Smithsonian Institution, between 2000-2011, 228 monitored volcanoes experienced unrest[9] and approximately half of them went on to experience eruptions within the 11 year time period.

A Volcano Observatory is an organisation (e.g. geological survey, national research institute, meteorology organisation, university or dedicated observatory) whose role it is to monitor active volcanoes and provide early warnings of anticipated volcanic activity to the authorities and usually also the public [CS12]. There are more than 100 Volcano Observatories worldwide and many have responsibility for multiple volcanoes. For each country, the exact constitution and responsibilities of a Volcano Observatory may differ, but it is typically the source of authoritative short term forecasts of volcanic activity as well as scientific advice about hazards and in some cases risk. They also have a critical role in ensuring aviation safety around the world working collaboratively with the world's Volcanic Ash Advisory Centres (VAACs [CS11]).

Ground-based monitoring programs for active volcanoes typically include[63]: a network of seismometers to detect volcanic earthquakes caused by magma movement[64,65]; a ground deformation network (e.g. Global Positioning System) to measure the rise and fall of the ground surface as magma migrates in the subsurface[24,66]; measurement of gas emissions into the atmosphere[67,68]; sampling and analysis of gases and water emitted from the summit and flanks of a volcano[69]; observations of volcanic activity using webcams and thermal imagery; measurements of other geophysical properties (e.g. strainmeters[25], infrasound[70]) and environmental indicators (e.g. groundwater levels). Volcano Observatories may have telemetry that enables real-time analysis of monitoring data or staff may undertake campaigns to collect data from sensors on a regular basis (e.g. daily, weekly).

Near real-time automatically processed monitoring data are increasingly being made available online by Volcano Observatories. Real-time monitoring allows the public and civil authorities to improve their understanding of monitoring methods and gain awareness of background activity during quiescence. Monitoring then facilitates real-time decision-making. For example, in Iceland before the Eyjafjallajökull eruption in 2010, some individuals self-evacuated before the official evacuation was announced when they saw the rapidly increasing numbers of earthquakes (http://en.vedur.is/earthquakes-and-volcanism/earthquakes/).

Ground-based monitoring instrumentation can be vulnerable to destruction by volcanic activity or other threats, such as theft or fire, so resources to maintain and restore monitoring if necessary are required. There are excellent examples of monitoring capability being developed very quickly and effectively and even improved after losses. For example the Vanuatu Geohazards Observatory was completely destroyed by fire in 2007, leaving Vanuatu with no monitoring capacity. Following this Vanuatu Geohazards and GNS Science, New Zealand, formed a partnership installing new monitoring equipment and improving the monitoring capabilities[71].

Information derived from satellite remote sensing can be a valuable addition to monitoring. High temporal and spatial resolution satellite remote sensing of volumetric changes in topography (of a growing lava dome) contributed to the rapid and timely evacuation at Merapi volcano, Indonesia in 2010[13] [CS7]. Radar (InSAR) is able to detect unrest at volcanoes previously thought to be dormant or extinct[72], but whether this unrest is caused by magmatic movement or other processes requires validation using ground-based methods[24]. Thermal anomalies can be correlated with eruption rate of magma, and ash and sulfur dioxide can also be detected in the atmosphere [39]. Only a few Volcano Observatories have the capacity to process satellite data in-house. However, initiatives such as Copernicus (ESA, 2014) and moves by the space agencies to respond to the Hyogo Framework for Action signal that satellite remote sensing has significant potential in disaster risk reduction [CS14]. One example of a multi-parameter volcano monitoring service is EVOSS (http://www.evoss-project.eu/) which provides processed information to Volcano Observatories and VAACs across Europe, Africa and the Caribbean. A wider participation in the International Charter for Space and Major Disasters and greater access to data and free and open-source software will undoubtedly contribute to further effective risk mitigation actions [CS6].

Real-time analysis of multi-parameter time-series datasets is necessary to make reliable and robust forecasts at volcanoes[63,67]. It has become evident that some signals or combinations of signals have more diagnostic value than others. Long period earthquakes have been used to make short-term forecasts of eruptions[64], for example at Popocatepetl, Mexico, in 2000 when thousands were evacuated 48 hours before a large eruption. Such earthquakes were also a strong indicator of imminent eruption at Soufrière Hills volcano, Montserrat, and elsewhere.

The ability of a Volcano Observatory to effectively make short-term forecasts about the onset of a volcanic eruption or an increase in hazardous behaviour is dependent on many things. They include having functioning monitoring equipment and telemetry, real-time data acquisition and processing, as well as some knowledge of the past behaviour of the volcano and a conceptual model for how the volcano works. There needs to be staff that includes skilled research scientists and technicians, with sufficient resources to respond when necessary, maintain equipment, acquire, process and interpret data, as well as disseminate knowledge and information on hazard (and possibly risk) to multiple stakeholders in a timely and effective way. Increasingly the ability to acquire and process Earth Observation data is necessary. Longer term forecasts over years or decades will be based mainly upon geological and geochronological data.

The Global Volcano Research and Monitoring Institutions Database (GLOVOREMID, [see CS16]) is in development. GLOVOREMID will allow an understanding of global capabilities, equipment and expertise distribution to be developed and will highlight gaps. GLOVOREMID began as a study of monitoring in Latin America, comprising 314 Holocene volcanoes across Mexico, Central and South America [CS16]. Efforts to expand GLOVOREMID to a global dataset are ongoing, but it is not yet complete.

A useful objective globally is to establish a minimum of baseline monitoring (e.g. seismometers) at all active volcanoes. Such monitoring levels will at least detect some signs of unrest so that enhanced monitoring networks can be rapidly deployed if necessary. There are nevertheless many locations where *rapid* deployment is not possible, a situation that should be considered in contingency planning.

5 Forecasting

An ability to forecast the onset of an eruption and significant changes during an eruption, are key components of an effective early warning system[5,26]. Intensive monitoring of recent eruptions has generated integrated time-series of data, which have resulted in several successful examples of warnings being issued on impending eruptions [CS4, CS6].

The great complexity of natural systems means that we cannot, in most cases give exact time and place predictions of volcanic eruptions and their consequences. There have been a few exceptions, for example, before the 1991 and 2000 eruptions of Hekla, Iceland, public warnings were issued tens of minutes before each eruption began with the likely time of eruption indicated[10,25]. The predictions were correct to within a few minutes. In general though, forecasting the outcomes of volcanic unrest and ongoing eruptions is inherently uncertain. They are becoming increasingly quantitative, evolving from empirical pattern recognition to forecasting based on models of the underlying eruption dynamics. This quantitative approach has led to the development and use of models for forecasting volcanic ash fall and pyroclastic flows, for example. Forecasting requires the use of quantitative probabilistic models to address aleatory uncertainty (irreducible uncertainties relating to the inherent complexity of volcanoes), as well as epistemic uncertainty (data- or knowledge-limited uncertainties). Forecasts of eruptions and hazards can be developed in a manner similar to weather forecasting [CS21][5].

Probabilistic forecast models for major hazards should ideally be used for managing risk at identified high-risk volcanoes, where both long-term mitigation actions such as moving critical infrastructure or short-term mitigation actions, such as evacuation, incur considerable costs.

Tools can be developed to support scientists in hazards analysis (e.g. modelling tools) and also to support consistent decision-making, such as raising and lowering alert levels. Event trees have been successfully used at many eruptions worldwide since the 1980s[4,73][CS4]. Bayesian Belief Network analysis is another method[26,74,75], which provides logical frameworks for discussing probabilities of possible outcomes at volcanoes showing unrest or already in eruption [5,73] [CS5]. Other Bayesian tools are particularly useful for short-term forecasting. They take account of available monitoring information [CS3, CS5], patterns of previous volcanic behaviour and can help to ensure consistency[4] of scientific advice, thereby assisting public officials in making urgent evacuation decisions and policy choices [CS7].

Such tools can be valuable for discussion between scientific teams, but also can facilitate communication with authorities and the public. The probability estimates might be based on past and current activity (empirical), expert elicitation[76], numerical simulations, or a combination of methods. The probabilities can be revised regularly as knowledge or methodologies improve or when volcanic activity changes.

6 Assessing volcanic hazards and risk

In order to make a thorough risk assessment, hazard, exposure and vulnerability must all be accounted for. In practice, most Volcano Observatories have focused on hazard assessments and where risk assessments are made there has been a tendency to focus only on hazard and exposure, and to consider only loss of life. Methods to quantify different aspects of vulnerability to volcanic hazards are improving and there are examples of detailed and comprehensive qualitative and semi-quantitative assessments of vulnerability to volcanic hazards[49,50], leading to risk mitigation recommendations. There is considerable potential to develop quantitative risk assessment methodologies to include loss of livelihoods, loss of critical infrastructure and economic losses for example.

Long term assessments of risk and forecasts of the likelihood of volcanic activity over a given period of time (e.g. 100 years) can be extremely useful for mitigation actions such as land use planning. Short-term forecasting and recognition of the very dynamic nature of risk is essential for rapid response actions such as evacuation.

6.1 Hazards

Given the large number of individual volcanic hazards, each of which has different characteristics, hazard assessment is inevitably multifaceted and reliable hazard assessment requires volcano by volcano investigation. In most countries, the Volcano Observatory (or official institution) provides scientific advice about hazards to the local and national authorities who hold the responsibility to take mitigation measures (e.g. evacuation). The actual mechanism for provision of this advice differs from country to country, depending on the relevant legislation.

An important concept in natural hazards is the *hazard footprint*, which can be defined as the area likely to be adversely affected by a hazard over a given time period. Hazards assessments thus usually take the form of maps. They are typically based upon one or more volcanic hazards and a knowledge of past eruptions from geological studies and historical records over a given period of time. Hazard maps take many forms, from circles of a given radius around a volcano, or different zones likely to be impacted by different hazards, to probabilistic maps based on hazard modelling. 'Risk management' maps integrate hazards and identify zones of overall increasing or decreasing hazard. Thus they show communities at highest risk. There are also a variety of probabilistic maps that depend on the nature of the hazard. For volcanic flows (pyroclastic density currents, lahars and lavas) the map typically displays the spatial variation of inundation probability over some suitable time period or given that the flow event takes place [CS17]. For volcanic ash fall hazard the probability of exceeding some thickness or loading threshold is typically presented[77]. Hazards maps and derivative risk management maps can be used for multiple purposes, such as raising awareness of hazards and identifying likely impacts to enable effective land use planning and to help emergency managers mitigate risks[4].

Once a volcanic eruption has begun, hazards maps may become rapidly obsolete as topography is changed. For example, valleys extending from a volcano's summit may fill with hot pyroclastic deposits enabling subsequent pyroclastic density currents to travel further. Frequent updates of some hazards maps may therefore be necessary.

Most hazard assessments focus at the volcano scale, but probabilistic methods can be now applied to ash fall hazards at regional[77] and global scales (Section III). Given that ash fall is the hazard that affects most people through a variety of different impacts, this approach provides a valuable way to manage and mitigate a number of risks.

6.2 Exposure and vulnerability

There can be many different kinds of loss as a consequence of volcanic eruptions including: loss of life and livelihoods[30,78]; detrimental effects on health [CS10]; destruction or damage to assets (e.g. buildings, bridges, electrical lines and power stations, potable water systems, sewer systems, agricultural land)[1]; economic losses[16]; threats to natural resources including geothermal energy[32]; systemic vulnerability; and loss of social capital. Each of these will have its own specific characteristics in terms of exposure and vulnerability, which, like hazards, will vary in space and time[79]. Therefore, moving from hazard to risk ideally requires an assessment of exposed populations and assets, as well as their vulnerability.

In the vicinity of volcanoes, the potential for loss of life has been the priority, and hazard 'footprints' are traditionally superimposed on census data to identify 'exposed' populations for preliminary societal risk calculations. Similarly hazard footprints can be used to identify exposed assets, such as buildings, critical infrastructure, environment, ecosystems and so on.

Vulnerability has many variables which may include physical, social, organisational, economic and environmental. In terms of social vulnerability, geographically, socially or politically marginalised communities are typically the most vulnerable. Within these communities the young, elderly and sick are some of the more vulnerable individuals. The resilience of livelihoods is increasingly recognised as a key factor that plays a role in the vulnerability and exposure of communities and individuals. For example, if subsistence farmers are evacuated, the longer the period of evacuation, the more likely it is that attempts will be made to return to evacuated at-risk areas to harvest crops and care for livestock and this has been documented many times around volcanoes (e.g. Philippines [80]; Ecuador[29]; Indonesia[81], Tonga[82]). Providing options (e.g. alternative farmland) has proven an effective risk mitigation technique in several places (e.g. Ecuador[29]). The same issues apply to all scales of private enterprise and there are examples of individuals and businesses trying to retrieve capital assets from high risk evacuated areas. Physical vulnerabilities are typically closely associated with social vulnerabilities and may include, for example, the type and quality of roofing, and the quality of evacuation routes and transport. Assessing the vulnerability of critical systems which support communities specifically addresses the complex nature of vulnerability with its many variables and enables the analysis of resilience[19]. Vulnerabilities are ideally assessed at a community level and with a strong understanding of the local social, cultural, economic and political landscape. Nevertheless, this should always be considered in a wider context. For example, tourists have been recognised as a vulnerable group unlikely to be aware of evacuation procedures or how to receive emergency communications when volcanic activity escalates[31]. Volcanic eruptions can lead to populations being evacuated and displaced for considerable periods of time and may ultimately lead in some cases to permanent resettlement[78]. If the conditions under which evacuees must live are poor, individuals are more likely to return to their homes in at-risk areas. For example, in Montserrat, Lesser Antilles, evacuated families were living in temporary shelters for months and ultimately years[21], and some individuals sought peace and quiet at their homes in the evacuated zone or continued to farm, resulting in 19 unnecessary deaths in 1997[20]. Concerns about looting also cause people to delay evacuation or return to at-risk areas.

A health and vulnerability study for the Goma volcanic crisis in 2002 considered human, infrastructural, geo-environmental and political vulnerability following the spontaneous and temporary evacuation of 400,000 people at the onset of the eruption[60]. The area was already in the grip of a humanitarian crisis and a chronic complex emergency involving armies and armed groups of at least six countries. The potential for cascading health impacts (e.g. cholera epidemic) as a result of such a large displaced and vulnerable population was extremely high, however in the case of Goma, the response was remarkable and catastrophic losses were averted [CS8].

The forensic analysis of past volcanic disasters offers an opportunity to identify and investigate risk factors in different situations and also to identify evidence of good practice (http://www.irdrinternational.org/projects/forin/). Long-lived eruptions such as Soufrière Hills volcano, Montserrat, and Tungurahua, Ecuador, offer opportunities to assess adaptation to extensive risks, for example coping with the cascading impacts of repeated ash fall[19].

Like natural hazards, understanding all the factors that contribute to vulnerability and exposure at any particular place at a particular moment in time is challenging. Nevertheless, growing knowledge, improved methodologies and an increasing willingness to integrate information across disciplines should contribute to increased understanding of risk drivers.

6.3 Volcanic risk

The priority in the vicinity of volcanoes has been risk to life and only in recent years have volcanologists started to try to quantify such risks. The great value of quantification is that it allows risks to be measured, ranked and compared. Quantifying vulnerability in particular is challenging and is only beginning to be applied for volcanic risk analysis[30]. To facilitate semi-quantitative approaches to risk, vulnerability is commonly converted to indices. For example the vulnerability of roofs to collapse following ash fall (physical vulnerability) can be assessed using an index of different roof types and thresholds for collapse under different conditions[49].

A common means of representing volcanic risk, following methods used for industrial accidents, is to consider the societal risk in terms of the probability of exceeding a given number of fatalities N and the cumulative frequency F of events having N or more fatalities. The resulting F-N curves have been used successfully in Montserrat [CS18]. Also in Montserrat, a study on the exposure of the population to very fine respirable ash[83] combined volcanology, sedimentology, meteorology and epidemiology to assess the probability of exposure to ash of different population groups over a 20-year period. The study illustrates the multidisciplinary character of risk assessments, where diverse experts are needed. Quantitative risk assessments are also being developed for cities exposed to particularly high risk volcanoes [CS2, CS3] where rigorous, repeatable and defendable analysis is essential.

Other potential losses, such as livelihoods, infrastructure, buildings, agriculture and environmental assets, would all benefit from rigorous hazard and risk assessment approaches. In most cases though, despite the considerable potential of quantitative risk assessment approaches, volcanic risks have so far been managed without being quantified. Where vulnerabilities have been identified and assessed in a qualitative manner, they can be addressed For example, identified vulnerable communities can be engaged in participatory risk reduction activities. A good example is the system of community '*vigías*' (volcano watchers) in place in Ecuador to support the Volcano Observatory and to ensure rapid communication between at-risk communities and civil authorities in the event of a sudden escalation in volcanic activity [CS23]. The communities themselves take account of the most vulnerable individuals in their evacuation planning.

More participation of communities in risk assessment, risk management and risk reduction can have considerable benefits to the community and can influence the psychological and sociological aspects of risk. For example, there is evidence that uncertainties may be better understood and there is more acceptance of risk reduction actions taken in the face of uncertainty. Participatory approaches can also benefit scientists and civil authorities through an increase in trust and greater awareness of local knowledge[84].

At a national, regional or global scale, the scale of risk assessments brings in different uncertainties and assumptions due to data availability. Care is needed that assessments do not appear contradictory at different scales. There is a need for harmonisation of methods and data sources. Exposure is largely dealt with through population data and vulnerabilities to various volcanic hazards are usually expressed using proxies, such as the Human Development Index (HDI). Building inventories including roof types could allow the application of established indices for structural vulnerability to ash fall.

For example, in SE Asia, volcanic ash fall is the volcanic hazard most likely to have widespread impacts since a single location may receive ash fall at different times from different volcanoes. Tephra fall thickness exceedance probability curves can be calculated using volcanic histories and simulations of eruption characteristics, eruption column height, tephra volume and wind directions at multiple levels in the atmosphere[77]. Exposure can be calculated using urban population density based on LandScan data and the HDI to contribute towards an estimate of risk across a region. Analysis shows the influence of each of the risk components to total risk for each city from a 1mm or greater fall of tephra, highlighting the different contributions made by hazard, exposure, and vulnerability [CS9].

Increasing the opportunities to integrate knowledge and experience from scientists (of all disciplines), authorities and communities at risk should enable improvements in understanding of risk, enhance resilience, support adaptation and reduce risk.

6.4 A new global assessment of volcanic risk

As part of this submission to the GAR15, a Volcano Hazard Index (VHI) has been developed to characterise the hazard level of volcanoes based on their recorded eruption frequency, modal and maximum recorded VEI levels and occurrence of pyroclastic density currents, lahars and lava flows [CS19]. A Population Exposure Index (PEI) is based on populations within 10, 30 and 100 km of a volcano, which are then weighted according to evidence on historical distributions of fatalities with distance from volcanoes [CS1]. A separate background paper (Section IV) is a compendium of regional and country profiles, which use these indices to identify high-risk volcanoes.

The VHI is too coarse for local use, but is a useful indicator of regional and global threat. The VHI can change for volcanoes as more information becomes available and if there are new occurrences of either volcanic unrest or eruptions or both. 328 volcanoes have eruptive histories judged sufficiently comprehensive to calculate VHI and most of these volcanoes (305) have had documented historical eruptions since 1500 AD. There are 596 volcanoes with post 1500 AD eruptions, so the VHI can currently be applied to just over half the World's recently active volcanoes. A meaningful VHI cannot be calculated for the remaining 1,223 volcanoes due to lack of information. The absence of thorough eruptive histories (based on geological, geochronological and historical research) for most of the world's volcanoes makes hazard assessments at these sites particularly difficult. This knowledge gap must be addressed.

Volcano population data derived from VOTW4.0 are used to calculate PEI, which is divided into 7 levels from sparsely to very densely populated areas. The PEI is an indicator of relative threat to life and can be used as a proxy for economic impact based on the distance from the volcano. This method does not account for secondary losses, such as disease or famine, or far-field losses due to business disruption as a result of volcanic ash and gas dispersion.

The VHI is here combined with the PEI to provide an indicator of risk, which is divided into Risk Levels I to III with increasing risk. The aim is to identify volcanoes which are high risk due to a combination of high hazard and population density. 156, 110 and 62 volcanoes classify as Risk Levels I, II and III respectively. In the country profiles (Section IV), plots of VHI versus PEI provide a way of understanding volcanic risk. Indonesia and the Philippines are plotted as an example (Figure 6). Volcanoes with insufficient information to calculate VHI should be given serious attention and their relative threat should be assessed through PEI.

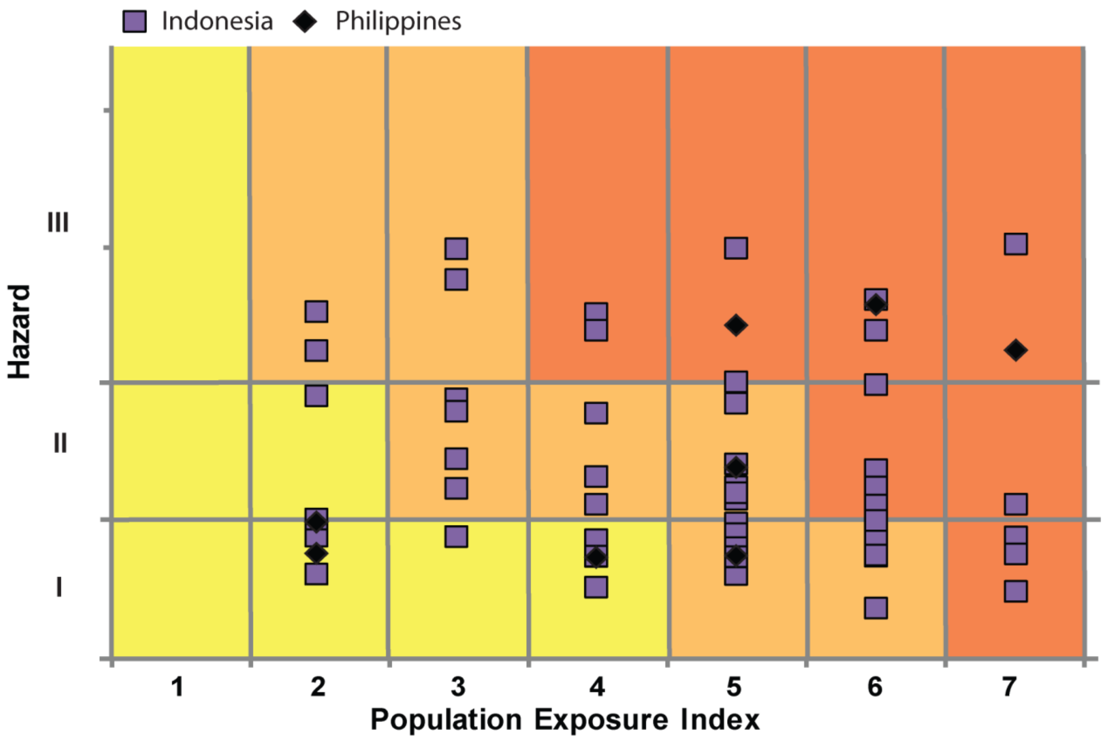

Figure 6. Plot of Volcanic Hazard Index (VHI) and Population Exposure Index (PEI) for Indonesia and the Philippines, comprising only those volcanoes with adequate eruptive histories to calculate VHI. The warming of the background colours is representative of increasing risk through Risk Levels I-III.

6.5 Distribution of volcanic threat between countries

In this section the distribution of volcanic threat (potential loss of life) is investigated to help understand how volcanic threat is distributed and to identify countries where threat is high. The term 'threat' is used as a combination of hazard and exposure. Two measures have been developed, combining the number of volcanoes in a country, the size of the population living within 30 km of active volcanoes (Pop30) and the mean hazard index score (VHI). Population exposure is determined using LandScan[85] data to calculate the total population within a country living within 30 km of one or more volcanoes with known or suspected Holocene activity. Countries are ranked using the two measures. Each measure focuses on a different perspective of threat. The full methodology and results are presented in CS20.

Measure 1 is of overall volcanic threat country by country based on the number of active volcanoes, an estimate of exposed population and average hazard index of the volcanoes.

Rank	Country	Normalised %
1	Indonesia	66.0
2	Philippines	10.6
3	Japan	6.9
4	Mexico	3.9
5	Ethiopia	3.9
6	Guatemala	1.5
7	Ecuador	1.1
8	Italy	0.9
9	El Salvador	0.8
10	Kenya	0.4

Table Table 2 shows the distribution of Measure 1 between the 10 highest scoring countries. Indonesia stands out as the country with two thirds of the share of global volcanic threat due to the large number of active volcanoes and high population density.

Measure 1 is an overall measure of threat distribution and may be misleading because individual countries may vary considerably in the proportion of their population that is exposed to volcanic threat as nation states vary greatly in size and in their populations from, for example, China with 1.3 billion people (<1% exposed) to St. Kitts and Nevis in the Caribbean with only 54,000 people (100% exposed).

$$\boldsymbol{Measure\ 1} = mean\ VHI\ x\ number\ of\ volcanoes\ x\ Pop30$$

Rank	Country	Normalised %
1	Indonesia	66.0
2	Philippines	10.6
3	Japan	6.9
4	Mexico	3.9
5	Ethiopia	3.9
6	Guatemala	1.5
7	Ecuador	1.1
8	Italy	0.9
9	El Salvador	0.8
10	Kenya	0.4

Table 2: The top 10 countries with highest overall volcanic threat. The normalised percentage represents the country's threat as a percentage of the total global threat.

Measure 2 ranks the importance of threat in each country that is independent of the country's size, so numbers of volcanoes and exposed population numbers are not included in the calculation. Measure 2 is defined:

$$\boldsymbol{Measure\ 2} = \frac{Pop30}{TPop}\ x\ Mean\ VHI$$

Rank	Country
1	UK-Montserrat
2	St. Vincent & the Grenadines
3	France – West Indies
4	St. Kitts & Nevis
5	Dominica
6	Portugal – Azores
7	St. Lucia
8	UK – Atlantic
9	El Salvador
10	Costa Rica

Table 3: The top 10 countries or territories ranked by proportional threat: the product of the proportion of the population exposed per country and the mean VHI.

Here the countries identified are those that have very high overall vulnerability to volcanic hazards and are completely different to the rankings using Measure 1. They are a collection of small island states and small countries (Table 3).

There is no suggestion which of these different country and regional rankings should be preferred. They are simply providing contexts and answers to different perspectives and questions. If the issue is to identify where most volcanic threat is concentrated then SE Asia and East Asian countries, such as Indonesia, the Philippines and Japan, have a large share of the total global volcanic threat. If the question is which countries and regions, irrespective of size, are most vulnerable to volcanic hazards then the West Indies and small nation states are indicated, where the potential losses could be highly significant in the context of the country's size.

7 Volcanic emergencies and disaster risk reduction

The official responsibility for volcanic risk management and risk reduction at a societal level usually lies with civil authorities, but to be effective also relies on the engagement of many different stakeholders, including scientists, communities, non-governmental organisations and the private sector. The role of Volcano Observatories in risk management and risk reduction is to provide timely and impartial information, volcanic hazards assessments, early warnings, and both long and short-term eruption forecasting to the civil authorities so they can make effective risk-based decisions, for example, about evacuation and land use planning. In practice, the scientists are likely to have useful knowledge and experience about the potential impacts of volcanic eruptions, and are thus also well-placed to offer advice on risk-based lessons learned at previous eruptions [CS5, CS21 - CS23]. Commonly scientists at Volcano Observatories work collaboratively with networks of international researchers, thus enhancing their access to new methods, research and ideas. However, the observatory itself should be the source of definitive scientific advice. Scientists are often involved in educational activities, so that authorities and the communities can better understand the potential hazards and risks from their volcano(es). This involvement may also involve regular exercises with civil protection agencies (and Volcanic Ash Advisory Centres) to test planning for eruption response. All of these activities require effective communication and long-term relationships between scientists and authorities, the public, NGOs and the private sector [CS21]. The understanding, communication networks and trust, which is built up over time, underpin effective risk reduction[27,84,86,87]

Several eruptions in recent years have resulted in significant scientific and risk management advances as a result of focused post-event analysis and consideration of lessons learnt. A key example was the installation of extensive monitoring at Nevado del Huila volcano in Colombia after the Nevado del Ruiz disaster, even though Huila had been dormant for more than 500 years. Early warning systems and emergency response activities were practiced between scientists, authorities, NGOs and communities, reportedly leading to timely evacuations and preventing many fatalities during eruptions in 2007-8. A more recent example is the Eyjafjallajökull eruption where significant progress in volcanic ash dispersal modelling and forecasting[38,88], data assimilation and observational methods has been achieved since the eruption as a result of cross-disciplinary efforts focused on clear scientific challenges and stakeholder needs[39]. In order to act on lessons learnt, take full advantage of opportunities and respond effectively to future eruptions, scientists are beginning to engage in formal collaborative and coordinated activities, groups and research across regions and internationally. Such collaborative and cross-disciplinary research is facilitating progress and has helped to ensure Volcano Observatories are able to draw useful research into operational activities. Following the controversial management of the 1976 eruption of La Soufrière in Guadeloupe (a large-scale evacuation of the capital city with no subsequent major eruption), a major effort in disaster risk reduction began in the area around the volcano. A dedicated Volcano Observatory was established and new methods in hazard and risk assessment are being developed alongside cost-benefit analysis in support of pragmatic long-term development and risk mitigation. Volcanic Alert Levels are a common way for Volcano Observatories to characterise the level of unrest or volcanic activity at a volcano and are designed primarily for people on the ground, to support communication and decision-making [CS13]. Such systems can be useful, especially if supported by an agreed common understanding and recognised procedures by authorities and the public [CS7]. However, they also need to be flexible to account for local context and uncertainty. The 2010 eruption of Merapi, Indonesia, showed rapid escalation of monitoring signals leading to an increased alert level and a series of evacuations saving the lives of 10-20,000 people [CS6][13]. The international aviation colour code system introduced by the International Civil Aviation Organisation provides a framework for notifications to the aviation sector [CS11] and aids communication between Volcano Observatories and Volcanic Ash Advisory Centres.

During a volcanic crisis, civil authorities and scientists are under immense pressure and must make decisions in short time-frames and often with limited information. Commonly an ‘emergency committee’ will meet and consider scientific advice before taking official action. Effective official response during an emergency is underpinned by long-term relationships, trust and mutual understanding of different institutional needs, priorities and contexts[27,84,86,87].

There are a variety of different disaster risk management options open to authorities. Attempts to reduce the hazard are rare, reflecting that this is in many cases not possible, but there have been some examples of lava flow diversion and lahar barriers which have had some effect. Short-term exposure can be reduced directly through evacuation of people and long-term exposure can be reduced by transferring existing assets to geographical areas of lower risk. Improved connectivity between risk management and development is very much needed so that new assets are built in areas of relatively low risk.

Where a known high risk volcano may erupt in the near future threatening large urban populations, for example Auckland, New Zealand [CS2], and Naples, Italy [CS3], the attention is on planning for the evacuation of large numbers of people in short periods of time. Planning typically assumes an effective short term alert or forecast is received. During some long-lived eruptions evacuations may become regular occurrences as populations continue to live and work alongside a sporadically active volcano (e.g. Tungurahua, Ecuador) or there may be permanent large scale movements of populations (e.g. Montserrat in 1997). Once a permanent evacuation has occurred, risk assessments are needed to manage access into evacuated areas, to manage access and land use in marginal zones (e.g. Montserrat), and to consider the potential for hazards of even greater impact than previously experienced. At White Island, New Zealand, risk assessments have been used to enable land managers to make decisions on the timing of access to a popular hiking trail that was impacted in the 2012 eruptions. Risk assessments have also been used by the Volcano Observatory to guide decisions on when scientists can access areas for monitoring tasks. In Indonesia, provision is now made for farmers to move animals during some evacuations.

Tools are needed to support scientific and risk management decision-making and there are good examples already available. One effective way to build a bridge between civil authorities and scientists is to combine hazards and risk assessments with cost benefit analysis, for example an analysis of the costs and benefits of an evacuation [CS2]. Recently, the argument for studying the trade-offs involved in taking mitigating action in the interests of public safety within the economic decision framework of cost benefit analysis[89,90] has gained traction [CS3]. These trade-offs may be important to ensure populations are not at more risk when evacuated (e.g. from disease, conflict, security). Cost benefit analysis does in some cases raise some difficult issues, such as the value of human life, but can be used to support any aspect of decision-making not just evacuation, such as land use planning and the establishment of monitoring capability. Importantly cost benefit analysis can be done before any crisis develops. Response decisions, about evacuation for example, may be based on pre-defined thresholds and probabilities. Such methods can also be applied retrospectively to examine decision-making in the past, for example the controversial evacuations in Guadeloupe[75] in 1976, which may in fact have been justified.

The desire to attract visitors to support livelihoods in the tourism sector (e.g. in spa towns associated with geothermal areas) can lead to a lack of transparency in terms of making information about hazards and risk available. Tourists often come to volcanic areas because of the volcanoes[31] and require appropriate information on the potential hazards, impacts and appropriate response to warnings. Ensuring tourists and tourism employees are aware of early warning and information systems and how to respond if a warning is issued is essential to reduce vulnerability. For example, at White Island, New Zealand, the Volcano Observatory is working in close partnership with regional and national civil protection to develop an understanding of the volcanic risks for both tourists and tourism employees alike.

The UN 'Hyogo Framework for Action 2005-2015' has been a good blueprint for risk reduction activities and the five priorities for action are all highly relevant to volcanic risk:

1. Ensure that disaster risk reduction is a national and local priority with a strong institutional basis for implementation.
2. Identify, assess and monitor disaster risks and enhance early warning.
3. Use knowledge, innovation and education to build a culture of safety and resilience at all levels.
4. Reduce the underlying risk factors.
5. Strengthen disaster preparedness for effective response at all levels.

The reduction in fatalities caused by volcanic eruptions through recent decades demonstrates how the application of science and technology largely coordinated through Volcano Observatories can lead to anticipation of hazards, increased societal resilience and can effectively reduce risk.

8 The way forward

Many aspects of volcanic hazards are localised around a particular volcano and each volcano is to some extent unique, as indeed are the communities that live around them. Thus dedicated Volcano Observatories and their staff, where they exist, are a very important component of disaster risk reduction. Observatories and their linked scientific institutions can help emergency managers, civil authorities and communities understand potential future eruption scenarios and volcanic hazards, and can provide monitoring, forecasts and early warning when a volcano threatens to erupt or change its behaviour. Ideally, a Volcano Observatory can be at the heart of a 'people-centred early warning system'[89] to support informed decision-making by individuals and authorities.

Scientific research across disciplines has a very significant role to play in enhancing the knowledge base, harnessing resources such as big data and new technologies, improving hazard and risk assessment approaches and carrying out analyses of past eruptions to establish lessons learnt. Some research funding opportunities have been very effective for facilitating international scientific cooperation and collaboration by making resources available for partners in all countries. Volcanic risk research projects should be developed in partnership with Volcano Observatories to ensure full integration into the DRR process and to support a 'single message'. Scientific advisory groups including scientists from Volcano Observatories, national institutions and universities are an excellent resource for emergency managers before, during and after volcanic crises.

Building resilience and living with an active volcano requires good communication between scientists, civil authorities, emergency managers and the public, effective planning and exercise of emergency responses, development of trust, and understanding of cultural factors that affect community responses.

This summary and associated reports highlight some of the wide range of hazards posed by volcanoes, describe their diverse impacts on communities and provide a new global analysis of volcanic hazards and risks. Based on this analysis we identify three key pillars for the reduction of risks associated with volcanic hazards worldwide and list recommended actions, with the underlying fundamental principle that volcanologists based in a specific country are the best to lead any national needs-analysis:

Pillar 1: Identify areas and assets at risk, and quantify the hazard and the risk.

Systematic geological, geochronological and historical studies are required to compile quality-assessed data on which rigorous hazard and risk assessments can be based. There is a fundamental need to characterise hazards and risk at many volcanoes worldwide where existing information is incomplete or lacking altogether.

Action 1.1 Those volcanoes shown to be poorly known with major knowledge gaps regarding their past activity and with a high population exposure index (in this study) should be prioritised for geological studies that document recent volcanic history with a hazard assessment context. Recommended studies include stratigraphy, geochronology, petrology, geochemistry and physical volcanology. Such studies greatly enhance the ability of volcanologists to interpret volcanic unrest and respond effectively when activity begins. In some cases, findings are likely to increase the currently known risk.

Action 1.2 Probabilistic assessment of hazard and risk that fully characterises uncertainty is becoming mandatory to inform robust decision-making. Assessments and forecasts are typically combinations of interpreting geological and monitoring data, and various kinds of modelling. Probabilistic event trees and hazard maps for individual volcanoes are best made by local or national scientists, with priority given to high-risk volcanoes. Some data from beyond the specific volcano in question are also needed for these trees and maps, especially if the volcano in question is poorly known.

Action 1.3 Global databases can serve as references for local scientists, providing analogue data and distributions of likely eruption parameters. Creation and maintenance of global databases on volcanoes, volcanic unrest and volcanic hazards, and quality assurance on data, hazard assessment methods, forecast models, and monitoring capacity are best done through international co-operation. Funding compilation of such databases does not fit easily into national and regional research funding and needs stronger international support.

Action 1.4 Forensic assessments of volcanic hazards, their impact and risk drivers are needed during and after eruptions. Such studies are essential to improve knowledge of hazards and vulnerability in particular and to improve and test methodologies, such as forecast modelling based on real observational data. National Governments should be encouraged to support their institutions to include timeline-based analysis of their actions and subsequent impacts, and to report successes and shortcomings of crisis responses. Evaluations of "lessons learnt" from past emergencies are important to improve future responses and avoid repetition of mistakes.

Action 1.5 Risks from volcanic ash fall associated with a particular volcano or region can be characterised by detailed probabilistic modelling, taking into account the range of physical processes (atmospheric and volcanic) and associated uncertainties. There is also a need to better understand the impacts of volcanic ash, and define thresholds of atmospheric concentration and deposit thickness for various levels of damage to different sectors. We recommend that further analysis be performed for all high-risk volcanoes, to enable more conclusive statements to be made about expected losses and disruption and to support resilience and future adaptation measures.

Pillar 2: Strengthen local to national coping capacity and implement risk mitigation measures.

Mitigation means implementing activities that prevent or reduce the adverse effects of extreme natural events. Broadly, mitigation includes: volcano monitoring, reliable and effective early warning systems, active engineering measures, effective political, legal and administrative frameworks. Mitigation also includes land-use planning, careful siting of key infrastructure in low risk areas, and efforts to influence the behaviour of at-risk populations in order to increase resilience. Good communication, education and community participation are critical ingredients to successful strategies. All these measures can help minimise losses, increase societal resilience and assure long-term success.

Action 2.1 Many active volcanoes are either not monitored at all, or have only rudimentary monitoring. Some of these volcanoes are classified in this study as high risk. A major advance for hazard mitigation would be if all active volcanoes had at least one volcano-dedicated seismic station with continuous telemetry to a nominated responsible institution (Volcano Observatory) combined with a plan for use of satellite services. For volcanoes in repose there are two suggested responses, namely implementation of low-cost systems for monitoring and raising awareness of volcanic hazards and risk among vulnerable populations. Provision of funding to purchase equipment must be complemented by support for scientific monitoring, training and development of staff and long-term equipment maintenance. We recommend this action as a high priority to address volcanic risk.

Action 2.2 Volcanoes identified as high-risk should ideally be monitored by a combination of complementary multi-parameter techniques, including volcano-seismic networks, ground deformation, gas measurements and near real-time satellite remote sensing services and products. This should be maintained, interpreted and responded to by a nominated institution (Volcano Observatory). Donations of equipment and knowledge transfer schemes need to be sustainable long-term with respect to equipment maintenance and consumables. Support for monitoring institutions and investment in local expertise is essential.

Action 2.3 Technological innovation should strive towards reducing costs of instrumentation and making application of state-of-the-art science as easy as possible so more volcanoes can be monitored effectively. For example, satellite observation offers a new and promising approach, but lower costs, easier access, technological training, and better and more timely sharing of data are needed to realise the potential. Many of the new models derived from research of volcanic processes and hazardous phenomena for forecasting can be made into accessible and easy to apply operational tools to support Observatory work and decision-making. More resources need to be put into converting potentially useful research into effective and accessible tools.

Action 2.4 Volcanic hazards, monitoring capacity, early warning capability and the quality of communication by volcanologists are key risk factors. The behaviour, attitudes and perceptions of scientists, decision-makers and communities also influence risk. Reducing risk is thus possible with better assessment and awareness of the hazards, effective communication by scientific institutions and authorities, well-practiced response protocols, participatory activities with communities and a greater awareness by all of key risk factors and how they can be managed/reduced. We recommend open, transparent interaction and communication with effective exchange of knowledge. In addition well thought out contingency plans for emergencies are essential in all sectors of society.

Pillar 3: Strengthen national and international coping capacity.

Efforts should be made to increase coping capacity to address a wide range of hazards, especially relatively infrequent events like major volcanic eruptions. Many countries are enhancing their own disaster preparedness as suggested in the Hyogo Framework for Action. Some volcanic emergencies cross borders and have regional or global impacts. Co-ordinated planning, mitigation, regulation and response from different countries are needed in these situations. A key challenge with all projects from donor countries is to be assured that they are needs-based, sustainable and well anchored in the host countries' own development plans. Another challenge is coordination between different projects and sectors.

Action 3.1 Exchange visits, workshops, summer schools, and international research collaboration are good ways to share experience and expertise in volcano monitoring, appraisal of unrest, assessment of hazard and risk, and communication. The value of interdisciplinary science is becoming more evident and an understanding of methodologies available in other disciplines can greatly strengthen effective collaboration. Collaborative regional networks of countries are an efficient way to build capacity, carry out research, carry out coordinated monitoring and planning, and make effective use of leveraged resources.

Action 3.2 There needs to be much more effort to integrate volcanic hazard and risk assessments with sustainable development and land use planning activities, preferably before eruptions occur, so issues around livelihood, evacuation and potential resettlement are considered as part of resilience building and risk reduction activities.

Action 3.3 Free and easy access to the most advanced science and data will greatly enhance the ability to manage and reduce volcanic risk. Access to knowledge is globally very uneven between the developed and developing nations. For volcanic hazards, easy and reliable access to the internet, high-resolution digital elevation data and remote sensed data, together with appropriate training would significantly improve the scientific capacity of many countries. We encourage ISDR to promote open access of scientific knowledge to all and support the deployment of advanced technologies and information wherever it is needed. Equally important, ground-based data need to be shared among Volcano Observatories and with the EO community (for validation purposes).

Action 3.4 Index-based methods to characterise hazard, exposure, threat and monitoring capacity used in this study are straightforward, and are intended to provide a basic broad overview of volcanic hazard and risk across the world as well as highlight knowledge gaps. The Volcanic Hazards

Index and Population Exposure Index should not be used to assess or portray hazard and risk in detail at individual volcanoes, which is the responsibility of national institutions and Volcano Observatories.

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Case Studies

CS1 Populations around Holocene volcanoes and development of a Population Exposure Index
Brown, S.K., Auker, M.R., and Sparks, R.S.J.

CS2 An integrated approach to Determining Volcanic Risk in Auckland, New Zealand: the multi-disciplinary DEVORA project
Deligne, N.I., Lindsay, J.M., and Smid, E.

CS3 Tephra fall hazard for the Neapolitan Area
Marzocchi, W., Selva, J., Costa, A., Sandri, L., Tonini, R., and Macedonio, G.

CS4 Eruptions and lahars of Mount Pinatubo, 1991-2000
Newhall, C.G. and Solidum, R.

CS5 Improving crisis decision-making at times of uncertain volcanic unrest (Guadeloupe, 1976)
Komorowski, J-C., Hincks, T., Sparks, R.S.J., Aspinall, W., and CASAVA ANR project consortium

CS6 Forecasting the November 2010 eruption of Merapi, Indonesia
Pallister, J. and Surono

CS7 The importance of communication in hazard zone areas: case study during and after 2010 Merapi eruption, Indonesia
Andreastuti, S., Subandriyo, J., Sumarti, S. and Sayudi, D.

CS8 Nyiragongo (Democratic Republic of Congo), January 2002: a major eruption in the midst of a complex humanitarian emergency
Komorowski, J-C. and Karume, K.

CS9 Volcanic ash fall impacts
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CS10 Health impacts of volcanic eruptions
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CS18 Risk assessment case history: the Soufrière Hills Volcano, Montserrat
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CS20 Global distribution of volcanic threat
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CS21 Scientific communication of uncertainty during volcanic emergencies
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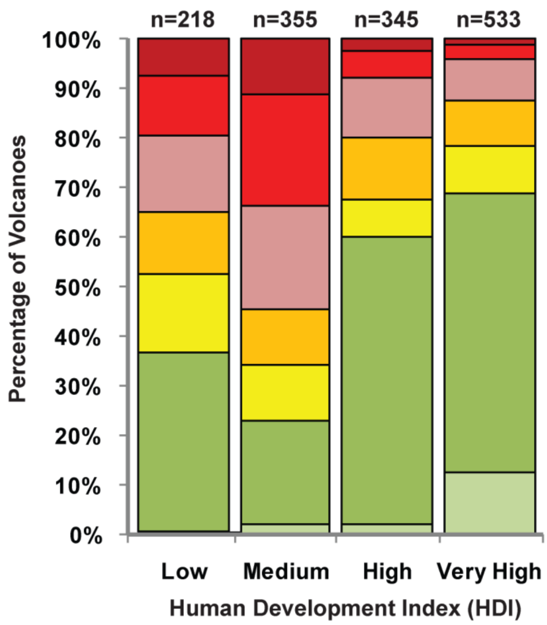
CS1. Populations around Holocene volcanoes and development of a Population Exposure Index

S.K. Brown, M.R. Auker and R.S.J. Sparks

School of Earth Sciences, University of Bristol, UK

Population exposure provides an indication of direct risk to life from volcanic hazards such as pyroclastic density currents and lahars and can be used as a proxy for threat to livelihoods, infrastructure and economic assets. This index doesn't account for indirect fatalities from famine and disease or far-field losses in the aviation and agriculture industries caused by the distribution of volcanic ash, gas and aerosols. The direct threat to the population is affected by the distance from the volcano. >800 million people live within 100 km of active volcanoes in 86 countries. Indonesia, the Philippines and Japan top the list for the greatest number of people living close to volcanoes, however some countries have a higher proportion of their total population within 100 km of a volcano (e.g. Guatemala and Iceland with >90%). Eruptions can produce hazardous flows that extend for tens of kilometres. The Population Exposure Index (PEI 1-7) is therefore determined from the population within 100 km, weighted for circle area and fatality incidence within radii of 10, 30 and 100 km.



PEI	Weighted Summed Population	Number of Volcanoes (%)	% Total Weighted Population
7	>300,000	61 (3.9%)	59.9%
6	100,000-300,000	128 (8.3%)	23.8%
5	30,000-99,999	188 (12.1%)	11.4%
4	10,000-29,999	178 (11.5%)	3.5%
3	3,000-9,999	157 (10.1%)	1.0%
2	<3,000	642 (41.4%)	0.4%
1	0	197 (12.7%)	0%

Figure 7 The number and percentage of volcanoes at each PEI level shown with the HDI.

Most volcanoes classify as PEI 2, accounting for <1% of the total population under threat. Just 4% of volcanoes are ranked at PEI 7, but these account for 60% of that total population. The greatest numbers of high PEI (5 - 7) volcanoes are in the Indonesia, Mexico & Central America and Africa & Red Sea regions, however as a proportion of its volcanoes, the Philippines and SE Asia ranks highest, with ~70% of volcanoes classified as PEI 5 – 7. More volcanoes are located in countries of Very High HDI than Low, however only <15% of volcanoes in High – Very High HDI countries classify with PEI≥5, rising to 45% in Low – Medium HDI countries, indicating a broad relationship between a lower level of development and a higher percentage of volcanoes with high proximal populations. These countries may have fewer resources to dedicate to disaster mitigation and may experience greater relative losses in the event of volcanic activity. PEI provides a first order method of identifying volcanoes close to large populations, which might therefore have priority in resource allocation. Full assessment based on local factors such as volcano morphology may lead to different conclusions about priorities.

CS2. An integrated approach to Determining Volcanic Risk in Auckland, New Zealand: the multi-disciplinary DEVORA project

N.I. Deligne[1], J.M. Lindsay[2] and E. Smid[2]

[1]GNS Science, New Zealand, [2]School of Environment, University of Auckland, New Zealand

Auckland, New Zealand, home to 1.4 million people and over a third of New Zealand's population, is built on top of the Auckland Volcanic Field (AVF). The AVF covers 360 km^2, has over 50 eruptive centres (vents), and has erupted over 55 times in the past 250,000 years. The most recent eruption, Rangitoto, was only 550 years ago. Most vents are monogenetic, i.e. they only erupt once. This poses a considerable problem for emergency and risk managers, as it is unknown where or when the next eruption will occur. The DEterming VOlcanic Risk for Auckland (DEVORA) program is a 7 year multi-agency research program primarily funded by the government, and has a mandate to investigate the geologic underpinnings, volcanic hazards, and risk posed by the AVF. DEVORA researchers work in collaboration with Auckland Council (local government) and Civil Defence (crisis responders) to implement findings into policy. The main challenges facing Auckland and other populated areas coinciding with volcanic fields include:

- Uncertainty of where and when the next eruption will be;
- Communicating to the public how an eruption of unknown location will impact them and how they can best prepare;
- Planning for an event which hasn't occurred in historic time;
- Foreseeing and appropriately planning for the range of possible impacts to the built environment, local, regional, and national economy and psyche.

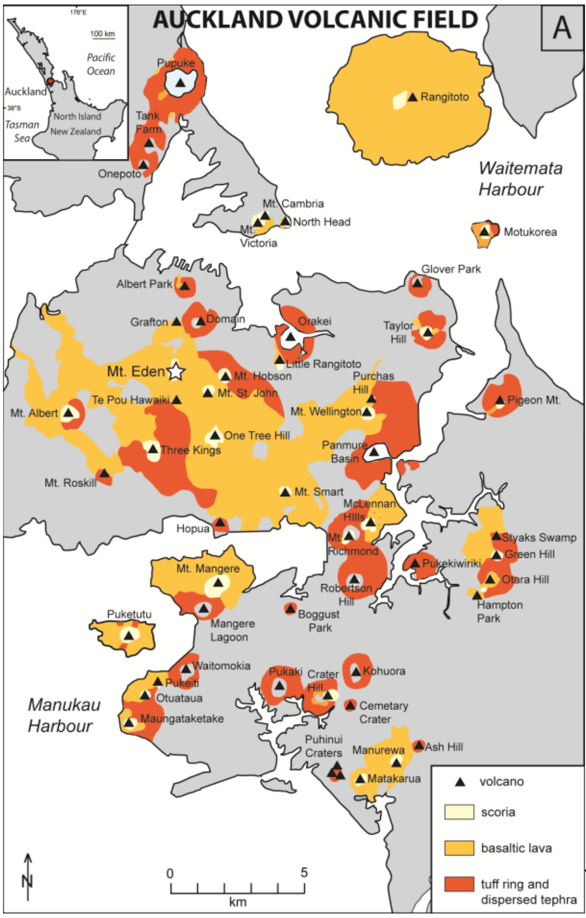


Figure 8 (A) Map of Auckland Volcanic Field (© modified from Lindsay et al (2011)); star indicates location of Mt Eden. (B) View of Mt Eden looking to the north highlighting the complete overlap of AVF and city (© Auckland Council).

CS3. Tephra fall hazard for the Neapolitan area

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[1] INGV, Roma, Italy; [2]INGV, Bologna, Italy; [3]INGV, Naples, Italy

The Neapolitan area represents one of the highest volcanic risk areas in the world, both for the presence of three potentially explosive and active volcanoes (Vesuvius, Campi Flegrei and Ischia), and for the extremely high exposure (over a million people located in a very large and important metropolitan area). Risk management has to be based on the evaluation of the long-term impact of the volcanoes (long-term volcanic hazard), and on tracking the space and time evolution of potential pre-eruptive signals. The Osservatorio Vesuviano (INGV-OV) of the Istituto Nazionale di Geofisica e Vulcanologia is continuously monitoring these volcanoes using advanced techniques to record the evolution of seismic activity, ground deformation, geochemical signals, and of many other potential pre-eruptive indicators. Moreover, INGV-OV provides updated hazard information to the Italian Civil Protection Department that is responsible for planning risk mitigation actions.

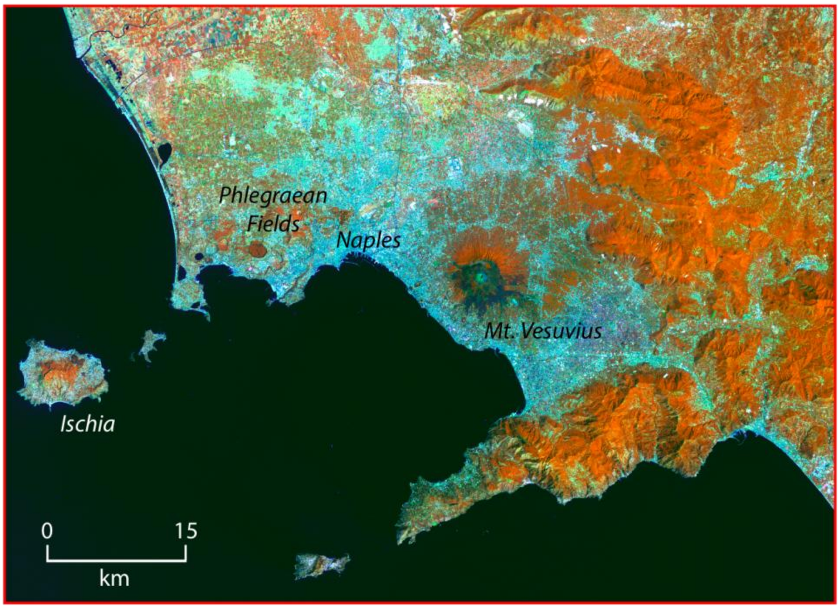

Figure 9: Satellite map of the Neopolitan area. Modified from Laboratorio di Geomatica, INGV-OV

Because of the large and ubiquitous uncertainties in the knowledge of pre-eruptive processes, hazard information essentially consists of the probabilistic assessment of different types of threatening events. The presence of such uncertainties poses several major challenges to scientists and decision makers:

- Volcanologists have to articulate scientific information including all known uncertainties, and merge different types of knowledge including: data, expert opinion, and models.
- Naples illustrates the importance of multi-hazard analysis, because it is threatened by three volcanoes that may produce diverse hazards such as ash fall, pyroclastic flows and lavas flows, as well as related threats like earthquakes, ground deformation and tsunamis; this

requires study of different physical processes, and understanding of cascading events that can amplify the overall risk.

- Decision makers have to plan risk mitigation strategies with uncertain scientific information. Since the societal and economic costs of most feasible mitigation actions may be extremely high, a sound risk mitigation strategy requires a careful evaluation of what is feasible, and what is affordable accounting for costs and benefits.
- Any kind of risk mitigation plan in high risk areas requires an efficient risk communication strategy during volcanic unrest, and a strong educational program during quiescence to improve the preparedness of the population and their resilience.
- There are no past monitored eruptions in Neapolitan area. This encourages volcanologists and decision makers to share their knowledge and to learn from experience gained from other analog cases from around the world.

CS4. Eruptions and lahars of Mount Pinatubo, 1991-2000

C.G. Newhall[1] and R.U. Solidum[2]

[1]Earth Observatory of Singapore, Singapore; [2]Philippine Institute of Volcanology and Seismology, Philippines.

After sleeping for ~ 500 years, Mount Pinatubo (Philippines) began to stir in mid March 1991, and produced a giant eruption on 15 June 1991, the second largest of the 20th century. About 20,000 indigenous Aetas lived on the volcano, and ~1,000,000 lowland Filipinos lived around it. Two large American military bases, Clark Air Base and Subic Bay Naval Station, were also at risk.

- Despite considerable uncertainties, the eruption was correctly forecast and more than 85,000 were evacuated by 14 June. Many aircraft were also protected from the eruption.
- About 300 lowlanders died from roof collapse during the eruption, but nearly all of the Aetas survived. At least 10,000 and perhaps as many as 20,000 were saved by timely warnings and evacuations.
- Regrettably, ~500 Aeta children died of measles in evacuation camps, because their parents distrusted Western-trained doctors and refused help.
- The hazard lasted far beyond the eruption – and, indeed, continues today though at a much-reduced level. Voluminous rain-induced lahars continued for more than 10 years, and sediment-clogged channels still overflow today during heavy rains.
- Although about 200,000 were "permanently displaced" by lahars, only about 400 died from lahars. Timely warnings from scientists and police helped to keep most people safe.
- Warnings and evacuations before the eruptions were clearly cost effective; lahar warnings and evacuations were also cost-effective. Construction of sediment control structures might or might not have been cost effective, depending on how one counts costs and benefits.

Figure 10 Lahars repeatedly buried the town of Bacolor from 1991-1995. Only roofs of 2-storey buildings are visible. Photo by Chris Newhall, USGS

CS5. Improving crisis decision-making at times of uncertain volcanic unrest (Guadeloupe, 1976)

J-C. Komorowski[1], T. Hincks[2], R.S.J. Sparks[2], W. Aspinall[2,3,] and the CASAVA ANR project consortium

[1]Institut de Physique du Globe Paris, France; [2]University of Bristol, UK; [3]Aspinall & Associates, UK

Scientists monitoring active volcanoes are increasingly required to provide decision support to civil authorities during periods of unrest. As the extent and resolution of monitoring improves, the process of jointly interpreting multiple strands of indirect evidence becomes increasingly complex. During a volcanic crisis, decisions typically have to be made with limited information and high uncertainty, on short time scales. The primary goal is to minimise loss and damage from any event, but social and economic loss resulting from false alarms and evacuations must also be considered. Although it is not the responsibility of the scientist to call an evacuation or manage a crisis, there is an increasing requirement to assess risks and present scientific information and associated uncertainties in ways that enable public officials to make urgent evacuation decisions or other mitigation policy choices.

Increasingly intense seismicity was recorded and felt at La Soufrière 1 year prior the eruption which began with an unexpected explosion on 8 July 1976. Ash-venting associated with sulfur (H_2S, SO_2) and halogen-rich (HCl, HF, Br) gases released during the eruption led to moderate environmental impact with short-term public health implications. Given evidence of continued escalating pressurisation and the uncertain transition to a devastating eruption, authorities declared a 4-6-month evacuation of ca. 70000 people on August 15. The evacuation resulted in severe socio-economic consequences until long after the crisis had subsided. The costs have been estimated as 60 % of the total annual per capita Gross Domestic Product of Guadeloupe in 1976 excluding losses of uninsured personal assets and open-grazing livestock. There were no fatalities, but this eruption stills ranks amongst the most costly of the 20th century. Hence analysis, forecast, and crisis response were highly challenging for scientists and authorities in the context of markedly escalating and fluctuating activity as well as the societal pressures cast in an insular setting.

As the extent and resolution of monitoring improves, the process of jointly interpreting multiple strands of indirect evidence becomes increasingly complex. The use of new probabilistic formalism for decision-making (e.g. Bayesian Belief Network analysis, Bayesian event decision trees) can significantly reduce scientific uncertainty and better assist public officials in making urgent evacuation decisions and policy choices when facing volcanic unrest.

A recent retrospective Bayesian Belief Network analysis of this crisis demonstrates that a formal evidential case would have supported the authorities' concerns about public safety and their decision to evacuate in 1976.

At present, following the controversial management of the 1976 eruption, a major effort in infrastructural development has begun in the area potentially at risk from volcanic activity. Hence, risk assessment, monitoring, and cost-benefit analysis must continue to be enhanced in support of pragmatic long-term development and risk mitigation policies.

CS6. Forecasting the November 2010 eruption of Merapi, Indonesia

J. Pallister[1], Surono[2]

[1]Volcano Disaster Assistance Program, US Geological Survey, USA; [2]Indonesian Geology Agency, Indonesia

Merapi volcano (Indonesia) is one of the most active and hazardous volcanoes in the world. It is known for frequent small to moderate eruptions, pyroclastic flows produced by lava dome collapse, and the large population settled on and around the flanks of the volcano that is at risk. Its usual behaviour for the last decades abruptly changed in late October and early November 2010, when the volcano produced its largest and most explosive eruptions in more than a century, displacing about 400,000 people, and claiming nearly 400 lives. Despite the challenges involved in forecasting this 'hundred year eruption', the magnitude of precursory signals (seismicity, ground deformation, gas emissions) was proportional to the large size and intensity of the eruption. In addition and for the first time, near-real-time satellite radar imagery played a major role along with seismic, geodetic, and gas observations in monitoring and forecasting eruptive activity during a major volcanic crisis. The Indonesian Center of Volcanology and Geological Hazard Mitigation (CVGHM) was able to issue timely forecasts of the magnitude of the eruption phases, saving an estimated 10,000–20,000 lives.

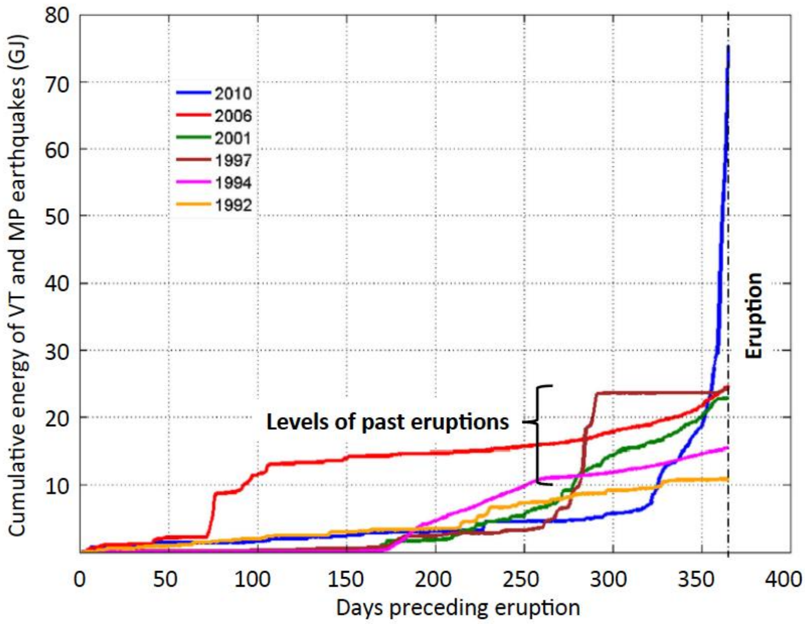

Figure 11. Cumulative seismic energy release of volcano-tectonic (VT) and multiphase (MP) earthquakes for eruptions of Merapi in 1997, 2001, 2006 and 26 October 2010. Modified from Budi-Santoso et al. (2013).

CS7. The importance of communication in hazard zone areas: case study during and after 2010 Merapi eruption, Indonesia

S. Andreastuti, J. Subandriyo, S. Sumarti, D. Sayudi

Geological Agency of Indonesia, Indonesia

Merapi is one of the most active volcanoes in Indonesia. Eruptions during the 20th and 21th Centuries resulted in: 1369 casualties (Thouret et al 2000) (1930-1931), 66 casualties (1994), and 386 casualties (2010). The 2010 eruption had impacts that were similar to unusually large 1872 eruption, which had widespread impacts and resulted in approximately 200 casualties (Hartmann 1934): a large number given the relatively sparse population in the late 19th century compared to today.

The 2010 Merapi eruption affected 2 provinces and 4 regencies, namely Magelang (west-southwest flank), Sleman (south flank), Klaten (southeast-east flank, and Boyolali (northern flank). The eruption led to evacuation of 399.000 people and resulted in a total loss of US $3,12 billion (National Planning Agency).

Indonesia applies 4 levels of warnings for volcano activity. From the lowest to highest: at Level I (Normal), the volcano shows a normal (background) state of activity, at Level II (Advisory) visual and seismic data show significant activity that is above normal levels, at Level III (Watch) the volcano shows a trend of increasing activity that is likely to lead to eruption, and at Level IV there are obvious changes that indicate an imminent and hazardous eruption, or a small eruption has already started and may lead to a larger and more hazardous eruption. At Level III people must be prepared for evacuation and at Level IV evacuations are required.

	ALERT LEVEL	DATES	RADIUS	ERUPTION
DECREASING	NORMAL	15-9-2011		
	ADVISORY	30-12--2010		
	WATCH	3-12-2010		
		4-11-2010	20 KM (11:00 UTC)	4 Nov. 17:05 UTC (16,5 km)
INCREASING		3-11-2010	15 KM (08:05 UTC)	3Nov. 08:30 UTC (9 km)
	WARNING	25-10-2010,	10 KM (11:00 UTC)	26-10-2010, (10:02 UTC)
	WATCH	21-10-2010		
	ADVISORY	20-9-2010		
	NORMAL	17 -9-2010		

Figure 12 Chronology of warnings and radius of evacuations during the Merapi eruption in 2010 (time increases from the bottom of the diagram upwards).

During the time of the 2010 crisis, there was rapid escalation of seismicity, deformation and rates of initial lava extrusion. All of these monitoring parameters exceeded levels observed during previous eruptions of the late 20th century. This raised concerns of an impending much larger eruption. Consequently, a Level IV warning was issued and evacuations were carried out and then extended progressively to greater distances as the activity escalated. The exclusion zone was extended from 10 to 15 and then to 20 km from Merapi's summit.

The 2010 Merapi eruption offers an excellent lesson in dealing with eruption uncertainties, crises management and public communication. Good decision making depends not only on good leadership, but also on the capabilities of scientists, good communication and coordination amongst stakeholders, public communication and on the capacity of the community to respond. All of these factors were in place before the 2010 eruption and contributed to the saving of many thousands of lives.

Impacts of Merapi eruptions on the human and cultural environment, livelihood and properties provide a lesson that in dense-populated areas around a volcano there is a need for regular review of hazard mitigation strategy, including spatial planning, mandatory disaster training, contingency planning and for regular evacuation drills. Merapi is well known for a capacity building program named wajib latih (mandatory training) required for people living near the volcano. The aim of this activity is to improve hazard knowledge, awareness and skill to protect self, family and community. In addition to the wajib latih, people also learn from direct experience with volcano hazards, which at Merapi occur frequently. However, the 2010 Merapi eruption showed that well trained and experienced people must also be supported by good management, and that training and mitigation programs must consider not only "normal" but also unusually large eruptions (Mei et al 2013).

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CS8. Nyiragongo (Democratic Republic of Congo), January 2002: a major eruption in the midst of a complex humanitarian emergency

J-C. Komorowski[1] and K. Karume[2]

[1]Institut de Physique du Globe Paris, France; [2]Observatoire Volcanologique de Goma, Democratic Republic of Congo

Nyiragongo is a 3470 m high volcano located in the western branch of the East African Rift in the Democratic Republic of Congo (DRC), close to the border with Rwanda. It has a 1.3 km wide summit crater that has been filled with an active lava lake since 1894. The area is affected by permanent passive degassing of carbon dioxide (CO_2). Fatal concentrations of CO_2 can accumulate in low-lying areas, threatening the permanent population and internally displaced persons (IDPs) in refugee evacuation centres. Nyiragongo volcano is responsible for 92% of global lava-flow related fatalities (ca. 824) since 1900.

On January 17 2002, fractures opened on Nyiragongo's upper southern flanks triggering a catastrophic drainage of the lava lake. Two main flows entered the city producing major devastation, and forcing the rapid exodus of most of Goma's 300,000 – 400,000 inhabitants across the border into neighbouring Rwanda. There were international concerns about the evacuation causing an additional humanitarian catastrophe exacerbating the ongoing regional ethnic and military conflict. Lava flows destroyed about 13 % of Goma, 21% of the electricity network, 80 % of its economic assets, 1/3 of the international airport runway and the housing of 120,000 people. The eruption caused about 470 injuries and about 140-160 deaths mostly from CO_2 asphyxiation and from the explosion of a petrol station near the active hot lava flow.

This was the first time in history that a city of such a size had been so severely impacted by lava flows. The eruption caused a major humanitarian emergency that further weakened the already fragile lifelines of the population in an area subjected to many years of regional instability and military conflicts. The medical and humanitarian community feared a renewal of cholera epidemics that caused a high mortality in refugee evacuations centres after the 1994 genocide. However, rapid and efficient response by relief workers from UN agencies, numerous non-governmental organisations (NGOs), and local utility agencies prevented major epidemics.

The limited number of fatalities in 2002 is attributed to:

- timely recognition by the Goma Volcano Observatory (GVO) of the reactivation of the volcano about 1 year prior to the eruption and their efficient communication with authorities once the eruption began;
- memory of the devastating 1977 eruption which triggered life-saving actions by villagers;
- panic-less self-evacuation of the population;
- presence of a large humanitarian community in Goma;
- occurrence of the eruption in the morning, and the relatively slow progression of eruptive vents towards Goma with the dike and fractures stopping before the water-saturated zone and the lake.

Had any one of these parameters been negatively exaggerated, the death told would have been much greater and potentially catastrophic.

CS9.Volcanic ash fall impacts

T. M. Wilson[1], S.F. Jenkins[2], and C. Stewart[3]

[1]University of Canterbury, New Zealand; [2]University of Bristol, UK; [3] Massey University, New Zealand

All explosive eruptions produce volcanic ash (fragments of volcanic rock < 2mm), which is then dispersed by prevailing winds and deposited as ash falls hundreds or even thousands of km away. The wide geographic reach of ash falls, and their high frequency, makes them the volcanic hazard most likely to affect the greatest numbers of people. However, forecasting how much ash will fall, where and with what characteristics is a major challenge. In addition, ash fall impacts are wide-ranging, influenced by environmental agents such as wind and rain, and often not well understood. As a very general rule, three zones of impact may be broadly expected; these are summarised in Figure 13 where physical ash impacts to selected societal assets are depicted against deposit thickness, which generally decreases with distance from the source volcano. Thick ash falls (>100 mm) may damage infrastructure, crops and vegetation, damage buildings, and create major clean-up demands, but are typically confined to within tens of km of the vent. Relatively thin falls (<10 mm) may cause adverse health effects for vulnerable individuals and can disrupt critical infrastructure services, aviation and other socio-economic activities over potentially very large areas.

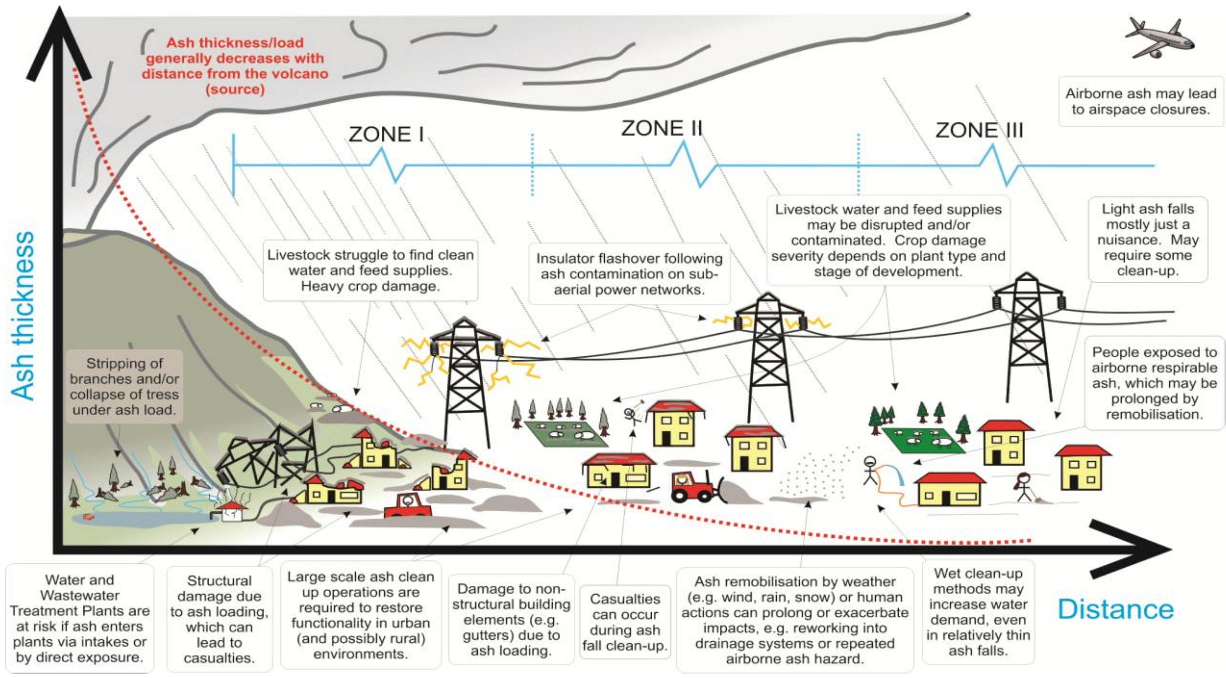

Figure 13 Schematic of some ash fall impacts with distance from a volcano. This assumes a large explosive eruption with significant ash fall thicknesses in the proximal zone and is intended to be illustrative rather than prescriptive. Three main zones of ash fall impact are defined: 1) Destructive and immediately life-threatening (Zone I); 2) Potentially harmful to health, damaging and/or disruptive (Zone II); 3) Mildly harmful to health, disruptive and/or a nuisance (Zone III).

Impacts depend not only upon the amount of volcanic ash deposited and its characteristics (hazard), but also the numbers and distribution of people and assets (exposure), and the ability of people and assets to cope with ash fall impacts (vulnerability). While volcanic eruptions cannot be prevented, the exposure and vulnerability of the population to their impacts may, in theory, be reduced, through the considerable tasks of hazard and risk assessment, improved land use planning, risk education and communication and increasing economic development.

CS10. Health Impacts of Volcanic Eruptions

C. Horwell[1], P. Baxter[2] and R. Kamanyire[3]

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Volcanoes emit a variety of products which may be harmful to human and animal health. Some cause traumatic injury or death; others may trigger disease or stress, particularly in the respiratory and cardiovascular systems.

Injury agents. Injury and death are caused by a range of volcanic hazards, which can be summarised by their impact on the body: 1) mechanical injury (lahars, rock avalanches, ballistics and tephra falls) where the body is crushed; 2) thermal injury (pyroclastic flows and surges, lava flows) where the body is burned; 3) toxicological effects (gases, ash and aerosols) where emissions react with the body; 4) electrical impact (lightning).

Volcanic gases. Volcanoes emit hazardous gases (e.g. CO_2, SO_2, H_2S & radon). Gas exposures occur during and following eruptions, and during periods of quiescence, and may be proximal or distal to the vent, depending on the size of eruption. Most gas-related deaths occur by asphyxiation near the volcano, but large eruptions may generate mega-tonnes of SO_2 which can be transported globally, potentially triggering acute respiratory diseases, such as asthma, where populations are exposed.

Volcanic ash. Whilst ash may cause skin and eye irritation, the primary concern for humans is ash inhalation; the style of eruption and composition of the magma govern the size and composition of the particles which, in turn, control their pathogenic potential when inhaled. The most hazardous eruptions generate fine-grained, crystalline silica rich ash which has the potential to cause silicosis. Inhalation of fine particles (sub-2.5μm diameter) affects both cardiovascular and respiratory mortality and morbidity.

Figure 14 Ash mobilization in Yogyakarta following the 2014 Kelud eruption. Photo: Tri Wahyudi.

Secondary effects. Large populations brought together in evacuation camps may contract diseases through poor sanitation. Some evacuees may suffer mental stress and other psychological disorders related to displacement. Widespread ashfall or gas impact (acid rain) may lead to crop failure, loss of livestock and contamination of water supplies which, in turn, may trigger famine and related diseases. Heavy ashfall can cause roof collapse and is slippery, making clean-up and driving hazardous. Infrastructure may be impacted, affecting healthcare responses.

Hazard/Impact Planning and Response. A key aspect of public health planning and response is the assessment of population exposure to ash and gas through air quality monitoring networks, which should provide real-time data and be set up in advance. Syndromic surveillance of respiratory symptoms can also inform public health advice. The International Volcanic Health Hazard Network (www.ivhhn.org), the umbrella organisation for volcanic health-related research and dissemination, has produced pamphlets and guidelines on volcanic health issues for the public, scientists, governmental bodies and agencies. IVHHN has also developed protocols for rapid characterisation of ash (such as particle size, crystalline silica content and basic toxicology) giving timely information to hazard managers during, or soon after, an eruption, to facilitate informed decision-making on health interventions.

Key Resources

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CS11. Volcanoes and the aviation industry

P. Webley

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247 volcanoes have been active, some with multiple eruptions, since the start of commercial airline travel in 1950s. Volcanic ash encounters from 1953 – 2009 have been documented by Guffanti et al. (2010). Two of the most significant encounters occurred in the 1980's which resulted in total engine shut-down (Casadevall, 1994)., and along with those from the 1991 eruption of Mount Pinatubo (Casadevall et al., 1996) led the International Civil Aviation Organization (ICAO) to set up 9 regional volcanic ash advisory centres or VAAC's (ICAO, 2007). They provide volcanic ash advisories to the aviation community for their own area of responsibility.

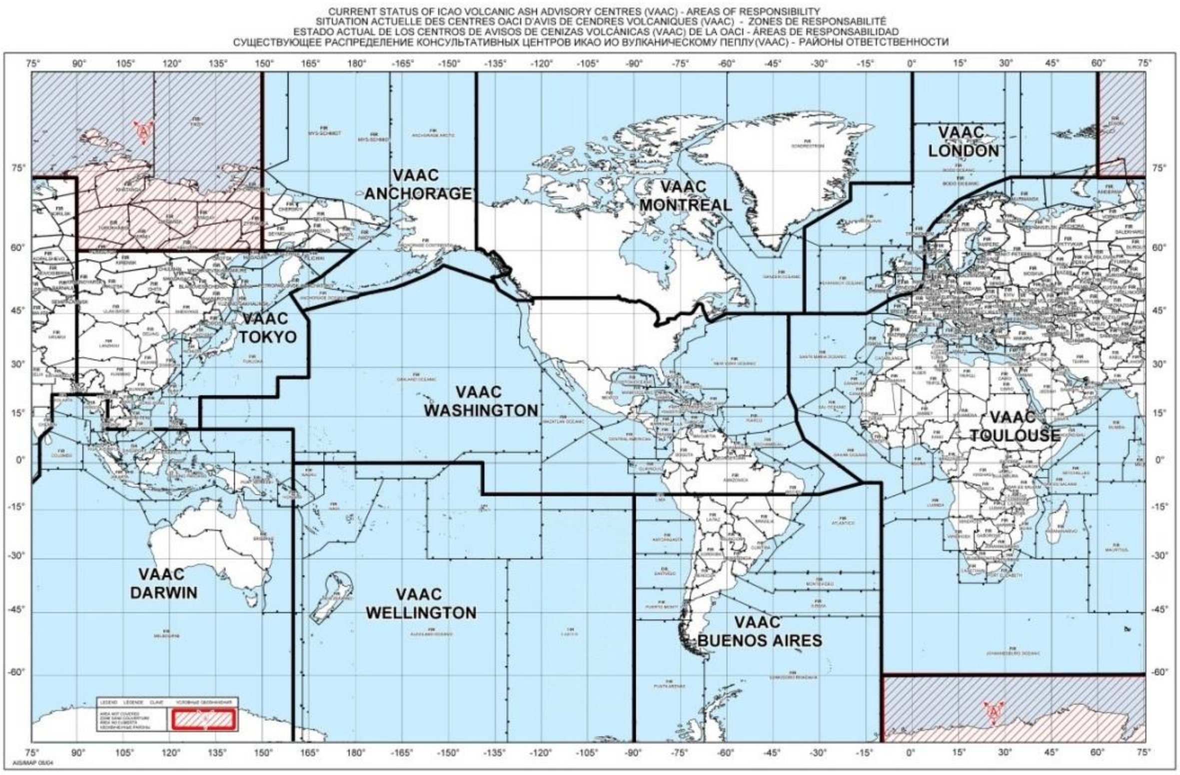

Figure 15: Map of the areas of responsibility for the ICAO Volcanic Ash Advisory Centres VAACs.

There are several different alerting systems used worldwide, each with the aim to update both local population centres close to the volcano and the aviation community. One common system used across the North Pacific is the United States Geological Survey (USGS) colour code system, see Gardner and Guffanti (2006). This uses a green-yellow-orange-red system for aviation alerts, which with its corresponding text (USGS, 2014), allows the aviation community to stay informed on the activity levels of the volcano. Risk mitigation to minimise aviation impact is dependent on real-time monitoring of volcano activity, detection and tracking of ash clouds using satellite data, dispersion modelling to forecast ash movement and global communication of timely information. International working groups, task forces and meetings have been assembled to tackle the questions related to volcanic ash in the atmosphere. The World Meteorological Organization (WMO) and International Union of Geology and Geophysics (IUGG) held workshops on ash dispersal forecast and civil aviation in 2010 and 2013 (WMO, 2013). Additionally, ICAO assembled the International Volcanic Ash Task Force (IVATF) as a focal point and coordinating body of work related to volcanic ash at global and regional levels.

Globally, there can be many volcanoes active and potentially hazardous to the aviation industry. Therefore, the VAAC's and local volcano observatories work closely together to provide the most effective advisory system and ensure the safety of all those on the ground and in the air.

CS12. The role of volcano observatories in risk reduction

G. Jolly

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Volcanic risk reduction is a partnership between science, responding agencies and the affected communities. A critical organisation in the volcanic risk reduction cycle is a volcano observatory (VO), which is an institute or group of institutes whose role it is to monitor active volcanoes and provide early warnings of future activity to the authorities. For each country, the exact constitution and responsibilities of a VO may differ, but that establishment is the source of authoritative short term forecasts of volcanic activity. There are over 100 VOs around the world to monitor ca. 1500 volcanoes considered to be active or potentially active. Some of these VOs have responsibility for multiple volcanoes. In some countries an academic institute may have fulfil both the monitoring and research function for a volcano.

To be able to effectively monitor their volcanoes, VOs potentially have a very wide suite of tools available to them, however, the range of the capability and capacity of VOs globally is enormous. Many active volcanoes have no monitoring whatsoever, whereas some VOs in developed countries may have hundreds of sensors on a single volcano. This leads to major gaps in provision of warnings of volcanic activity, particularly in developing countries.

Monitoring programs typically include: tracking the location and type of earthquake activity under a volcano; measuring the deformation of the ground surface as magma intrudes a volcano; sampling and analysing gases and water being emitted from the summit and flanks of a volcano; observing volcanic activity using webcams and thermal imagery; measurements of other geophysical properties such as electrical conductivity, magnetism or gravity. VOs may have ground-based sensors measuring these data in real-time or they may have staff undertaking campaigns to collect data on a regular basis (e.g. weekly, monthly, annually). Some VOs may also the capability to collect and analyse satellite data.

VOs play a critical role in all parts of the risk management cycle. VOs are often involved in outreach activities in times of volcanic quiet so that the authorities and the communities can better understand the potential risk from their volcano(es); this may also involve regular exercising with civil protection agencies to test planning for eruption responses. During the lead up to an eruption, VOs may provide regular updates on activity which inform decisions on evacuations or mitigation actions to reduce risk to people or to critical infrastructure. For example, power transmission companies may choose to shut off high voltage lines if there is a high probability of ashfall. During an eruption, VOs will then provide up-to-date information about the progression of activity. For an explosive eruption, information might include the duration, the height that ash reaches in the atmosphere and areas being impacted on the ground. This can inform decisions such as search and rescue attempts or provide input to ash dispersion forecasts for aviation. After an eruption has ceased, VOs can aid recovery through advice about ongoing hazards such as remobilisation of ash deposits during heavy rainfall.

The World Organisation of Volcano Observatories (WOVO) is an IAVCEI commission that aims to co-ordinate communication between VOs and to advocate enhancing volcano monitoring around the globe. WOVO is an organisation of and for VOs of the world (www.wovo.org). One of the main recent roles of WOVO has been to link VOs with Volcanic Ash Advisory Centres for enhancing communication between VOs and the aviation sector. Early notification of eruptions is critical for air traffic controllers and airlines so that they can undertake appropriate mitigation of risk to aircraft.

The role of VOs is critical in reducing risk from volcanoes, both on the ground and in the air. Volcanic risk reduction can only improve if VOs are adequately resourced by national governments.

CS13. Developing effective communication tools for volcanic hazards in New Zealand, using social science

S. Potter and G. Leonard

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New Zealand has a number of active volcanoes in a wide range of risk and geological settings. The effective communication of information about volcanic hazards to society is important to reduce the risk from these volcanoes, and is achieved by integrating the disciplines of social science and volcanology. This includes:

- The development of a new Volcanic Alert Level system for New Zealand. Qualitative research methods allowed the needs of stakeholders to be incorporated into the new system, resulting in a more effective communication tool to inform their decision-making (Potter et al., 2014).
- The improvement of lahar warnings and hazard information for visitors to the ski areas on Mt Ruapehu (Figure 16). The observation of responses to multiple simulated events indicated changes to education and procedures to improve future responses (Leonard et al., 2008). This is supported by longitudinal surveys of hazard perception and safety action recall.
- The creation of a crisis volcanic hazard map for eruptions at Mt. Tongariro in 2012 (Figure 16; Leonard et al., 2014). The area impacted by the eruptions included a section of the popular Tongariro Alpine Crossing walking track. Requirements of stakeholders were considered alongside scientific modelling and geological information to develop an effective communication product.

By incorporating social science, information derived from volcano monitoring and data interpretation can be used more effectively to reduce the risk of volcanic hazards to society.

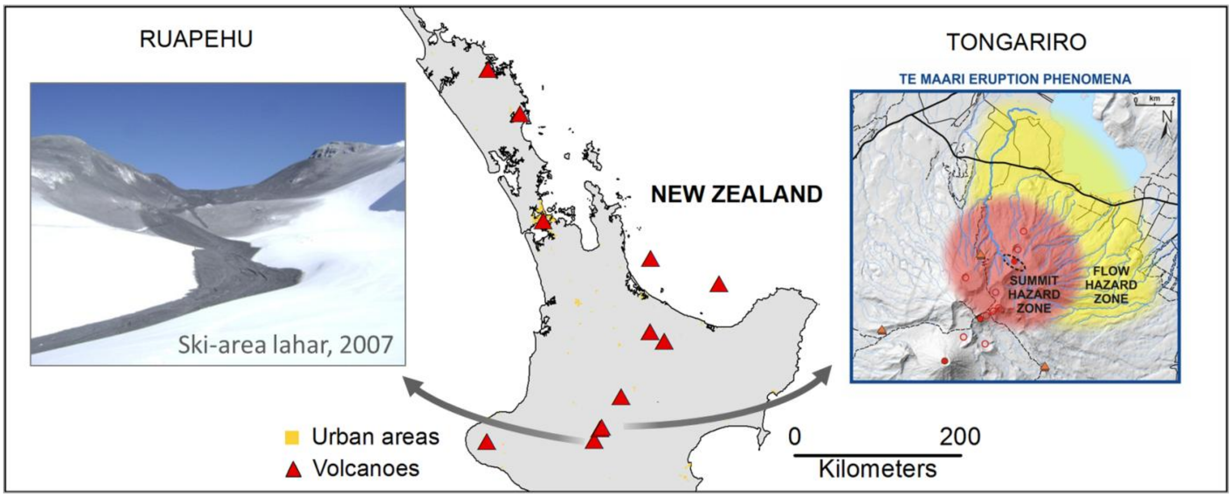

Figure 16: Volcanoes in New Zealand. The comprehensive Tongariro hazard map can be found at www.gns.cri.nz/volcano.

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CS14. Volcano monitoring from space

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Unfortunately, only some of Earth's active volcanoes are continuously monitored; the others are too remote or lack of infrastructure (often due to limited financial resources in the host country) for systematic observation. This lack of monitoring is a critical gap in hazards assessment and risk management. Volcanic eruptions are usually preceded by days to months of precursory activity, unlike other natural processes like earthquakes and tornados. Detecting such warning signs at an early stage thus provides the best means to plan and mitigate against potential hazards.

Satellite-based Earth Observation (EO) provides the best means of bridging the currently existing volcano-monitoring gap. EO data are global in coverage and provide information on some of the most common eruption precursors, including ground deformation, thermal anomalies, and gas emissions. Once an eruption is in progress, continued tracking of these parameters, as well as ash emission and dispersal, is critical for modelling the temporal and spatial evolution of the hazards and the likely future course of the eruption. The need for volcano-monitoring EO data is demonstrated by a number of international projects, including:

- the 2012 the International Forum on Satellite EO and Geohazards, which articulated the vision for EO volcano monitoring (http://www.int-eo-geo-hazard-forum-esa.org/)
- the Geohazard Supersites and Natural Laboratories initiative, which aims to reduce loss of life from geological disasters through research using improved access to multidisciplinary Earth science data (http://supersites.earthobservations.org/)
- the European Volcano Observatory Space Services (EVOSS), which has the goal of providing near-real-time access to gas, thermal, and deformation data from satellites at a number of volcanoes around the world (http://www.evoss-project.eu/)
- the Disaster Risk Management volcano pilot project of the Committee on Earth Observation Satellites (CEOS), which is designed to demonstrate how free access to a diversity of remote sensing data over volcanoes can benefit hazards mitigation efforts

To be useful for operational volcano monitoring, EO data must be temporally extensive to allow for time series analysis, available with low latency to facilitate rapid utilization by scientists and emergency managers, and be available at minimal or no cost, as few countries and agencies can afford commercial prices for satellite imagery.

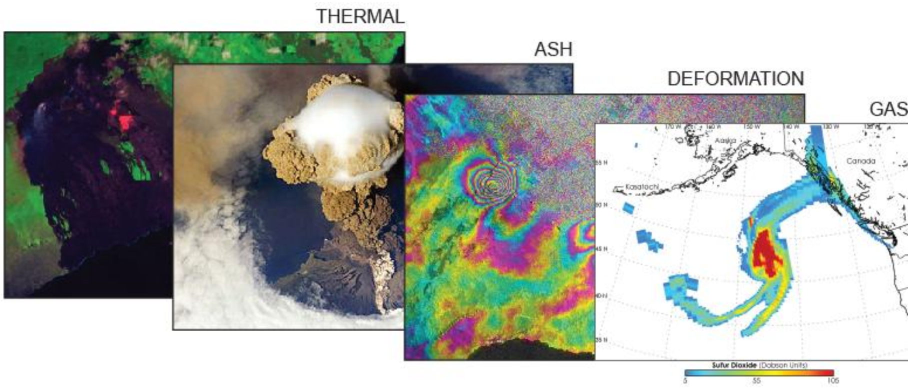

Figure 17. Examples of space-based volcano-monitoring products, to detect thermal anomalies, ash emissions, deformation of Earth's surface, and gas emissions.

CS15. Volcanic unrest and short-term forecasting capacity

J. Gottsmann

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It is important that early on in a developing unrest crisis scientists are able to decipher the nature, timescale and likely outcome of volcano reawakening following long periods of quiescence. There are major challenges when assessing whether unrest will actually lead to an eruption or wane with time. An analysis of reported volcanic unrest between 2000 and 2011 (Fig. 1) showed that that the median pre-eruptive unrest duration was different across different volcano types (Phillipson et al., 2013) lasting between a few weeks to few months. The same study also showed that volcanoes with long periods of quiescence between eruptions will not necessarily undergo prolonged periods of unrest before their next eruption.

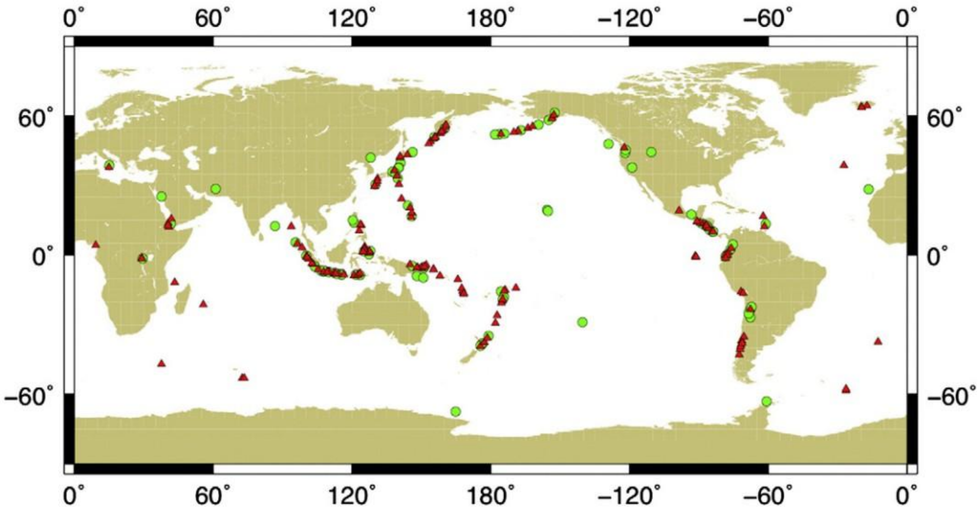

Figure 18 Location maps of 228 volcanoes with reported unrest between January 2000 and July 2011. Green circles show volcanoes with unrest not followed by eruption within reporting period, while red triangles show those with eruption.

Forecasting the outcomes of volcanic unrest requires the use of quantitative probabilistic models (Marzocchi and Bebbington, 2012) to adequately address intrinsic (epistemic) uncertainty as to how an unrest process may evolve as well as aleatory uncertainty regarding the limited knowledge about the process. To improve the knowledge-base on volcanic unrest, a globally-validated protocol for the reporting of volcanic unrest and archiving of unrest data is needed. Such data are important for the short-term forecasting of volcanic activity amid technological and scientific uncertainty and the inherent complexity of volcanic systems. Selection of appropriate mitigation actions based on informed societal decision-making using probabilistic forecast models and properly addressing uncertainties is particularly critical for managing the evolution of a volcanic unrest episode in high-risk volcanoes, where mitigation actions require advance warning and incur considerable costs.

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CS16. Global monitoring capacity: development of the Global Volcano Research and Monitoring Institutions Database and analysis of monitoring in Latin America

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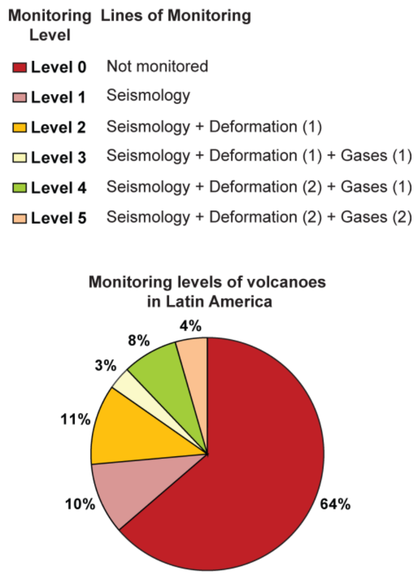
Volcano observatories and monitoring institutions play a critical role in real-time information, providing hazard assessments and enabling timely evacuations. Their monitoring capacity is fundamental in disaster risk reduction. The Global Volcano Research and Monitoring Institutions Database (GLOVOREMID) has been developed to collate data on institutional capacity including techniques used, and instrumental and laboratory capabilities. This is being expanded to a global dataset, but began as a study of monitoring capacity across 314 volcanoes through Mexico, Central and South America. Monitoring Levels of 0 to 5 are assigned to volcanoes based on the use of seismic, deformation and gas monitoring. 200 Latin American volcanoes classify as Level 0 as they are not continuously monitored using these techniques. Several countries have no monitoring systems in place, however of these few have confirmed Holocene eruptions. There are however 30 unmonitored volcanoes with recorded historical eruptions. Their presence suggests that resources may be required to better equip the region for anticipation and monitoring of volcanic activity. Of the monitored volcanoes, most are Level 2, with dedicated seismic and deformation stations. 15% of Latin American volcanoes are monitored using these and gas analysis. With just 13% and 20% respectively of Colombian and Costa Rican volcanoes being unmonitored and 100% of their historically active volcanoes being monitored, these countries are proportionally best for having at least minimal monitoring. Coupled with monitoring Levels 3-5 at over 50% of their volcanoes, these countries show the most comprehensive monitoring regimes. As expected, there is an overall positive correlation between the monitoring of volcanoes and their hazard and risk levels.



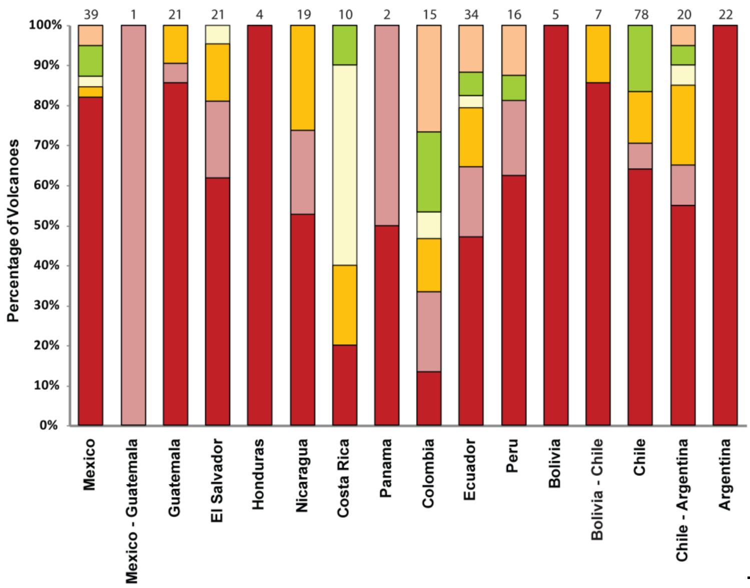


Figure 19 The percentage of volcanoes in each country of Latin America with different monitoring levels. The Levels and their defining characteristics are shown (top).

CS17. Volcanic Hazard Maps

E. S. Calder[1], K. Wagner[2] and S.E. Ogburn[2]

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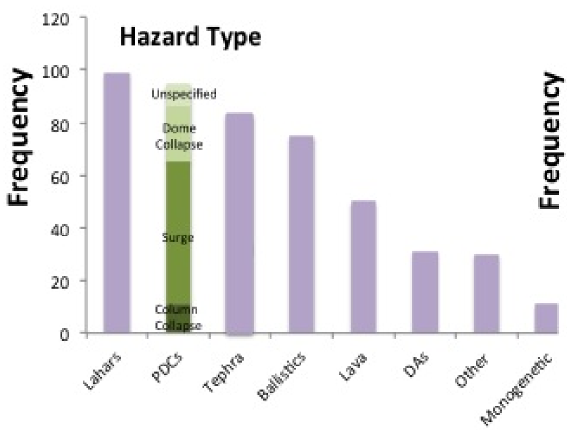
Generating hazard maps for active or potentially active volcanoes is recognised as a fundamental step towards the mitigation of risk to vulnerable communities. The responsibility for generating such maps most commonly lies with government institutions but in many cases input from the academic community is solicited. A wide variety of methods are currently employed to generate such maps, and the respective philosophies on which they are based varies; there is also acknowledgement of the notion that one model cannot fit all situations. Some hazard maps are based solely on the distribution of prior erupted products, others take into account estimated recurrence intervals of past events, or use computer models of volcanic processes to gauge potential future extents of impact. Those that are based on modelling generally use empirical, or relatively simple models that capture the essence of a complex process. Simulations are then used to indicate the outcome of an eruptive scenario, or set of scenarios, or, less frequently, are applied probabilistically.

A recent review undertaken of 120 volcanic hazard maps provides the following information: The hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps are: lahars (volcanic mudflows), pyroclastic density currents (PDCs), tephra fall, ballistics, lava flows, debris avalanches (volcanic landslides), and monogenetic eruptions (Figure 20a). Hazard maps can be categorised into five main types, which, in order of decreasing frequency, are: Geology-based maps: Indicate hazard footprints for the relevant suite of hazards based on the distribution of past eruptive products. Integrated qualitative maps: Display integrated information on the hazards, usually as zones of high, medium, low hazard levels. Modelling based maps: Involve scenario-based application of simulation tools often for a single hazard type. Administrative maps: Combine hazard zones with administrative needs to generate a zonation map used for crisis management. Probabilistic hazard maps: Involve probabilistic application of simulation tools usually for a single hazard type (Figure 20b).



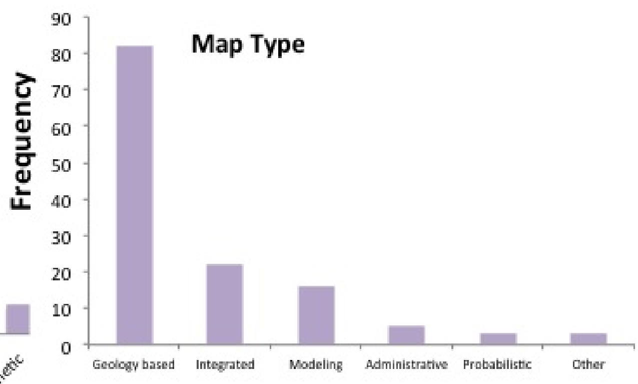


Figure 20 a). Types of hazards in the 120 maps reviewed, including: lahars, PDCs, tephra fall, lava flows, debris avalanches and monogenetic volcanism. PDCs were further distinguished based on specific type (column collapse, surge, dome collapse, or unspecified). 75% of maps include lahars and/or PDCs and 63% include tephra. Less than half include lava and/or debris avalanches, while less than 10% include hazards associated with unknown source locations, such as monogenetic eruptions. b). Hazard maps can be subdivided into categories based on how and what information is conveyed. Those based solely on the geologic history of the area are significantly more common (63%) than all other map types. Integrated qualitative maps make up a further 17% of maps. Map complexity increases to the right as the number of maps in that category decreases.

The volcanology community currently lacks a coherent approach for hazard mapping but there is consensus that improved quantification is necessary. The variation in currently utilised approaches results in part from differences in the extent of understanding and capability of modelling the respective physical processes (for example tephra fall hazards are currently better quantified than other hazards). Probabilistic hazard maps, in particular, are highly variable in terms of what they represent. Yet there is the need for probabilistic approaches to be fully transparent; they are used to communicate and inform stakeholders, for whom an understanding of the significance of the uncertainties involved is crucial. A recent initiative through the newly-formed IAVCEI Commission on Volcanic Hazards and Risk, will focus on hazard mapping with the objective of constructing a framework for a classification scheme for hazard maps, promoting the harmonization of terminology and providing guidelines for best practices. Driven by the needs of today's stakeholders there is also a need for future research efforts to advance the science that would aid in the production of a new generation of robust, fully quantitative, accountable and defendable hazard maps.

CS18. Soufrière Hills Volcano, Montserrat: risk assessments from 1997 to 2014

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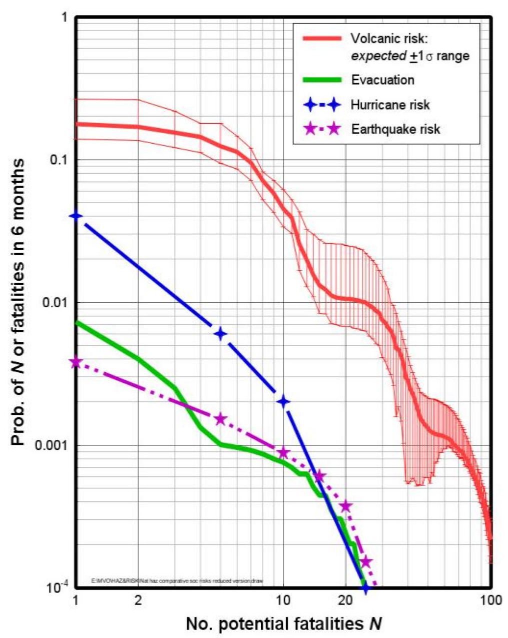
The Soufrière Hills Volcano (SHV), Montserrat, has been erupting episodically since 1995, with life-threatening pyroclastic flows generated by dome collapse and explosive events. Volcanic activity is monitored by the Montserrat Volcano Observatory (MVO), with an international panel - the Scientific Advisory Committee on Montserrat Volcanic Activity (SAC) - providing regular hazard and risk assessments. Advanced quantitative risk analysis techniques have been developed, forming an important basis for mitigation decisions.

Over 18 years, the SAC has used the following sources of information and methods: MVO data on current activity at the SHV; knowledge of other dome volcanoes; computer models of hazardous volcanic processes; formalised elicitations of probabilities of future hazards scenarios; probabilistic event trees; Bayesian belief networks; census data on population numbers and distribution, and Monte Carlo modelling of risk levels faced by individuals, communities and the island population.

Important findings of the SAC's work have been:

- For hazards, the performance of probabilistic event forecasts against actual outcomes has been measured using the Brier Skill Score: more than 80% of life-critical forecasts had positive scores indicating dependable hazard anticipation. These hazard assessments are crucial for risk estimation and mitigation decisions.



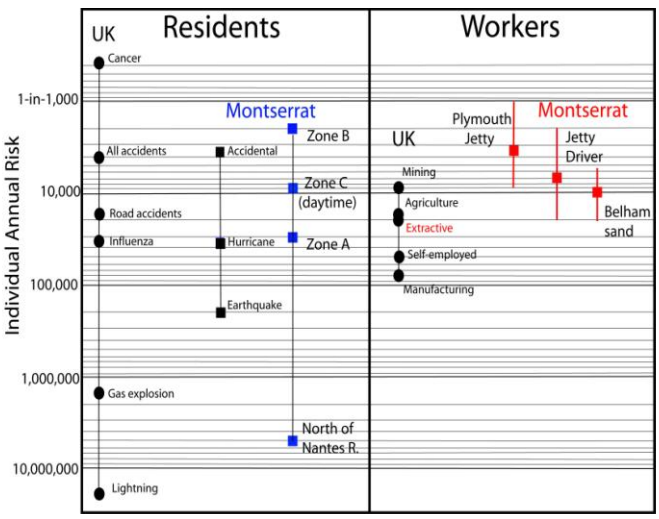


Figure 21 F-N plot for 2003 and risk ladder for 2011. See text.

- It is vital that risk assessments are presented to the authorities and public via open reports in a manner that is understandable. Societal casualty risks and individual risk of death are both calculated. The *F-N* plot from 2003 (left) shows the probability of *N* or more fatalities due to the volcano (red, with uncertainty), the reduced risk if the main at-risk area is evacuated (green), and comparative hurricane and earthquake risks. An individual risk ladder from 2011 is shown (right) with both residential zone risk levels and work-related risk levels plotted, with uncertainties. Comparative values from familiar circumstances are shown for reference.
- Appraising how the authorities respond to specific risk assessments and evaluating outcomes in societal terms has proved difficult, partly because there is no formal feedback mechanism.
- Whilst observatory operations, political aspects and social contexts have changed greatly over this drawn-out episode, the SAC has adopted a uniform approach to risk assessment. This continuity has ensured a consistent approach to scientific advice and helped build public trust. Since risk assessments began in late 1997 there have been no further casualties from volcanic activity, even though it escalated significantly in subsequent years.

SAC risk assessment reports are available from www.mvo.ms.

CS19. Development of a new global Volcanic Hazard Index (VHI)

M.R. Auker[1], R.S.J. Sparks[1], S.F. Jenkins[1], W. Aspinall[1], S.K. Brown[1], N.I. Deligne[2], J. Ewert[3], G. Jolly[2], S.C. Loughlin[4], W. Marzocchi[5], C. Newhall[6], J.L. Palma[7]

[1]School of Earth Sciences, University of Bristol, UK; [2]GNS Science, New Zealand; [3]Cascades Volcano Observatory, USA; [4]British Geological Survey, UK; [5]INGV, Italy; [6]Earth Observatory of Singapore, Singapore; [7]Universidad de Concepción, Chile

A Volcano Hazard Index (VHI) has been developed to characterise the hazard level of volcanoes based on their recorded eruption frequency, modal and maximum recorded VEI levels and occurrence of pyroclastic density currents, lahars and lava flows. VHI is based on a scoring of these hazards indicators with subsequent use of these scores to classify volcanoes into three levels (I, II and III). There are 596 historically active volcanoes, 305 of which have sufficiently detailed eruptive histories to calculate VHI; VHI can be applied to about half the World's recently active volcanoes. A further 23 Holocene volcanoes have a valid VHI score. A meaningful VHI cannot be calculated for the remaining volcanoes due to sparse records.

The volcanoes with an assigned VHI divide between the three levels: I (41%), II (32%) and III (27%). The levels indicate the relative hazard of individual volcanoes. However, **all volcanoes pose significant hazards,** so Level I volcanoes should not be regarded as benign. Scores should not be used as precise numerical values: e.g. a Level III volcano with a score of 24 should not be considered as twice as hazardous as a Level II volcano with a score of 12. VHI is an ordinal characterisation and should not be used for spurious quantification. Volcanoes with the same score may pose quite different hazards. These indices cannot be used for specific hazard assessment. The VHI can change as more data becomes available and if there are new occurrences of either unrest or eruptions.

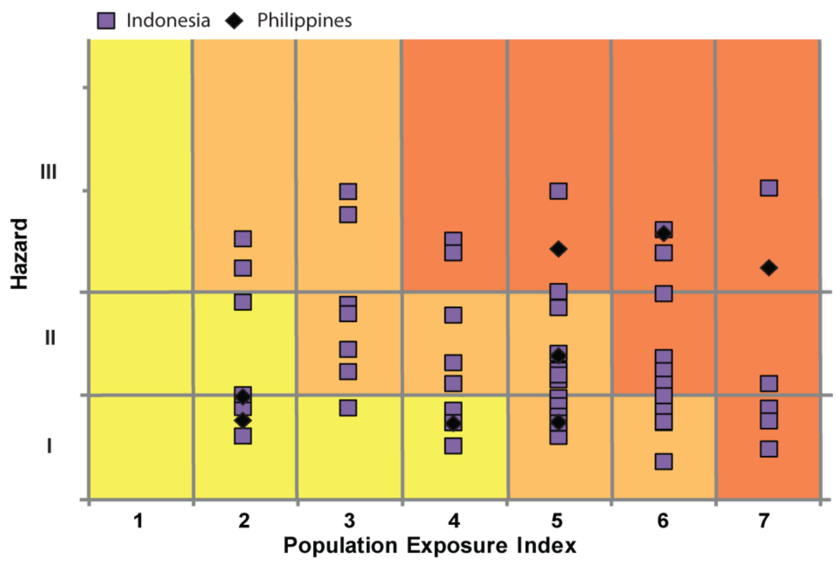


Figure 22: Hazard and PEI in SE Asia, shown for volcanoes with well a well constrained VHI. The warming of the background colours is representative of increasing risk through Risk Levels I-III.

The Population Exposure Index (PEI) is derived from a population at 10, 30 and 100 km from the volcano, weighted according to the historic occurrence of fatalities and area (See CS1). PEI is divided into 7 levels from sparsely to very densely populated areas. VHI is combined with the PEI to provide an indicator of risk, which is described as Risk Levels I to III with increasing risk at individual volcanoes. The essential aim of the scheme is to identify volcanoes which are high risk due to a combination of high hazard and population density. 156, 110 and 62 volcanoes classify as Risk Levels I, II and III respectively. In the country profiles plots of VHI versus PEI provide a way of understanding volcanic risk. Indonesia and the Philippines are plotted as an example. Relative threat can be assessed through PEI where VHI cannot be calculated. The absence of thorough eruptive histories for most of the world's volcanoes and hence absence of VHI is a knowledge gap that must be addressed.

CS20. Global distribution of volcanic threat

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University of Bristol, UK

An understanding of the total volcanic threat born by each country is gained through the calculation of two measures, combining the number of volcanoes per country, the total population living within 30 km of active volcanoes within the country (Pop30), the total population (Tpop) and the mean hazard score (VHI). The mean VHI per country is determined from the hazard scores of the classified volcanoes and proxy hazard scores derived by volcano type for unclassified volcanoes, permitting a global analysis of the volcanic threat.

The first measure developed here considers the overall threat to life, identifying those countries with the highest threat due to a combination of large numbers of people living within 30 km of active volcanoes, large numbers of volcanoes and high hazard scores.

$$Overall\ threat = mean\ VHI\ x\ number\ of\ volcanoes\ x\ Pop30$$

Indonesia, the Philippines and Japan rank most highly using this measure, all with large populations living within 30 km distance and numerous volcanoes. The sum of the resultant risk scores from the global dataset provides the total global threat and as a proportion of this Indonesia has an astounding dominance, with about two-thirds of the global threat within its borders. As expected, some correlation is observed between threat and the occurrence of fatalities.

The second measure considers the proportion of the population within a country exposed to the volcanic threat, disregarding the numbers of volcanoes.

$$Proportional\ threat = \frac{Pop30}{TPop}\ x\ Mean\ VHI$$

The countries in which volcanic threat is highly significant in terms of the proportion of population exposed are dominantly the small-area nations and island states, with much of the West Indies and Central America ranking most highly.

Both measures provide quite crude assessments of threat and do not take any important local controls on risk into account, such as monitoring capabilities or hazard mitigation measures. However the differences between the two measures illustrate how in the event of volcanic activity without advance mitigation measures losses could be greatest in absolute terms in some countries ranked highly through Measure 1, whilst the relative social and economic losses could be much greater in smaller countries where a larger proportion of the population would be affected (Measure 2).

CS21. Scientific communication during volcanic crises

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One of the most challenging aspects when managing a volcanic crisis is scientific communication. Volcanology is by its nature an inexact science, such that an appropriate scientific communication should convey information not only on the volcanic activity itself, but also on the uncertainties that always accompany any estimate or prediction. Deciphering the nature of unrest signals (volcanic reactivation) and determining whether or not an unrest episode may be precursory to a new eruption requires knowledge on the volcano's past, current and future behaviour. In order to achieve such a complex objective it is necessary to have different specialists involved in information exchange including those from disciplines such as field studies, volcano monitoring, experimentation, modelling and probabilistic forecasting. It is hence important that these stakeholders communicate on a level that caters for needs and expectations of all disciplines; i.e. to share a common technical language. This is particularly relevant when volcano monitoring is carried out on a systematic survey basis without continuous scientific scrutiny of monitoring protocols or interpretation of data. In an emerging unrest situation, difficulties may arise with communication between different stakeholders with different levels of involvement from different disciplines.

Of particular importance is the communication link between scientists with Civil Protection agents and decision makers during evolving volcanic crises. In this case, it is necessary to translate the scientific understanding of volcanic activity into a series of clearly explained scenarios that are accessible to the decision-making authorities. Also, direct interaction between volcanologists and the general public is rather common both during times of quiescence and activity. Information coming directly from the scientific community has a special influence on risk perception and on the confidence that people put in scientific information. Therefore, effective volcanic crisis management requires identification of feasible actions to improve communication strategies at different levels including: scientists-to-scientists, scientists-to-technicians, scientists-to-Civil Protection, scientists-to-decision makers, and scientists-to-general public.

The main goal of eruption forecasting is to identify how, where, and when an eruption will occur. To answer these questions we need to use probabilities, which is a way to quantify the intrinsic uncertainty of each parameter. However, communicating probabilities and, in particular, the degree of uncertainty they may have, is not an easy task, and may require a very different approach depending on who is the receiver of such information. Making predictions on what is going to be the future of a volcano follows basically the same reasoning as in other natural hazards (storms, landslides, earthquakes, tsunamis etc), but does not necessarily have the same level of understanding by the population and decision-makers. This is in part due to lack of experience in making predictions on the behaviour of volcanoes. Compared to meteorologists who have much more data and observations, volcanologists have to deal with a higher degree of uncertainty, mainly derived from this lack of observational data. It is also important to consider that all volcanoes behave in a different way, so a universal model to understand the behaviour of volcanoes does not exist. Each volcano has its own particularities depending on magma composition and physics, rock rheology, stress field, geodynamic environment, local geology, etc., which make them unique, so that what is indicative in one volcano may be not relevant in another. All this makes volcano forecasting very challenging and even more difficult to communicate such high degrees of uncertainty to the population and decision makers. In order to improve scientific communication during volcanic crises comparisons between communication protocols and procedures adopted by different volcano observatories and scientific advisory committees is recommended, in order to identify difficulties and best practice at all levels of communication: scientist-scientist, scientist-technician, scientist-Civil Protection, scientist-general public. Experience from the management and communication of other natural hazards should be brought in and common communication protocols should be defined based on clear and effective ways of showing probabilities and associated uncertainties. Although each cultural and socio-economic situation will have different communication requirements, comparison between different experiences will help to improve each particular communication approach, thus reducing uncertainty in communicating eruption forecasts.

CS22. Volcano Disaster Assistance Program: Preventing volcanic crises from becoming disasters and advancing science diplomacy

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The Volcano Disaster Assistance Program is a cooperative partnership of the USAID Office of U.S. Foreign Disaster Assistance (OFDA) and the U.S. Geological Survey (USGS). Founded in 1986 in the wake of the Nevado del Ruiz catastrophe wherein more than 23,000 people perished needlessly in a volcanic eruption, VDAP works by invitation to reduce volcanic risk, primarily in developing nations with substantial volcano hazards. The majority of emergency responses and capacity building projects occur in, but are not limited to, Pacific Rim nations. The single most successful VDAP operation was its response with the Philippine Institute of Volcanology and Seismology to the reawakening and subsequent eruption of Mount Pinatubo in 1991. This response alone saved 20,000 lives, including U.S. military personnel at Clark Air Base, and a conservative estimate indicates that at least 250 million dollars in tangible assets were removed from harm's way ahead of the eruption (Newhall et al. 1997). More recently, in late 2010 VDAP assisted Indonesia's Center for Volcanology and Geologic Hazard Mitigation respond to the eruption of Merapi volcano, which saved 10,000-20,000 lives.

Figure 23. Map of VDAP deployments 1986 – 2012

Over the past 25 years, the VDAP program has served as a development and proving ground for much of the volcano monitoring technology and eruption forecasting science that is applied at U.S. volcanoes. International experience in crisis response and risk mitigation has informed, strengthened, and helped guide development of domestic capabilities.

Newhall, C., Hendley II, J.W. and Stauffer, P.H. 1997. Benefits of volcano monitoring far outweigh costs–the case of Mount Pinatubo, U.S. Geological Survey Fact Sheet 115-97.

CS23. Communities coping with uncertainty and reducing their risk: the collaborative monitoring and management of volcanic activity with the *Vigias* of Tungurahua

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Volcán Tungurahua in the Ecuadorian Andes has been in eruption since 1999. Enforced evacuations ended with acrimonious re-occupation within 3 months and the management of risk has been more collaborative ever since.

A network, formed from volunteers already living in the communities at risk, was created with two main goals in mind: (i) to facilitate timely evacuations as part of the Civil Defence communication network, including the management of sirens, and (ii) to communicate observations about the volcano to the scientists. They are called '*vigias*' and around 25 of them are equipped with VHF radios to communicate regularly with observatory scientists and local civil protection.

Since 2000 the *vigias* have provided early warnings to and effective evacuations of their communities (Stone et al, 2014). They also provide detailed updates of increases in activity and hazardous flows to the scientists. In combination this has helped to minimise loss of life and enabled the communities to maintain their lives and livelihoods in the face of dynamic risk. The network has been sustained for >14 years resulting in improved communication pathways and an active involvement in risk reduction at a community level. *Vigias* also maintain scientific instruments and have been able to coordinate the response to fires, road traffic accidents, medical emergencies, thefts, assaults and to plan for future earthquakes and landslides. Motivation to continue the network is provided by its strong value to the community and the mutually beneficial trust-based relationships that it brings, particularly between the scientists and the *vigias*.

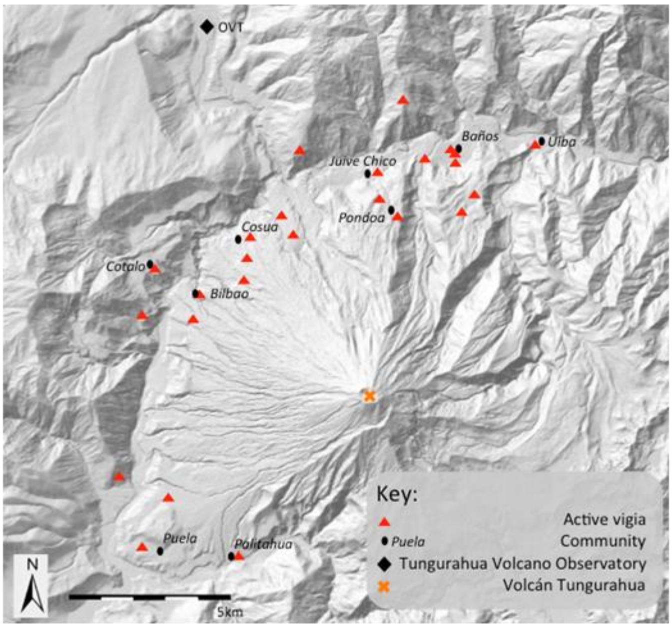

Figure 24 Map showing the location of the vigias and significant communities affected by volcanic hazards (adapted from Stone et al. 2014)

CS24. Multi-agency response to eruptions with cross-border impacts

B. Oddsson

National Commissioner of the Icelandic Police, Department of Civil Protection and Emergency Management

Iceland lies on the Mid-Atlantic Ridge, the spreading boundary between the Eurasian and North American tectonic plates. In this dynamic environment there are more than 30 volcanic systems, the most frequently active of which lie under Vatnajökull, Europe's largest ice sheet. Since the settlement of Iceland in the late ninth century, over 200 eruptions have been documented, with three in the last 4 years. The eruption of Eyjafjallajökull in 2010 significantly disrupted aviation in Europe and the north Atlantic causing global financial losses. Locally, the sustained ashfall from the Eyjafjallajökull eruption had severe effects on farming in southern Iceland. The fissure eruption at the Barðarbunga volcanic system (ongoing at the time of writing) has at times resulted in high concentrations of volcanic gases in populated areas of Iceland and sulfur dioxide from the eruption has been detected in the UK.

The Icelandic Meteorological Office (IMO) is responsible for monitoring and warning of natural hazards in Iceland (http://en.vedur.is/), while The National Commissioner of the Icelandic Police, Department of Civil Protection and Emergency Management (DCPEM) is responsible for general emergency coordination, first response in a crisis, communications with the public and mitigation action and recovery (http://www.almannavarnir.is/).

The IMO, DCEPM, University of Iceland and other relevant institutes in Iceland work together during volcanic emergencies at the National Crisis Coordination Center. Two innovative and major initiatives are now underway in Iceland supported by national and international funding to develop risk products and to enhance multiagency collaboration and data/information sharing:

The first is supported by the national Government and the International Civil Aviation Organisation (ICAO) and aims are to:

- Build an online accessible Catalogue for all active volcanoes in Iceland including their main characteristics, eruption histories and possible future eruption scenarios (ICAO)
- Develop an interagency plan and general response for the public in case of an eruption
- Develop risk assessments and plans with communities close to active volcanoes, including mitigation actions and response plans
- Develop risk assessments for large, explosive eruptions

The second is development of a 'Supersite' in Iceland with support from the EUFP7 project 'FUTUREVOLC', a consortium of 26 partners across Europe. The supersite concept implies integration of space and ground based observations for improved monitoring and evaluation of volcanic hazards, and there is an open data policy. The project is led by University of Iceland together with the Icelandic Meteorological Office (http://futurevolc.hi.is/).

CS25: Planning and preparedness for an effusive volcanic eruption: the Laki scenario

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As a consequence of the eruption of Eyjafjallajökull volcano (Iceland) in 2010 which affected airspace across Europe, the government department handling civil protection in the UK, the Civil Contingencies Secretariat (CCS) of the Cabinet Office, included volcanic risks in the UK National Risk Register (NRR) for the first time. In order to enhance UK preparedness for, and increase resilience to, most types of eruption in Iceland and their distal impacts, two scenarios were included in the NRR based on past events: a small-moderate explosive eruption of several weeks duration (the 2010 Eyjafjallajökull eruption) and a large fissure eruption of several months duration (the 1783-4 'Laki' eruption of Grimsvötn volcano).

The 'Laki' eruption occurred over a period of ~8 months in 1783-84 from a fissure in south-eastern Iceland with huge outpourings of mainly lava, volcanic ash, gases and aerosols. It is the second largest fissure eruption in Iceland in historical time. The impact on Iceland was devastating and there are also historical accounts of environmental and health impacts across Europe. Volcanic eruptions do not respect national borders and some eruptions may have hemispheric or even global impacts, so planning for the distal impacts of volcanic eruptions may be valuable in many countries that do not actually have an active volcano.

Assessing the potential risks to the UK of such an eruption in modern times is challenging. Potential distal hazards of concern to the UK might include volcanic gases and aerosol (air pollution $PM_{2.5}$ and PM_{10}) at flight and ground levels, acid rain and deposition of acids and other aerosols. In order to be hazardous, materials need to be present at harmful concentrations and this is being investigated using modelling. Scientists have characterised a 'Laki scenario' by using expert judgement and a stochastic modelling approach for the source and then running a number of dispersal simulations to provide outputs suitable for further distal health and environmental modelling. Since the incorporation of the Laki scenario in the NRR, cross-cutting work coordinated by the CCS has brought together Government, research institutions and academia to investigate volcanic risks to the UK, better understand uncertainties, build UK resilience to volcanic risks and prepare our response to them. Such collaboration is essential in order to identify risks, assess them and to facilitate proportionate planning.