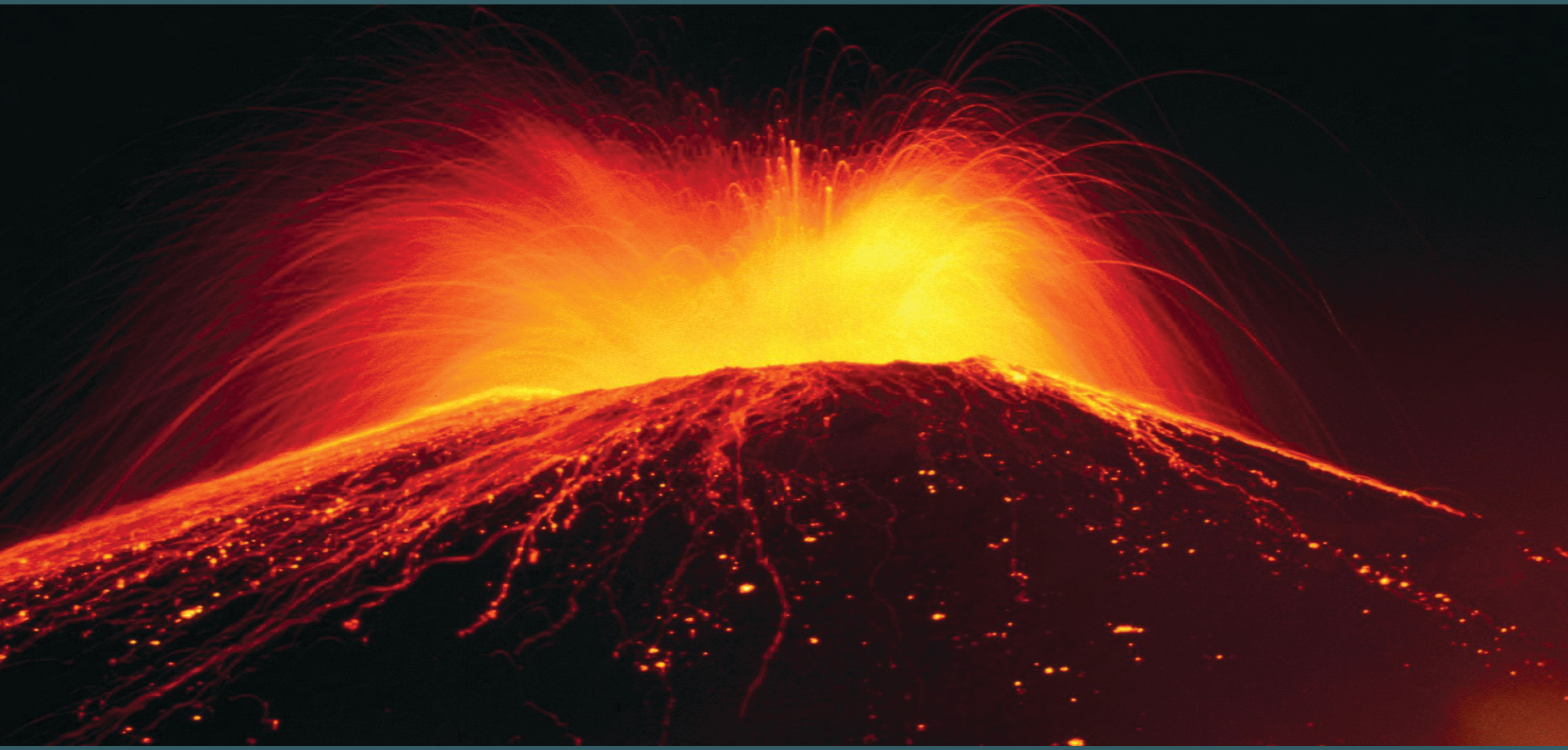
GFDRR, VOLCANO RISK STUDY

VOLCANO HAZARD AND EXPOSURE IN GFDRR PRIORITY COUNTRIES AND RISK MITIGATION MEASURES



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Summary

This report presents the results of a pilot study on the risk posed by volcanoes in the priority countries of the Global Facility for Disaster Reduction and Recovery (GFDRR) of the World Bank. The aim of the study was to establish science-based evidence for better integration of volcanic risks in national Disaster Risk Reduction (DRR) programmes in priority countries, as well as regional cooperation in DRR programmes for all countries supported under GFDRR.

Summary (cont.)

The study comprised a preliminary assessment of the potential volcanic eruption impacts in the GFDRR priority countries, assessment of exposure of population and important infrastructure to various volcano hazards, and an assessment of the national capacities to cope with the volcano risk.

A method for measuring the physical threat posed by individual volcanoes inside the GFDRR priority countries was developed. The method is used to assign each volcano to a hazard level 1, 2 or 3 and an uncertainty level 1, 2 or 3. Additionally, a Population Exposure Index was applied for measuring the number of people threatened by each volcano in order to give an indicator of population vulnerability. Finally, a simple estimate of population risk for each volcano was computed by combining the Hazard Level and Population Exposure Index.

Another objective of this study was to investigate national capacity for coping with volcanic risk in GFDRR priority countries. To this end, a monitoring index was created in order to allow for comparison of the GFDRR priority countries in terms of monitoring capability for each of their volcanoes. The monitoring index accounts for both the frequency of monitoring and existence/proximity of seismic networks. A bar chart is used to depict the distribution of each country's volcanoes across the monitoring levels.

Contents

Appendices

1 Introduction

This report presents the results of a pilot study on the risk posed by volcanoes in the priority countries of the Global Facility for Disaster Reduction and Recovery (GFDRR) of the World Bank. The GFDRR priority countries are: Burkina Faso, Ethiopia, Ghana, Madagascar, Malawi, Mali, Mozambique, Senegal, Togo, Indonesia, Marshal Islands, Papua New Guinea, Solomon Islands, Vanuatu, Vietnam, Bangladesh, Cambodia, Laos, Pakistan, Philippines, Sri Lanka, Colombia, Costa Rica, Ecuador, Haiti, Panama, Guatemala, Kyrgyz Republic, Nepal, Yemen and Djibouti.

The aim of the study was to establish science-based evidence for better integration of volcanic risks in national Disaster Risk Reduction (DRR) programmes in priority countries, as well as regional cooperation in DRR programmes for all countries supported under GFDRR.

The Norwegian Geotechnical Institute (NGI) was the Technical Executing Organisation and carried out the study in close collaboration with Bristol Environmental Risk Research Centre (BRISK) which is part of the Cabot Institute at the University of Bristol.

After an initial screening of the global volcano risk in GFDRR priority countries, an in-depth analysis of volcanic "hot spots" – i.e. geographical areas where volcanic risk is highest either because of recent activity and/or proximity to major population centres – was carried out. This comprised a preliminary assessment of the potential volcanic eruption impacts in the countries with hot spots, and an assessment of the national capacities to cope with the volcano risk. The focus of the study was on assessing the exposure of population and important infrastructure to various volcano hazards. Performing a detailed quantitative assessment of the economic risk associated with volcanic eruptions was beyond the scope of this study.

It should be noted, however, that human responses to volcanic threats are influenced by many factors, such as culture, belief systems, education, awareness, trust (or lack of trust) in experts and authorities, indigenous knowledge and past experiences. Thus approaches to risk reduction should not only involve improvements in scientific knowledge on the physical hazards, monitoring capacity and ability to give early warning, but also on human behaviour and controls on societal resilience.

The last section of this report provides general comments and guidance on the appropriate policy for dealing with the volcano risk. Distinction is made between the recommended practices for countries with hot spots and recommendations for countries with low risk, for which monitoring programmes (at regional or global level) might suffice.

2 Volcano Hazards

Volcanoes are very diverse in their styles of eruption, in their magnitudes, intensities, and frequencies of eruption. This variety comes about because the processes of magma generation in the Earth's interior, the processes that allow magma to reach the Earth's surface and the interaction of erupting volcanoes with surface environments are complex. Although volcanoes can be broadly classified into different types based on magma chemistry, size and dominant eruptive styles, each volcano has some distinctive characteristics and each of its eruptions is unique in certain ways.

There are several different kinds of volcanic hazards, which have very different spatial and temporal characteristics. Thus hazard assessment is inevitably multi-faceted and, to a considerable extent, generalizations are of very limited value; reliable hazard assessment requires volcano by volcano investigation.

The following is a brief listing of the major kinds of volcanic hazards that create risks for human beings, their home places and livelihoods:

> *Ballistics*
> Ballistics (also referred to as blocks or bombs) can be ejected out to perhaps 5 kilometres from a volcano, although hazards due to the biggest blocks and bombs are confined to areas close to the vent. Fatalities, injuries and structural damage caused by ballistics occur mostly as a result of direct impacts, and very hot ballistics can also start fires. Even quite small ballistics, falling from great height some kilometres from a strong explosion, can cause injury or death.
>
> *Tephra hazard*
> Most volcanic eruptions generate turbulent columns of volcanic ash particles and gases, which rise as buoyant plumes into the atmosphere (Figure 1.1), to heights ranging from a few kilometres to as much as 50 kilometres in the most powerful explosive eruptions. Ash is transported by wind blown in plumes that can cause hazards at large distances from the volcano (Figure 1.2). The presence of tephra in the atmosphere can cause wide-spread hazards to humans, infrastructure systems and the environment. Fatalities and injuries occur as a result of roof collapse and health hazards can also arise, while heavy ash deposits can damage and destroy crops, clog up machinery and damage electronic and electrical systems. Airborne volcanic ash is a major hazard to aviation and other forms of transport, jeopardizing food supplies, provision of emergency services and other essential services.

Figure 1.1 The eruption column at Mount Pinatubo, Philippines, from explosive eruptions on 12 June 1991. The column results from the intense discharge of hot volcanic fragments and gas. The column widens with height as it mixes with and heats air. High in the atmosphere at around 18 km it spreads out laterally.

Figure 1.2 Ash plume distributed to the west by prevailing winds from the Merapi Volcano, Central Java, on November 10, 2010 captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. Such ash plume spread tens to hundreds of kilometres where they pose hazards to aviation. (Image courtesy of NASA MODIS Rapid Response Team).

Pyroclastic flows and surges

Pyroclastic flows and surges are hot, high velocity mixtures of hot volcanic particles and gases that flow across the ground (Figure 1.3). Pyroclastic flows are concentrated avalanches that typically are confined to valleys (Figure 1.4), while pyroclastic surges are more dilute turbulent clouds of ash and hot gases that can spread widely across the landscape. They are the most lethal kind of volcanic hazard: escape is difficult and survival very rare. Pyroclastic flows and surges can cause severe damage to buildings, vegetation and land (Figure 1.5).

Figure 1.3 Pyroclastic flow from Santiaguito volcano, Guatemala. The flow is confined by the steep valleys around the volcano and was formed by the collapse of a growing lava dome. (Image courtesy of Dr Matthew Watson, University of Bristol).

Lahars and floods

Lahars are fast-moving mixtures of volcanic debris and water, sometimes hot, often arising from intense rain eroding loose deposits during an eruption. Lahars are, together with pyroclastic flows, a major cause of loss of life in volcanic eruptions, but communities can be protected by being evacuated or learning to escape to high ground when warning is given (Figure 1.6). Floods are also commonly associated with volcanic activity.

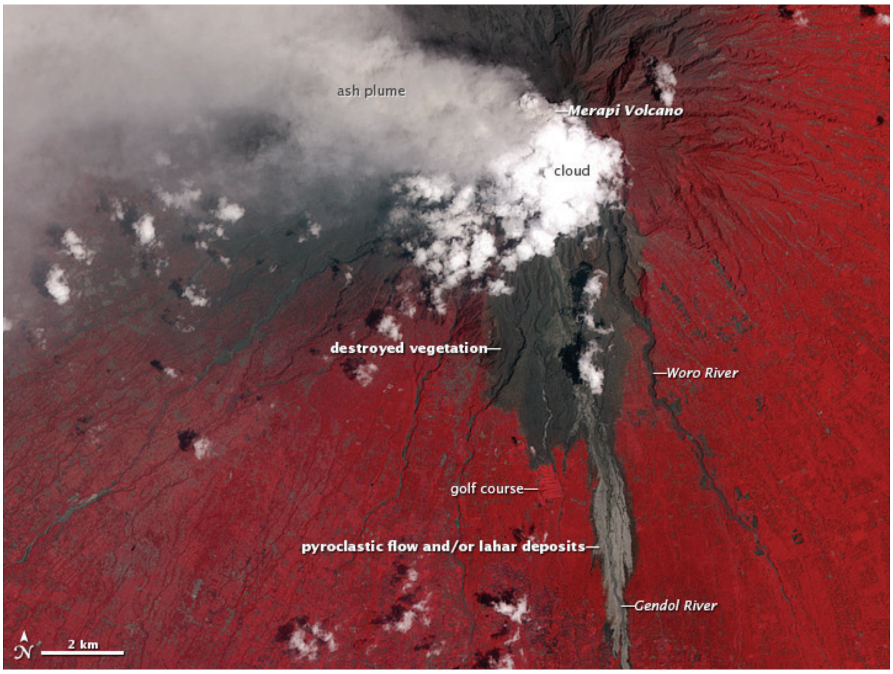


Figure 1.4 False-colour satellite image from the ASTER instrument on NASA's Terra satellite shows a large pyroclastic flow deposit erupted on 6th November 2010 eruption along the Gendol River south of Mount Merapi. The flow caused several tens of fatalities and great devastation. The ash plume is blown to the north-west. (Image courtesy of NASA GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team).

Figure 1.5 Village of Bronggang, Indonesia on the flanks of Mount Merapi on the side of Snedol valley inundated by pyroclastic flows on 6th November 2011. The dilute hot surge cloud above the pyroclastic spilled out to the valley into the village with 49 deaths. The picture shows the burnt vegetation and damage to houses (Image courtesy of Jessica Kandlbauer).

Figure 1.6 An eruption on the glacier-covered volcano Nevado del Huila, south west Colombia in 2007 led to major lahars that inundated surrounding valleys and threatened the town of Belalcazar, Cauca. The lahars travelled 48 km to reach the town. Timely warnings by INGEOMINAS led to temporary evacuation with no loss of life. The images show the valley before (February 2007), during (April 2007) and after (November 2008) the passage of the lahars. (Images courtesy of Dr Marta Calvache).

Debris avalanches and landslides
Landslides are common on volcanoes, whether currently active or not. Debris avalanches are caused by the failure of unstable volcanic edifices, commonly triggered by an eruption. However, some volcano landslides and debris avalanches are unrelated to volcanic activity, such as those caused by hurricanes or regional tectonic earthquakes.

Gas emissions
Many gases, dissolved in magmas, are released during eruptions. While the most plentiful of these is water vapour, other common volcanic gasses can directly cause fatalities, health effects, and vegetation and property damage.

Lava flows
Lava flows advance slowly enough to allow people to escape, but anything in the pathway of a lava flow can be damaged or destroyed: buildings and vegetation are commonly set on fire; land can be rendered unproductive or uninhabitable.

Volcanic tsunamis
Various volcanic processes may lead to the generation of tsunamis, such as eruptions of submarine volcanoes and high-volume pyroclastic flows, debris flows and volcanic landslides entering water. Tsunamis can cause huge loss of life; their scale, speed, and possible distant impact can devastate coastal populations.

Volcanic earthquakes
Earthquakes are closely associated with volcanism, but typically are small in magnitude. The cumulative effects of repeated volcanic earthquakes include damage to manmade structures, as well as ground deformation and cracks; few fatalities are directly caused by volcanic earthquakes.

Shock and infrasonic waves
Intense volcanic explosions can cause shock and infrasonic waves in the atmosphere, which can shatter windows and damage delicate equipment (e.g. electronic doors) at distances of several kilometres from the volcano.

Environmental and secondary effects
The effects of many volcanic phenomena can lead to damaging secondary hazards: crop failure and livestock losses can cause famine and epidemic disease outbreaks can occur. Very large explosive eruptions are known to effect climate and have global atmospheric impacts.

While this is a catalogue of generic hazards that can be caused by erupting volcanoes, not all these hazards are generated in every eruption or by every volcano. Individual volcanic eruptions are characterised by their magnitude (mass of erupted material), intensity (the rate of mass eruption), duration and eruptive phenomena (e.g. lava flows or explosions). Each eruption will have its own set of "hazard footprints", which can be defined as the areas affected by each of the hazardous processes. Most eruptions are rapid onset events, following periods of dormancy, which are commonly much longer than the duration of eruptions. There are, however, examples of persistently active volcanoes, which pose threats to surrounding communities much of the time.

Almost all eruptions are preceded by periods of unrest as magma attempts to reach the Earth's surface. Examples of unrest can include small earthquakes, ground movements, and changes in the temperatures, emission rates and chemistry of hot springs and fumaroles. However, there are many cases when such unrest does not lead to eruption and there can be other kinds of geophysical unrest at volcanoes, which are unrelated to magma movement. This means that when volcanoes show unrest there is usually considerable uncertainty about whether an eruption will occur. Intensification of the unrest sometimes makes it evident that an eruption could be on the point of starting, but this is typically only a few days or hours in advance. These traits mean that there can be false alarms and that evacuations are commonly only called at the last moment.

Ability to forecast the course of an eruption, once started, varies considerably. For frequently active volcanoes past eruptions provide guidance, while infrequently active volcanoes rely on geological studies of past behaviour, which is inevitably less detailed since inferences have to be made from understanding of the deposits rather than direct experience of the eruptions, or by knowledge transfer from other, similar volcanoes.

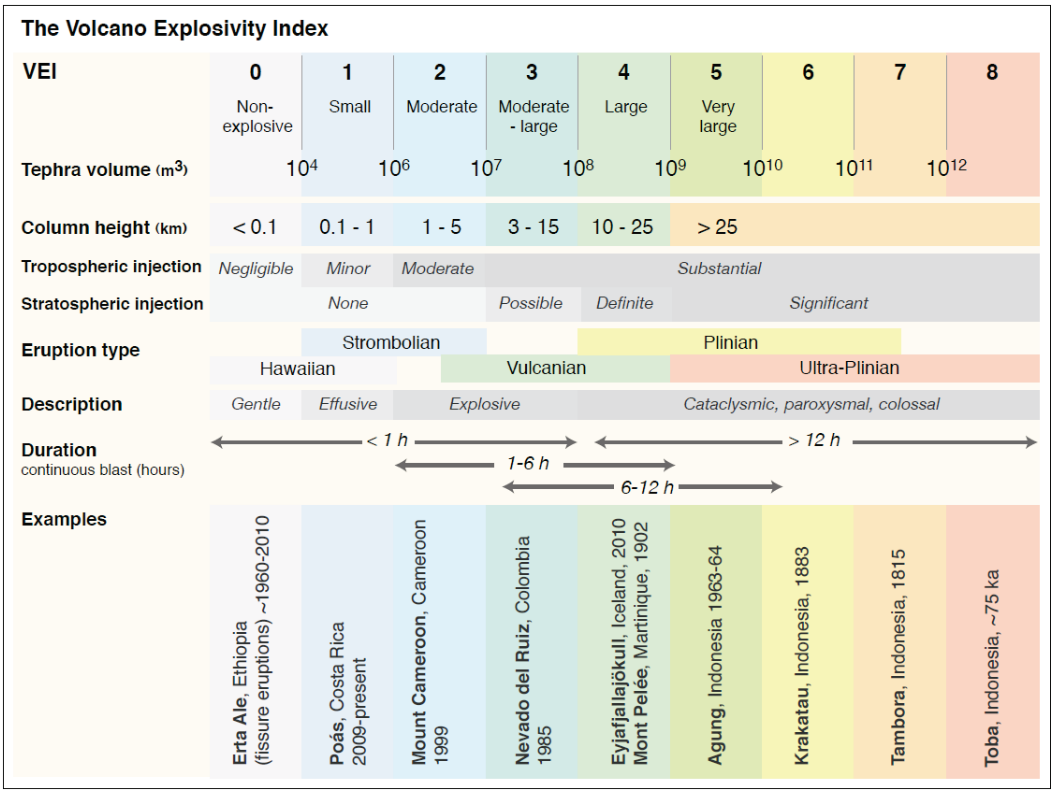
The resilience of populations living around volcanoes depends on many factors, but two generalisations can be made. Those living around frequently active volcanoes can become accustomed to recent behaviour patterns, and can get misled into thinking that they have seen the worst and not envisage different or more intense hazards. Where eruptions are infrequent – in some cases the last eruption pre-dates any societal memory – it can be difficult to get a community to understand the meaning and nature of the incipient risks and to accept that mitigation measures may be necessary.

Thus, in determining the risk exposure of different populations, the recurrence rate of eruptions from "their volcano" is a key factor.

3 Recurrence Rates of Volcanic Eruptions

The recurrence rates of explosive volcanism in the study countries were estimated based on analysis of a global database of large magnitude explosive volcanic eruptions (LaMEVE). The LaMEVE database is being developed at the University of Bristol as part of an international project called VOGRIPA. Magnitude of a volcanic eruption is defined as the Log of mass of magma erupted minus 7. This definition means that magnitude and VEI (Volcanic Explosivity Index, see Figure

3.1) are equivalent to first order. The technical aspects of the analysis are given in Appendix B.



The Volcano Explosivity Index

VEI	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Non-explosive	Small	Moderate	Moderate - large	Large	Very large			
Tephra volume (m³)		10^4	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}
Column height (km)	< 0.1	0.1 - 1	1 - 5	3 - 15	10 - 25	> 25			
Tropospheric injection	*Negligible*	*Minor*	*Moderate*	*Substantial*					
Stratospheric injection		*None*		*Possible*	*Definite*	*Significant*			
Eruption type		Strombolian			Plinian				
	Hawaiian		Vulcanian			Ultra-Plinian			
Description	*Gentle*	*Effusive*	*Explosive*		*Cataclysmic, paroxysmal, colossal*				
Duration continuous blast (hours)	*< 1 h*				*> 12 h*				
			1-6 h						
				6-12 h					
Examples	**Erta Ale**, Ethiopia (fissure eruptions) ~1960-2010	**Poás**, Costa Rica 2009-present	**Mount Cameroon**, Cameroon 1999	**Nevado del Ruiz**, Colombia 1985	**Eyjafjallajökull**, Iceland, 2010 **Mont Pelée**, Martinique, 1902	**Agung**, Indonesia 1963-64	**Krakatau**, Indonesia, 1883	**Tambora**, Indonesia, 1815	**Toba**, Indonesia, ~75 ka

Figure 3.1 Definition of VEI (Volcanic Explosivity Index), a scale that uses both quantitative measurements and subjective descriptions of eruptive phenomena to provide a relative measure of the explosivity of volcanic eruptions.

The LaMEVE database consists of 1989 entries from 481 Quaternary volcanoes. Figure 3.2 summarises the global relationship between magnitude and return period with upper bound and lower bounds from analysis of uncertainties. Not all volcanoes in the study countries are explosive. To provide simple estimates of the return rate of eruptions above a given magnitude in the country profiles we have taken the global return rate and multiplied that by the ratio of number of explosive volcanoes in the region to the global number of explosive volcanoes in the GVP database (440). The numbers of volcanoes in several of the countries are too few for the down-scaling to be done for every country except for those countries with many volcanoes. Rates are presented for Indonesia, the Philippines, Ethiopia, Colombia and Ecuador together, and for the Central American region for the case of Costa Rica, Panama and Guatemala. The global return periods for explosive volcanic eruptions to two significant figures are indicated in Figure 3.2, noting uncertainties for return periods of approximately 50% for magnitudes 3 to 6, and up to 200% for magnitudes greater than 7.

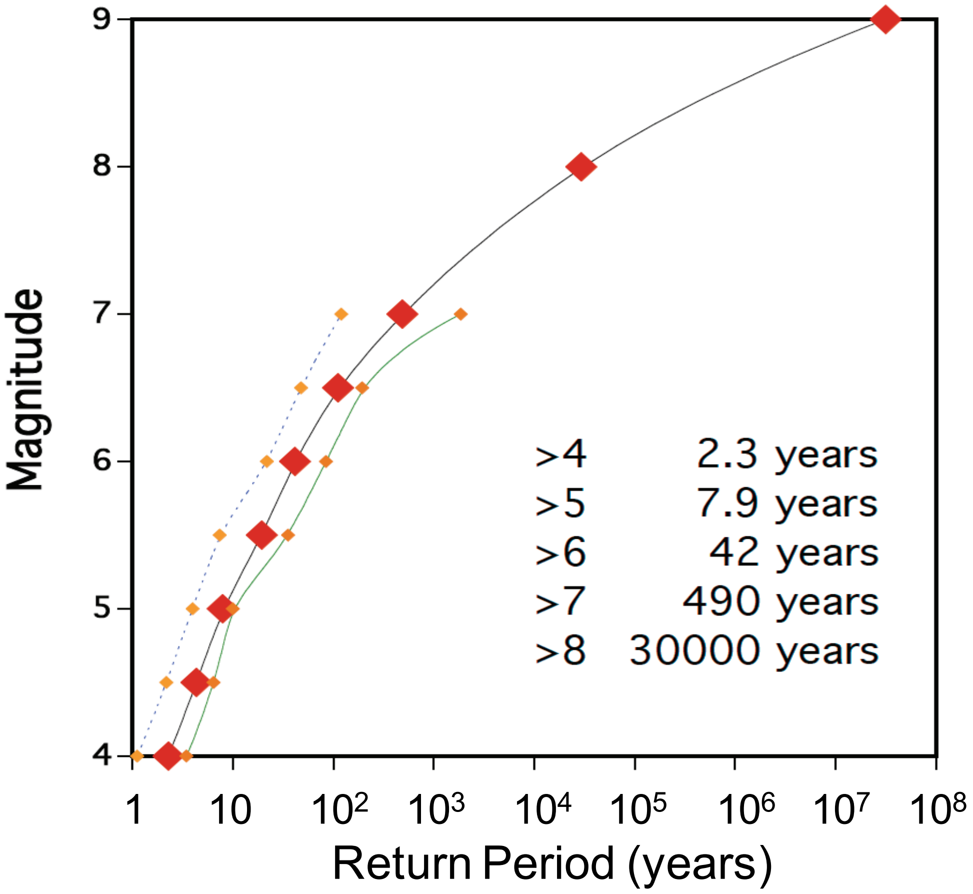


Figure 3.2 Magnitude versus return rate for global explosive volcanism with uncertainty bounds indicated.

4 Methodology for Volcano Hazard, Exposure and Risk Assessment

The thirty-one GFDRR priority countries were divided into three categories based on their proximity to volcanoes:

- Category A: Countries with volcanoes within their borders
- Category B: Countries with no volcanoes within their borders, but with volcanoes within 200 km of their borders
- Category C: Countries with no volcanoes, either within their borders or within 200 km of their borders.

The classification was carried out using information from the Smithsonian Institution's Global Volcanism Program database of worldwide Holocene volcanoes, available online. The countries in each category are listed in Table 1. Figure 4.1 shows the geographical locations of the GFDRR priority countries in each category.

Table 1: Classification of GFDRR priority countries based on volcano locations

Category A – 16 Countries	**Category B – 5 Countries**	**Category C – 10 Countries**
Colombia Costa Rica Djibouti Ecuador (including Galápagos Islands) Ethiopia Guatemala Indonesia Madagascar Mali Panama Papua New Guinea Philippines Solomon Islands Vanuatu Vietnam Yemen	Cambodia Kyrgyz Republic Laos Malawi Pakistan	Bangladesh Burkina Faso Ghana Haiti Marshall Islands Mozambique Nepal Senegal Sri Lanka Togo

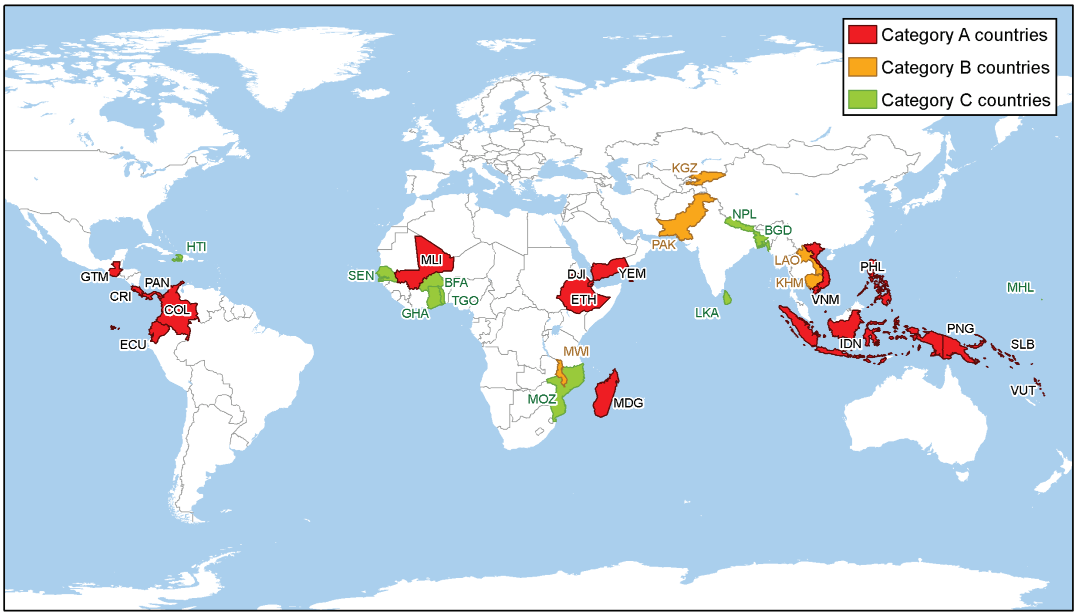


Figure 4.1 GFDRR priority countries categorised based on their proximity to volcanoes .

The methodologies used for volcano hazard, exposure, and risk assessment, as well as the national capacities in Category A countries for coping with the risks posed by volcanic eruptions, are described in detail in Appendix B. A brief outline is presented below.

4.1 Hazard and Uncertainty Assessment

A method for measuring the physical threat posed by individual volcanoes inside Category A countries was developed, building on and adapting the work of Ewert et al. (2005). The method is used to assign each volcano to a hazard level and an uncertainty level.

The following eight hazard-related elements are defined:

- Volcano type
- Crater lake or ice/ snow cap presence
- Pyroclastic flow hazard
- Lahar hazard
- Lava flow hazard
- Number of subfeatures
- Maximum VEI
- Eruption frequency

The method scores these elements, sums the scores, and then assigns them to one of three Hazard Levels (1, 2, or 3).

Uncertainty levels were developed which examine the extent to which the information and evidence on volcanic hazard exists or is available. Similarly to the hazard elements, six uncertainty scores are summed and then assigned to one of three Uncertainty Levels.

The reported outputs are a Hazard Level and Uncertainty Level for each volcano, where Level 1 means lowest hazard or uncertainty, and Level 3 means highest hazard or greatest uncertainty. The methodology needs further refinement that is discussed in the appendix and so the results of this study should be regarded as a preliminary view.

4.2 Population Exposure

A method for measuring the number of people threatened by each volcano was developed to give an indicator of population vulnerability. This was combined with the hazard level of each volcano to quantify population risk.

The method is adapted from the idea of the Volcano Population Index (Ewert and Harpel, 2004). The 2009 LandScan population database and volcano geographic coordinates are used to calculate estimates of the numbers of people living within 10 km and 30 km of each volcano. The populations are then multiplied by weightings, summed, and assigned to one of seven scores, referred to as the Population Exposure Index (Table 2).

Table 2: Population Exposure Index

Weighted Summed Population	**Population Exposure Index**
0	0
<3,000	0.5
3,000 – 9,999	1
10,000 – 29,999	1.5
30,000 – 99,999	2
100,000 – 300,000	2.5
>300,000	3

4.3 Risk to Population

A simple estimate of population risk for each volcano was computed by taking the product of the Hazard Level and Population Exposure Index. The numerical product is assigned to one of three Population Risk Levels as shown in Table 3.

Table 3: Population Risk Level cohorts

	Volcano Hazard Level		
Population Exposure Index	**1**	**2**	**3**
0, 0.5	1	1	1
1	1	2	2
1.5	1	2	3
2	2	2	3
2.5, 3	2	3	3

In developing a simplified risk level based on population one should recognise that there are many factors beyond where people live that affect their vulnerability and risk. Factors that influence how people respond to a volcanic crisis include risk attitude, risk perception, belief systems, education, trust in experts or authorities, indigenous knowledge, and experiences of previous eruptions. Other influences on vulnerability include, for example, ease of evacuation routes and extent to which authorities have made effective emergency plans and communication systems for early warning. These are by no means an exhaustive list, but they illustrate that population exposure provides only a partial measure of volcanic risk.

4.4 Ash hazard and Risk

The work on ash hazard in this study is limited to the first order question of identifying areas that might be adversely affected by suspended ash and ash fall. The main control on ash hazard is the wind direction profile above the volcano (see Figure 1.2), and the eruption column height which itself is related to eruption intensity. Here we have taken the view that eruptions of magnitude 3 and 4 (equivalent to VEI 3 and 4) will be quite frequent sources of ash-related hazards in most of the study countries. Further, these eruptions commonly transport ash in the atmosphere at heights of 8 to 16 km at which much commercial aviation is concentrated. The main prevailing wind directions at heights equivalent to atmospheric pressures of 250-100 mbar are displayed as a guide to ash hazard directionality in the country illustrations.

This simple analysis is not a substitute for a detailed assessment of ash hazard that takes account of the frequency of eruptions of different magnitude, wind intensity at all altitudes and complexities of ash transport processes. The method will also not properly capture ash hazard for low frequency, high magnitude events, and extrapolations should not be attempted.

5 National Capacity for Coping with Volcanic Risk

A monitoring index was created in order to allow comparison of the GFDRR priority countries to be made in terms of monitoring capability for each of their volcanoes. For this purpose, volcanoes are scored using two indices:

- Frequency of monitoring
- Existence and proximity of seismic networks

Each volcano is assigned a score between 0 and 3 for each index, where 0 corresponds to no monitoring or no seismic network, and 3 corresponds to continuous monitoring or a dedicated permanent seismic network. These two scores are then summed and assigned to Monitoring Levels 0 (unmonitored) to 3 (established, comprehensive monitoring).

The information used to derive the Monitoring Levels comes from websites and personal communications, which can differ in their reliability and accuracy and as such, carry a variable degree of uncertainty. This was accounted for by allocating uncertainty scores to each of the monitoring indices, from 0 (strong source) to 1 (unknown, or not confirmed information). This was averaged for both indices for each country (rather than each volcano), and the country's Monitoring Level uncertainty was then classified as low (0 – 0.5), low-medium (0.5 – 1), medium-high (1 – 1.5) or high (1.5 – 2).

A bar chart is used to depict the distribution of each country's volcanoes across the four Monitoring Levels (0, 1, 2, or 3), with colouring used to indicate Risk Level (1, 2 or 3), as in Figure 6.7. The country-averaged Uncertainty Level is shown above the plot.

6 Volcano Hazard and Risk in GFDRR Priority Countries

Appendix C provides the detailed hazard, exposure and risk profiles of the sixteen Category A countries listed in Table 1, while Appendix D presents an overview of the national capacities of the Category A countries to cope with the volcano risk. A summary of these assessments is provided in this section.

Figure 6.1 gives a graphical presentation of the volcanoes with different Risk Levels in Category A countries. Table 4 provides an overview of the population proximity to volcanoes in Category A countries.

Figure 6.2 displays the number of volcanoes with Risk Level 3 versus the number of volcanoes in each country, and Figure 6.3 displays the number of volcanoes with Risk Level 3 versus the number of volcanoes with Uncertainty Level 3.

Table 4: Population proximity to volcanoes in Category A countries

Country	No. of volcanoes	Population within 100 km of volcano(es)	Population within 30 km of volcano(es)	Population within 10 km of volcano(es)
Indonesia	142	185,378,000	68,045,000	8,525,000
Ethiopia	65	39,791,000	9,546,000	1,304,000
Papua New Guinea	56	4,182,500	829,000	172,000
Philippines	47	89,966,000	31,743,000	3,140,000
Ecuador	33	6,827,000	3,980,000	586,000
Guatemala	22	11,883,000	7,346,000	1,341,000
Colombia	15	12,021,000	2,822,000	360,000
Vanuatu	14	205,200	97,000	25,000
Yemen	12	15,950,000	3,719,000	623,000
Costa Rica	10	4,214,500	3,059,000	125,000
Solomon Islands	8	300,000	98,000	5,000
Vietnam	6	19,465,000	1,649,000	137,000
Madagascar	5	6,959,000	879,000	64,000
Panama	2	2,780,000	224,000	15,000
Djibouti	1	724,000	22,000	2,000
Mali	1	2,000	< 1,000	< 1,000

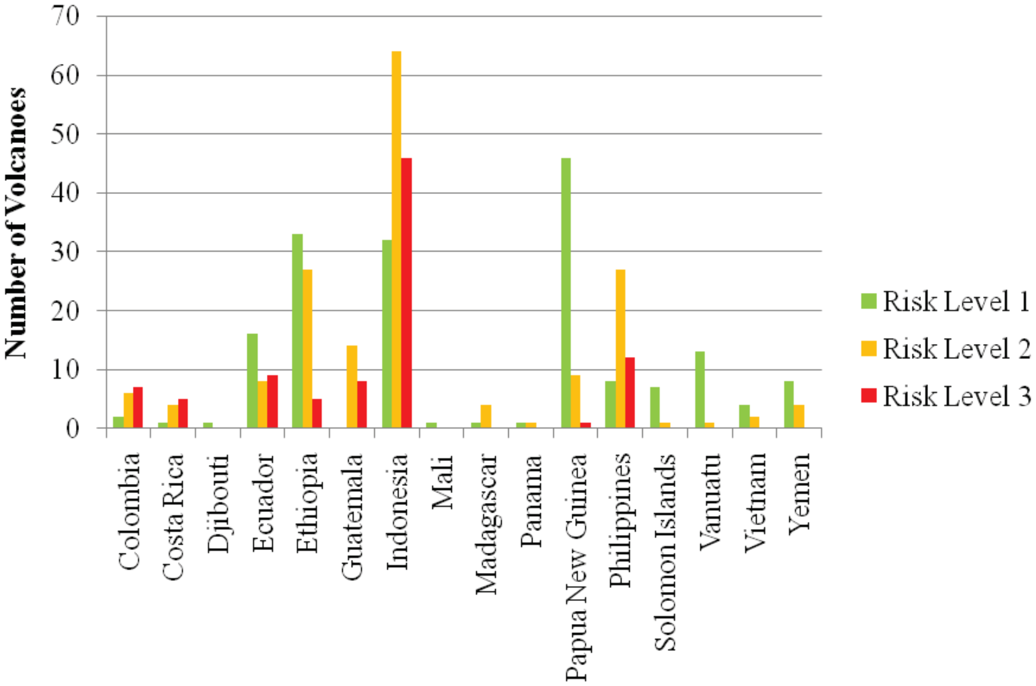


Figure 6.1 Number of volcanoes with different Risk Levels in Category A countries.

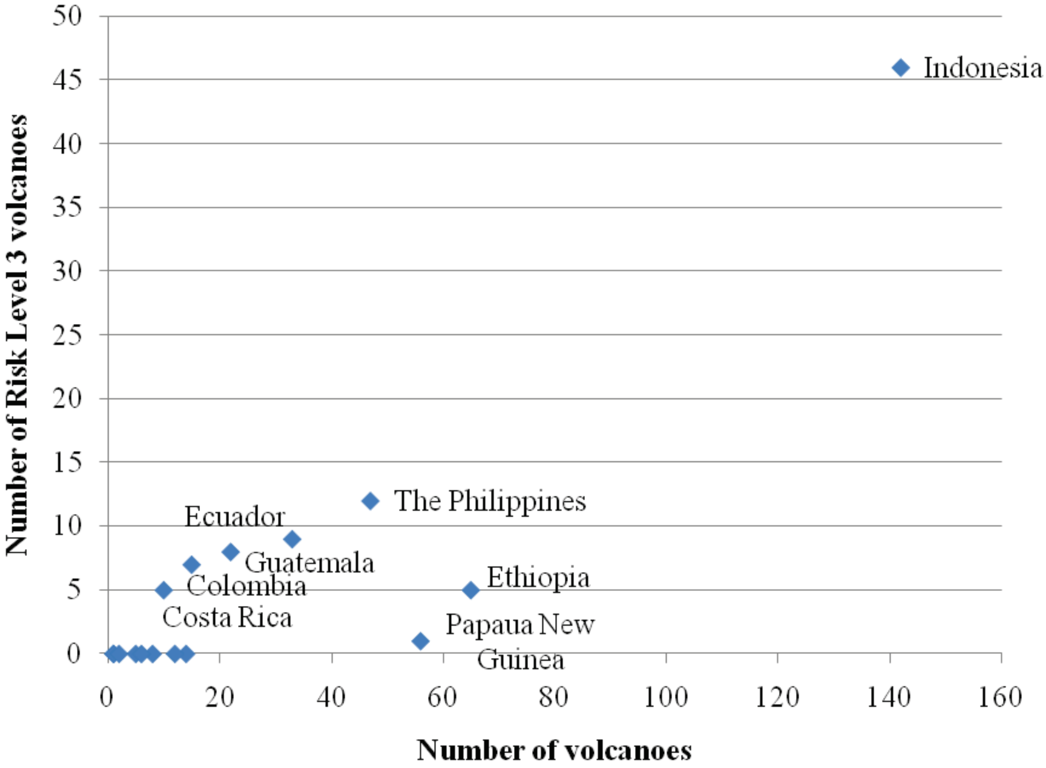


Figure 6.2 Number of volcanoes with Risk Level 3 versus total number of volcanoes in Category A countries.

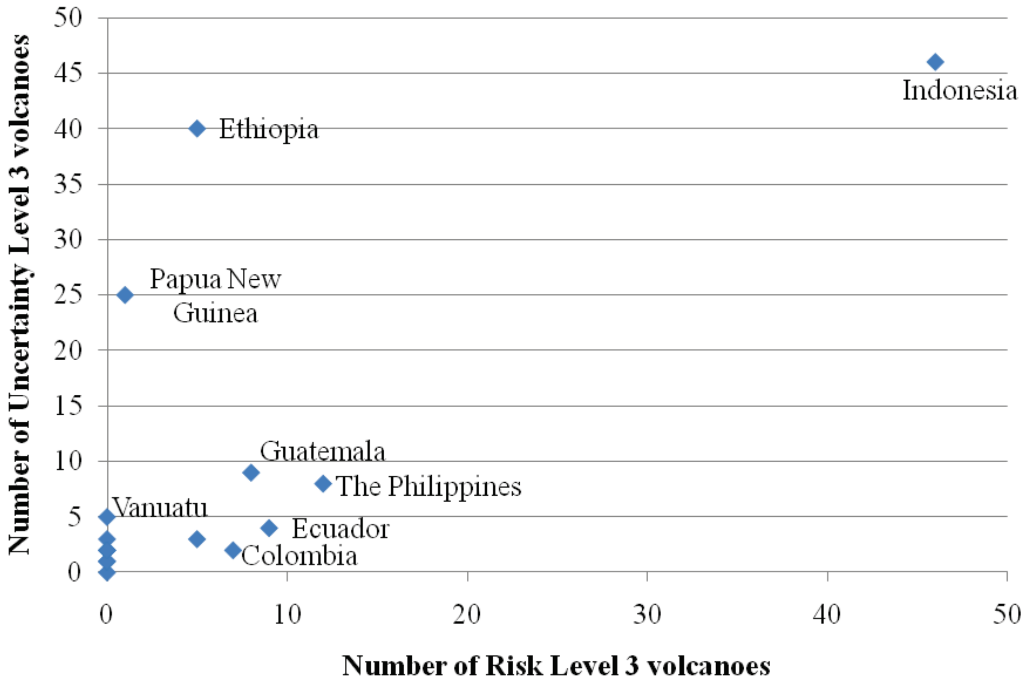


Figure 6.3 Number of volcanoes with Risk Level 3 versus number of volcanoes with Uncertainty Level 3 in Category A countries.

The detailed results presented in Appendix C for each Category A country include the location of volcanoes and key cities, volcanic facts, key socio-economic data, hazard and uncertainty assessment, exposure assessment for population and key infrastructure, and frequency of explosive volcanism for some of the countries. Figures 6.4 through 6.7 show example plots of the results presented in Appendix C.

A study of volcanic risk in the Asia-Pacific region by Simpson et al. (2011) provides a complementary analysis of Indonesia, Papua New Guinea, The Phiilipines, The Solomon Islands and Vanuatu. Their results are in general in agreement with this study.

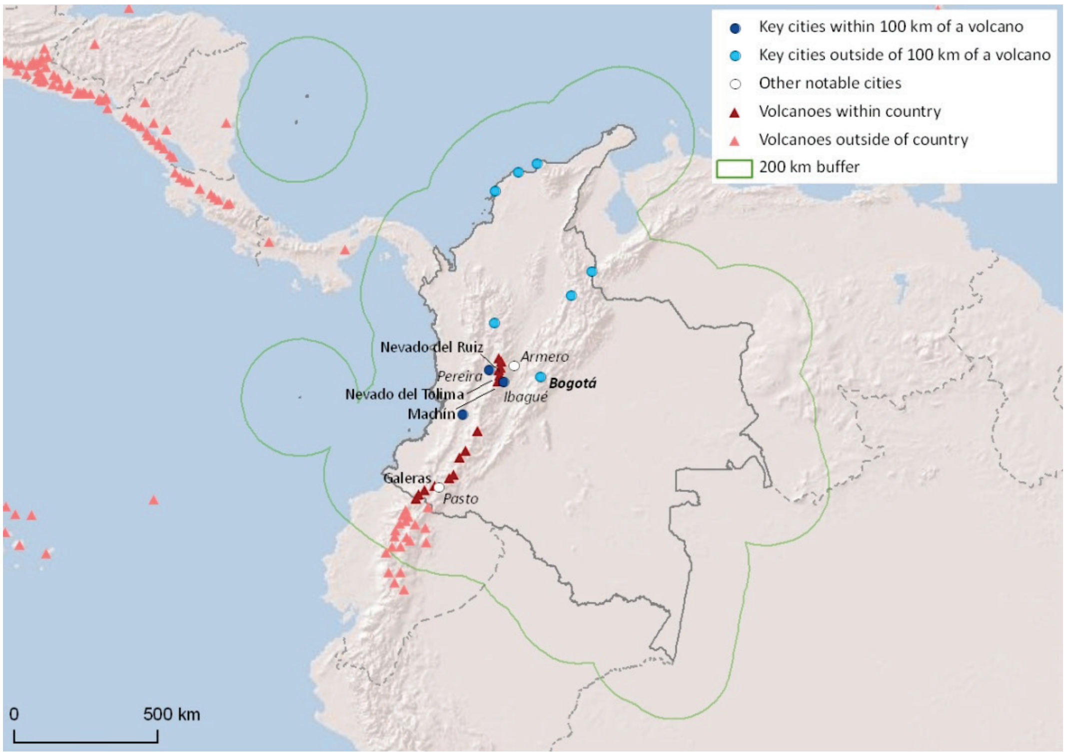
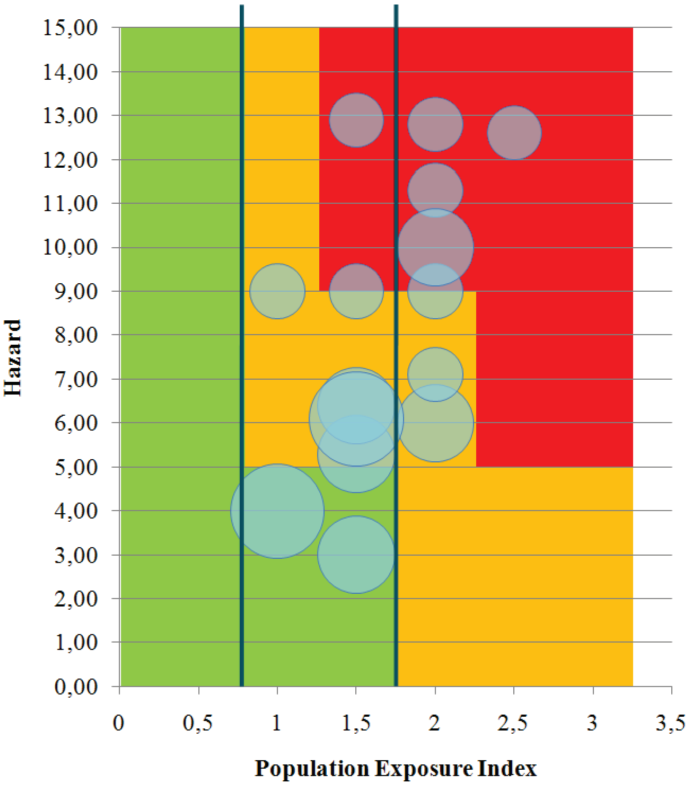


Figure 6.4 Locations of Colombia's volcanoes, ten largest cities, and other notable cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Colombia.

Figure 6.5 Distribution of Colombia's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels. Larger circles indicate greater uncertainty. Volcanoes plotting within the red areas are high risk, those in orange are medium risk and those in green areas are low risk.



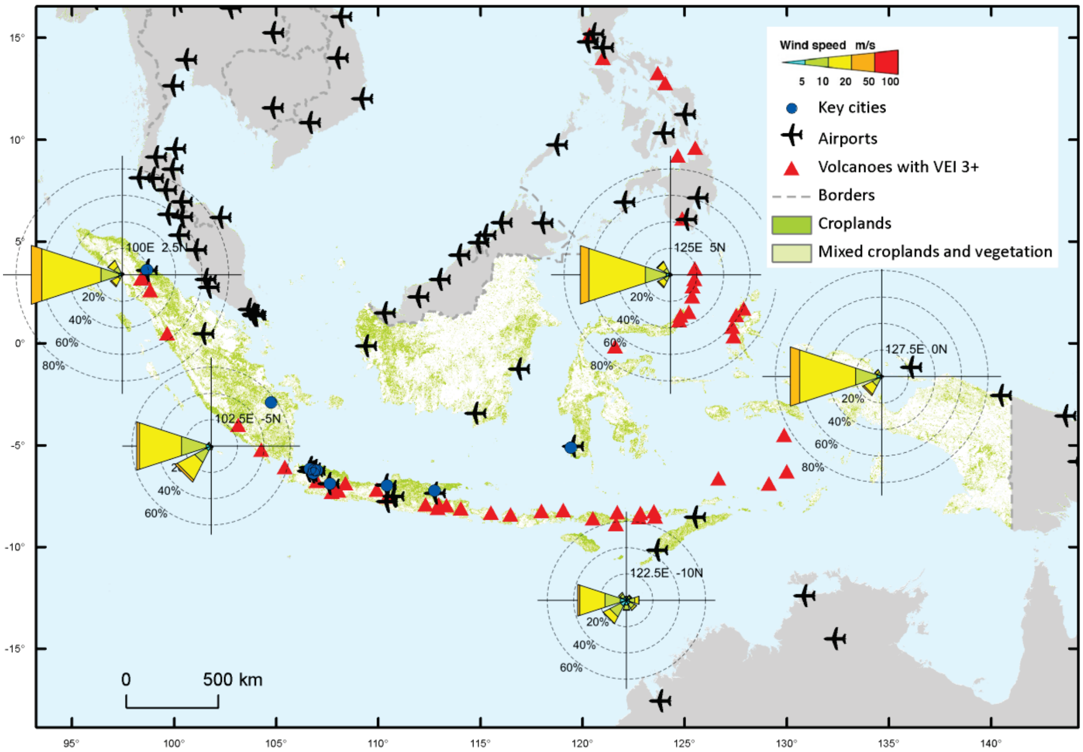


Figure 6.6 Map showing elements exposed to ash hazards in Indonesia, with wind roses indicating dominant wind directions and speeds.

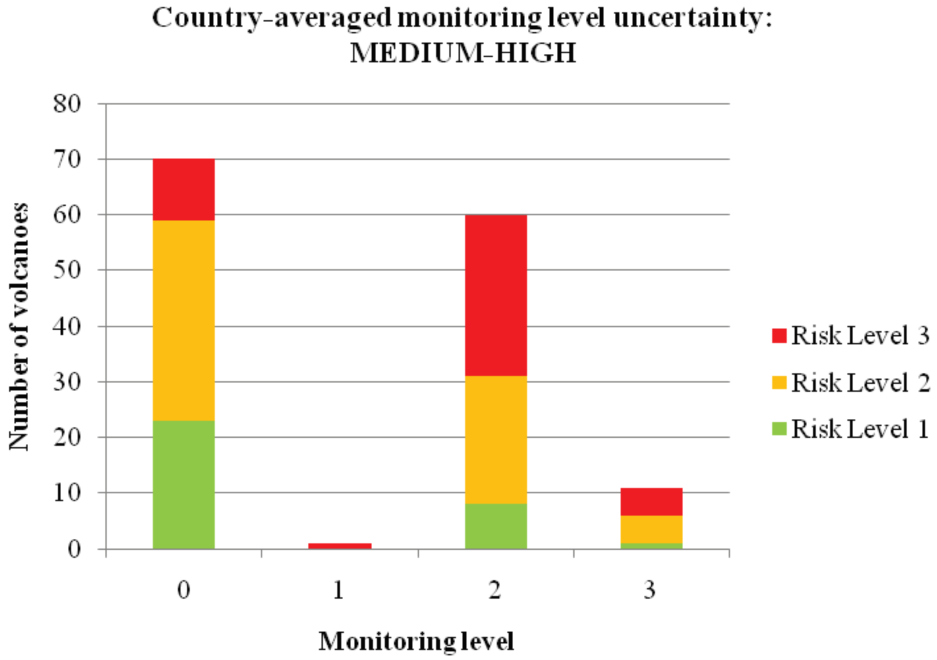


Figure 6.7 Distribution of Indonesia's volcanoes across Monitoring and Risk Levels.

7 Recommendations and Key Priorities for Action

Mitigation and prevention of the risk posed by natural hazards have not attracted widespread and effective public or political support in the past. However, the situation has changed dramatically during the past decade, and it is now generally accepted that a proactive approach to risk management is instrumental in significantly reducing the loss of lives and material damage associated with natural hazards. The wide media attention on major natural disasters during the last decade has clearly changed many people's mind in terms of acknowledging that disaster, and risk preparation measures can be a critical humanitarian and economic complement to reactive post-disaster emergency response management.

A milestone in international collaboration for natural disaster risk reduction was the approval of the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters" (International Strategy for Disaster Reduction, 2005: Hyogo Framework for Action 2005-2015). This document, which was approved by 164 UN countries during the World Conference on Disaster Reduction in Kobe, January 2005, clarifies international working modes, responsibilities and priority actions for the coming 10 years. The Hyogo Framework of Actions states three fundamental principles:

- Each nation has the prime responsibility for preventive measures to reduce disaster risk, and is expected to take concrete actions as outlined in the Action Plan.
- Governments in risk exposed countries shall regularly report progress achieved to the UN coordinating unit which is the ISDR Secretariat with headquarters in Geneva.
- International cooperation is called upon to assist countries that need help.

The Hyogo Framework of Action has clearly increased the awareness and importance of preventive measures. It will also contribute to a much better practice for the implementation of risk reduction projects for two reasons: a) by the fact that governments will be in the driving seat, which means that coordination is likely to be improved, and b) by the fact that UNISDR, given the responsibility for the follow-up of the plan, will put pressure for action from countries that are most exposed. Developing countries typically have limited resources and capacity to implement mitigation measures.

One can observe a positive trend internationally where the benefits of preventive measures are increasingly recognized, both at the government level and among international donors. There is, however, a great need for intensified efforts, because the risk associated with natural disasters has been clearly increasing far more rapidly than the efforts made to reduce this risk.

Three key pillars for the reduction in risk associated with natural hazards in developing countries are suggested:

Pillar 1: Identify and locate the risk areas, and quantify the hazard and the risk

Hazard and risk assessment are the central pillar in the management of the risk associated with natural hazards. Without knowledge and characteristics of hazard and risk, it would not be meaningful to plan and implement mitigation measures.

Pillar 2: Implement structural and non-structural risk mitigation measures, including early warning systems

Mitigation means implementing activities that prevent or reduce the adverse effects of extreme natural events. In a broad perspective, mitigation includes active engineering measures, effective early warning systems, 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 lifestyle and behaviour of endangered populations in order to get them to help reduce their risk. All these measures can help minimize the number of casualties.

Pillar 3: Strengthen national coping capacity

Most of the developing countries lack sufficient coping capacity to address a wide range of hazards, especially rare events like major volcanic eruptions. International cooperation and support are therefore highly desirable. A number of countries have over the last decade been supportive with technical resources and financial means to assist developing countries where the risk associated with natural hazards is high. A key challenge with all projects from the donor countries is to be assured that they are needs-based, sustainable and well anchored in the countries' own development plans. Another challenge is coordination which often has proven to be difficult because the agencies generally have different policies and the implementation periods of various projects do not overlap. A subject which is gaining more and more attention is the need to secure 100% ownership of the project in the country receiving assistance.

Specifically, to manage and reduce the risk posed by volcanic eruptions in GFDRR priority countries, the following actions are recommended:

- The hazard level of many volcanoes in GFDRR priority countries is highly uncertain, mostly reflecting the paucity of geological knowledge and in many cases a low frequency or absence of historic eruptions. Those volcanoes with a combination of high uncertainty level and high population exposure index should be prioritized for geological studies that document recent volcanic history within a hazard assessment context. Recommended studies include stratigraphy, geochronology, petrology, geochemistry and physical volcanology. Such studies greatly enhance the assessment of potential hazards if volcanic unrest or activity begins and, in some cases, findings are likely to increase the perceived hazard level.

- Many active volcanoes in GFDRR priority countries are either not monitored at all, or have some monitoring, but this is very limited and often outmoded. These include examples of volcanoes that are classified in this study as at high risk. A major advance for hazard mitigation would be if all high-risk volcanoes had at least one volcano-dedicated seismic station with continuous operation telemetry to the responsible institution. We recommend this action as a high priority to address volcanic risk.

- High risk volcanoes should be monitored by a combination of complementary multi-parameter techniques, including volcano-seismic networks, ground deformation, gas emissions and readily accessible remotely sensed data (e.g. various satellite-based geophysical change detection systems). We recommend that all high risk volcanoes should be provided with basic operational monitoring from all four domains. Donations of equipment and knowledge transfer schemes need to be sustainable long term with respect to equipment maintenance and consumables, and backing support for sustaining local expertise will be essential.

- In some cases training of staff and knowledge transfer will be beneficial from countries with experience and expertise in volcano monitoring, particularly in relation to the appraisal of unrest and communication of potential hazard scenario implications. Training opportunities and knowledge transfer mechanisms, such as workshops and summer schools, are needed in several fields to bring state-of-the-art science and techniques to scientists in many GFDRR priority countries. Topics include hazard mapping, physical volcanology, monitoring, process modelling especially with respect to practical hazards assessment and forecasting tools, remote sensing and risk assessment.

- Free and easy access to the most advanced science and data will greatly enhance the ability of GFDRR priority countries to manage volcanic risk. Knowledge and access to knowledge is globally very uneven between the developed, emerging and developing nations. For volcanic hazards easy access to high-resolution digital elevation data and remote sensed data, together with appropriate training would significantly improve the scientific capacity of many GFDRR priority countries. We recommend that the World Bank support open access for scientific publication and data.

- The methods developed in this study to assess and map hazard, exposure, risk and monitoring capacity are straightforward, intended to provide a basic broad overview of volcanic risk and hazard in each country. The information should not be used to assess hazard and risk in detail at individual volcanoes, which is the responsibility of national institutions. Nonetheless, there is much room for improving the methods for classifying hazards levels and mapping volcanic risk to provide more accurate and robust global and regional assessments. We note that there is scope for improvement of the methods, for example by applying statistical analyses of data from well-known volcanoes to poorly known volcanoes. We recommend that research is encouraged for such methodological developments in applied volcanology. The World Bank might consider supporting Research and Development efforts to improve methods of assessing ash fall, lahar and pyroclastic flow hazards, and methods to map population exposures at higher resolution. Such methods might be of sufficient accuracy to be useful at the level of an individual volcano, but methods should be developed in collaboration with national institutes so that they gain acceptance with the local population and demonstrate utility.

- Risk from volcanic ash hazard associated with a particular volcano or region can only 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 for various levels of damage (e.g. deposit depths and atmospheric concentrations) We recommend that further analysis be performed for all high risk volcanoes, to enable more conclusive statements to be made about expected loss and potential to disrupt aviation.

- Risk around volcanoes is determined not just by the volcanic hazards and monitoring capacity, but also by the behaviour, attitudes and perceptions of exposed people to risk. Reducing risk is thus likely to come from better awareness of the hazards, and good communication by scientific institutions and authorities. Resources are this needed to raise awareness and understand the responses of populations. In addition well thought out plans for emergencies are essential.

8 Acknowledgments

The authors of this report would like to thank their colleagues at The Smithsonian Institute for the fruitful discussions and sharing their data. The authors also wish to acknowledge the open sources for map data used in the analyses presented in the report. It would not have been possible to do the GIS analyses without the free data.

We thank many colleagues around the World, including several in the scientific institutions of some GFDRR priority study countries (e.g. AAU, GNS, IG(EPN), INGEOMINAS, MTU, CVGHM, OGA, OSOP) for their generosity in providing information and insights into their volcanoes and institutions.

The Bristol group were partially supported by the European Research Council Advanced grant for developing hazard and risk assessment methodologies.

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Appendix A - Definitions and Terms

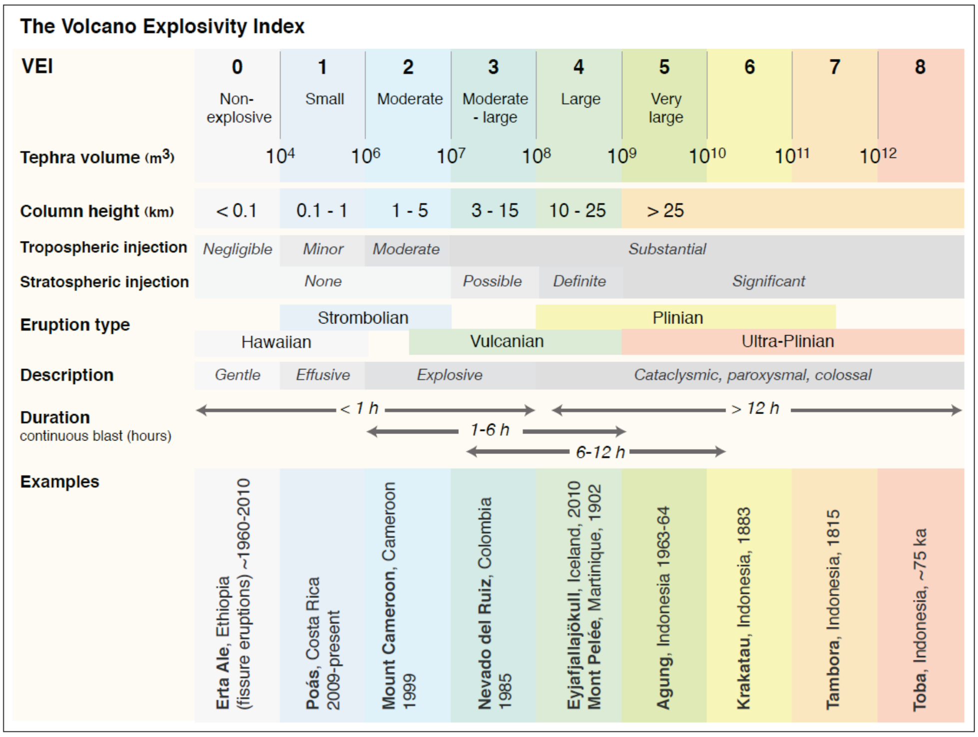
Contents

A1 Glossary of Terms for Volcano Hazard and Risk Assessment

- **Magnitude** – the total mass or ‘dense rock equivalent’ (DRE) volume (to account for void spaces) of erupted material.

- **Intensity** – rate of mass or energy release. Intensity is typically measured as either DRE volume of ejecta or mass per unit time (Walker, 1980).

- **VEI** (Volcanic Explosivity Index) – A scale using both quantitative measurements and subjective descriptions of eruptive phenomena to provide a relative measure of the explosivity of volcanic eruptions. Each increment represents an order of magnitude increase in eruption volume (see table below, based on Newhall and Self, 1982; and Simkin and Siebert, 1994). There have been no recorded events greater than VEI 8.



The Volcano Explosivity Index

VEI	**0** Non-explosive	**1** Small	**2** Moderate	**3** Moderate - large	**4** Large	**5** Very large	**6**	**7**	**8**
Tephra volume (m^3)	10^4	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	
Column height (km)	< 0.1	0.1 - 1	1 - 5	3 - 15	10 - 25	> 25			
Tropospheric injection	*Negligible*	*Minor*	*Moderate*	*Substantial*					
Stratospheric injection	*None*			*Possible*	*Definite*	*Significant*			
Eruption type		Strombolian			Plinian				
	Hawaiian		Vulcanian			Ultra-Plinian			
Description	*Gentle*	*Effusive*	*Explosive*		*Cataclysmic, paroxysmal, colossal*				
Duration continuous blast (hours)	*< 1 h*		*1-6 h*	*6-12 h*	*> 12 h*				
Examples	**Erta Ale**, Ethiopia (fissure eruptions) ~1960-2010	**Poás**, Costa Rica 2009-present	**Mount Cameroon**, Cameroon 1999	**Nevado del Ruiz**, Colombia 1985	**Eyjafjallajökull**, Iceland, 2010 **Mont Pelée**, Martinique, 1902	**Agung**, Indonesia 1963-64	**Krakatau**, Indonesia, 1883	**Tambora**, Indonesia, 1815	**Toba**, Indonesia, ~75 ka

- **Exposure** – elements at risk: people, property, systems, or functions at risk of loss exposed to hazards. In insurance, exposure is defined as the degree to which a risk or portfolio of risks is subject to the possibility of loss.

- **Population Exposure Index and Levels** – The Population Exposure Index (PEI) is a volcano-by-volcano measure of the number of people potentially affected by a volcanic eruption, calculated by weighting and summing the number of people within 10 km and 30 km of a volcano; the PEI ranges from 0 to 3. The PEI is assigned to Levels 1 to 3 (Level 1 lowest PEI, Level 3 highest).

- **Risk score and Level** – The risk score is the volcano-by-volcano product of Hazard Level and PEI Level, giving a one-number summary of population risk; risk scores range from 0 to 9. Risk scores are assigned to Risk Levels 1 to 3 (Level 1 lowest risk, Level 3 highest).

- **Monitoring score and Level** – The Monitoring score is a volcano-by-volcano measure of monitoring capabilities, calculated based on frequency of monitoring and proximity of seismic networks; monitoring scores range from 0 to 6. Monitoring scores are assigned to Monitoring Levels 0 to 3 (Level 0 worst monitoring, Level 3 best).

- **Recurrence interval** – estimate of the period of time between volcanic eruptions.

- **Return period** – The average time between occurrences of a defined event.

- **Vulnerability** – The degree to which a system is susceptible to adverse effects associated with a particular hazard or sequence of hazard events. Vulnerability is a function of the scale, extent and duration of the hazard(s) as well as the system's sensitivity, fragility and adaptive capacity. Some vulnerabilities can change over time and may depend on various physical, social, economic and environmental factors.

- **Holocene period** – the current geological epoch that began approximately 11,700 years before present (i.e. before A.D. 1950), around the end of the last glaciation. Part of the Quaternary period.

- **Geological record** – evidence of a geological event (e.g. volcanic activity) found in rock strata, sediment or ice cores and not directly observed by man.

- **Historical record** – evidence of a geological event (e.g. volcanic activity) directly observed and recorded by man.

- **Explosive volcanism** – a violent eruption style driven largely by the exsolution of gas from rising magma under high pressure. Explosive volcanoes can produce eruption columns tens of kilometres high, releasing gas and ash into the stratosphere. Pyroclastic flows, blasts and surges are a major hazard. Erupted material is generally ejected further from the vent during an explosive eruption than during an effusive one.

- **Effusive volcanism** – a less violent eruption style, generally characterised by lava flows. Lava flow velocity is dependent on lava composition, viscosity, volume, and eruption rate, as well as slope. In most instances, impacts from lava flows are less widespread than those resulting from explosive eruptions.

- **Hazard score and Level** – the hazard score is a volcano-by-volcano measure of physical threat posed, calculated based on eight hazard related elements; hazard scores range from 2 to approximately 15. Hazard scores are assigned to Hazard Levels 1 to 3 (Level 1 lowest hazard, Level 3 highest).

- **Uncertainty score and Level** – the uncertainty score is a volcano-by-volcano measure of the uncertainty surrounding the Hazard Level; uncertainty scores range from 0 to approximately 3. Uncertainty scores are assigned to Uncertainty Levels 1 to 3 (Level 1 lowest uncertainty, Level 3 highest).

A2 General Risk Management Terms

Annual Exceedance Probability (AEP) – The estimated probability that an event of a specified magnitude or greater will occur in any given year.

Consequence – The outcomes or potential outcomes arising from the occurrence of a hazard event expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Elements at risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by volcanic eruption (see exposure)

Frequency – A measure of likelihood expressed as the expected number of occurrences of an event in a given time. See also Likelihood and Probability.

Hazard – A condition with the potential for causing an undesirable consequence. The description of volcano hazards should include the location, intensity and the probability of occurrence within a given period of time.

Likelihood – Used as a qualitative description of probability or frequency.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event or the likelihood that a hazard will adversely impact a particular place.

There are two main interpretations of probability:

> *Statistical-frequency or fraction* – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
>
> *Subjective probability (degree of belief)* – Quantified measure of belief, judgement, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Risk – A measure of the probability and severity of an adverse effect to health, persons, property or the environment. Risk is often defined as the expectation value of losses (deaths, injuries, damage, economic loss) resulting from a hazard event, expressed as the product of probability × consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form, for example risk ranking based on subjective scoring of hazard, vulnerability and consequence.

Risk mitigation – The process of decision making for managing risk, and the implementation or enforcement of risk reduction or prevention measures.

Risk management – The complete process of risk assessment and risk control (or risk treatment), and the re-evaluation of measure effectiveness from time to time, often using the results of risk assessment updates as input.

Uncertainty – Describes any situation without certainty, whether or not described by a probability distribution. Uncertainty is caused by natural variation and/or incomplete knowledge (lack of understanding or insufficient data). In the context of hazards and their assesment, uncertainty can be attributed to (i) *aleatory uncertainty*: inherent variability in natural processes and events, and (ii) *epistemic uncertainty*: incomplete knowledge of processes, or of parameters for representing such processes in models.

A3 Synopsis of Volcanic Hazards

In Section 2 of the main Report text there is a list summarising the principal volcanic hazards that can be produced by an erupting volcano. The following paragraphs expand those descriptions, providing some additional detail and other information.

Ballistics

Ballistics (also referred to as blocks or bombs) are defined as pyroclastic fragments with dimensions of over 64 mm. Ballistic fragments range from several centimetres up to a few metres in diameter and in the strongest eruptions smaller ballistic fragments can be ejected out to perhaps 5 kilometres. Hazards due to the biggest blocks and bombs are confined to areas close to the vent. Fatalities, injuries and structural damage caused by ballistics occur mostly as a result of direct impacts, and very hot ballistics can also start fires. Even quite small ballistics, falling from great height some kilometres from a strong explosion, can cause injury or death.

Tephra hazard

Most volcanic eruptions generate vertical turbulent columns, which rise as buoyant plumes into the atmosphere. Columns containing volcanic particles and gases can ascend to heights ranging from a few kilometres to as much as 50 kilometres in the most powerful explosive eruptions. Tephra is a term used to describe any fragmented rock material ejected from a volcano during an eruption; ash is defined as tephra particles of less than 2 mm diameter. The fall of the tephra to the ground and the suspension of fine ash in the atmosphere can cause various, commonly wide-spread, hazards to humans, infrastructure systems and the environment. Fatalities and injuries occur as a result of roof collapse, where the weight of tephra deposits causes structural failure. Health hazards arise with respiratory problems caused by inhalation of fine, irritant particles, as well as abrasion of skin and conjunctiva. Blanket ash deposits can damage and destroy crops, while livestock can be harmed by chewing coarse ash when grazing or killed by eating plants covered by ash containing toxic volcanic volatiles such as fluorine. Ash can also clog up machinery and damage electronic and electrical systems. Modern electronics systems, including medical equipment, may be vulnerable to ash surface chemistry effects. Suspended and remobilised volcanic ash is a major hazard to aviation, potentially causing engine failure and other problems when airplanes fly through dense ash clouds, often requiring closure of airports. Other forms of transport can be disrupted, jeopardizing food supplies, provision of emergency services and other essential services.

Pyroclastic density currents

Pyroclastic density currents are hot, high velocity, gravity-driven mixtures of hot volcanic particles and gases. They are commonly called pyroclastic flows when the concentration of particles in the mixture is high and surges when the concentration of particles is low. Most pyroclastic density currents consist of both flow and surge components, but they vary widely in the relative proportions of the two components. Pyroclastic flows tend to be confined to valleys, while surges are less constrained by topography and in the most violent events can surmount topographical barriers of several hundred metres. Pyroclastic flows can form in various ways, including gravitational collapse of an explosively generated eruption column, lateral explosions, or collapse of unstable lava domes. Pyroclastic density currents are the most lethal kind of volcanic hazard. With typical temperatures of several hundred degrees centigrade and fast speed (commonly tens to hundreds of kilometres per hour) escape is difficult and survival very rare. Deaths occur as a result of obliteration from the force of the flow, from burns, asphyxiation, and heat-induced shock. Timely evacuation is the only viable strategy to protect populations. Pyroclastic density currents can cause severe damage to buildings, vegetation and land. They can commonly travel distances of many kilometres and in the larger magnitude explosive eruptions tens of kilometres. In some cases surge clouds can travel over water. Pyroclastic density currents can produce steam explosions if they enter large bodies of water.

Lahars and floods

Lahars (an Indonesian word) are fast-moving mixtures of volcanic debris and water, sometimes hot. Lahars are classed as either primary (occurring at the time of the eruption) or secondary (occurring some time after the eruption has ceased). The commonest cause of lahars arises from intense rain eroding loose volcanic deposits formed during an eruption. Other causes include eruptions of hot lava or explosive eruptions on glaciers or snow, break out of ephemeral lakes, and pyroclastic flows or volcanic landslides mixing with river water, and spontaneous discharges of mud from fractures in volcanic edifices, likely caused by volcanically-induced disturbances of ground water and hydrothermal systems. Lahars are, together with pyroclastic flows, a major cause of loss of life in volcanic emergencies. Lahars are normally guided by valley systems, but can spill out of channels in unpredictable ways if the lahar discharge exceeds the capacity of the valley. Lahars can carry very large blocks (several metres) and are very destructive to buildings and other structures such as bridge and dams when entrained blocks impact. Large lahars are known to have run-outs exceeding 100 kilometres. Thick deposits left behind cause extensive environmental change or degradation.. Communities can be protected from lahars by being evacuated or learning to escape to high ground when warning is given, but lahars can block evacuation routes.

Floods are commonly associated with volcanic activity. In some cases lahars will turn into floods downstream as they deposit sediment. Two common causes of volcanic floods are eruptions below glaciers, or failure of the walls of a crater lake. Eruptions below glaciers melt the ice rapidly creating large unstable sub-glacial water bodies, which are rapidly released in bursts known as jökulhlaups (an Icelandic word meaning glacier burst). Crater lakes can generate catastrophic floods if the walls fail or an eruption into the base of the lake causes the water to overtop its confines.

Debris avalanches and landslides

Landslides are common on volcanoes, whether currently active or not. Volcanoes form regions of rugged topography prone to mass wasting, and deformation, groundwater pore pressure fluctuations, loading by lavas, and seismic shaking can provide triggers for slope failure. Stratified tephra fall deposits commonly drape over rugged topography and become weathered. The tephra layers and weathered zones form potential weak failure horizons. Debris avalanches are caused by the failure of unstable volcanic edifices. The underlying trigger of debris avalanches is classed as one of either unstable slopes (due to gravity), or volcanic processes such as volcanic earthquakes or instability induced by subsurface magma intrusion. Some volcanic landslides and debris avalanches are unrelated to volcanic activity, such as those caused by hurricanes or regional tectonic earthquakes. Landslides and debris avalanches can travel long distances (up to tens of kilometres), and entrain very large-sized debris material. Further hazards may result if debris collapse material is deposited in a river, or blocks other drainage, and forms a dam which fails subsequently, causing major flooding. One of the most lethal situations on a volcano is when shallow magmatic intrusion or lava dome growth triggers flank collapse with formation of a debris avalanche which rapidly decompresses gas-charged magma that then explodes violently in a lateral volcanic blast (a violent kind of pyroclastic density current).

Gas emissions

Many gases are dissolved in magmas and released during eruptions. The most plentiful of these is water vapour, which, except when very hot, is essentially harmless. All other common volcanic gasses can directly cause fatalities. The most abundant of these is carbon dioxide (CO_2), which, in high enough concentrations, is an asphyxiant gas to humans. The most widely reported cases of such gas emission impacts are limnic (crater lake overturn) eruptions. Large volumes can, in rare cases, be released rapidly causing lethal flows of CO_2. Given that CO_2 is both invisible and odourless, detecting its presence and evacuating is difficult. Fluorine, chlorine, and sulphur compounds can dissolve in atmospheric water droplets to form acidic aerosols. These aerosols are damaging to the eyes, skin, and respiratory system, and may be fatal in severe cases. Acid rain can destroy vegetation and damage properties

Lava flows

Lava flows are the outpouring of hot, molten rock that spread across the ground. They advance slowly enough to allow people to escape, but anything in the pathway of a lava flow can be damaged or destroyed. Buildings and vegetation are commonly set on fire. Land can be rendered unproductive or uninhabitable. There are rare examples of lavas exploding for reasons that are not always clear.

Volcanic tsunamis
The Japanese word 'tsunami' refers to high waves or surges, which occur in the ocean or lake waters. Various volcanic processes may lead to the generation of tsunamis, such as eruptions of submarine volcanoes and high-volume pyroclastic flows, debris flows and volcanic landslides entering water. Tsunamis can cause huge loss of life; their scale, speed, and possible distant impact can devastate coastal populations.

Volcanic earthquakes
Earthquakes are patently associated with volcanism, but typically are small in magnitude. The cumulative effects of repeated volcanic earthquakes include damage to manmade structures, as well as ground deformation and cracks; few fatalities are directly caused by such hazards. A lively and largely unresolved debate centres around whether large regional or teleseismic tectonic earthquakes can trigger eruptions and also if major eruptions can trigger regional tectonic earthquakes.

Shock and infrasonic waves
Intense volcanic explosions can cause shock and infrasonic waves in the atmosphere, which can shatter windows and damage delicate equipment (e.g. electronic doors) at distances of several kilometres from the volcano.

Environmental and secondary effects
The effects of volcanic phenomenon on humans and the environment can lead to damaging secondary hazards. Total decimation of agricultural land may result following lahars, lava flows, pyroclastic flows, tephra fall, and tsunamis. Such destruction can cause severe food shortages due to crop failure and livestock death, and thus indirect deaths such as famine. Secondary fatalities can result from epidemic disease outbreaks, related to food shortages, damage to medical facilities, sanitation infrastructure and contamination of water supplies. Very large explosive eruptions are known to effect climate and have global reach through atmospheric impacts. The overall effect is global cooling for a few years following a major eruption, but the effects can be complicated with, for example, mid-summer frosts in the northern hemisphere and regions of heating or drought.

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Appendix B - Methodology for hazard & exposure assessment

Contents

B1 Methodology for Volcanic Hazard and Exposure Assessments

The volcanoes which are located within the thirty-one GFDRR priority countries differ in terms of both the physical hazards they pose, and their proximity to various exposed elements. A method was derived to quantify and rank the volcanoes with respect to hazard and risk, incorporating the varying quality of information available for doing so. The hazard, risk and uncertainty assessments can then be used as a basis for recommendations for mitigation measures.

B2 Classification of GFDRR Priority Countries Based on Volcano Locations

A preliminary step in gauging the physical volcanic hazard faced at the country scale was to divide the 31 GFDRR priority countries based on their proximity to volcanoes. Three categories were used:

- Category A: Countries with volcanoes within their borders
- Category B: Countries with no volcanoes within their borders, but with volcanoes within 200 km of their borders
- Category C: Countries with no volcanoes, either within their borders or within 200 km of their borders.

Table 1: Classification of GFDRR priority countries based on volcano locations.

Category A – 16 Countries	**Category B – 5 Countries**	**Category C – 10 Countries**
Colombia Costa Rica Djibouti Ecuador (including Galápagos Islands) Ethiopia Guatemala Indonesia Madagascar Mali Panama Papua New Guinea Philippines Solomon Islands Vanuatu Vietnam Yemen	Cambodia Kyrgyz Republic Laos Malawi Pakistan	Bangladesh Burkina Faso Ghana Haiti Marshall Islands Mozambique Nepal Senegal Sri Lanka Togo

The classification was carried out using the Smithsonian Institution's Global Volcanism Program database of worldwide Holocene volcanoes, available online. The countries in each category are listed in Table 1.

Focus for detailed hazard, risk and uncertainty evaluations was on the 439 volcanoes located within the sixteen Category A countries.

B3 Volcanic Hazard and Uncertainty Assessments

A method for measuring the physical threat posed by individual volcanoes inside Category A countries was next developed, which can be used to assign each volcano to a Hazard Level and an Uncertainty Level. The method was designed to be robust, whilst also being applicable using only information available from the Smithsonian Institution website.

The method adapts that of Ewert et al. (2005); it scores eight weighted hazard related elements, sums these scores, and then assigns them to one of three levels.

The eight hazard-related elements are assigned weightings that reflect the level of hazard represented (lahars and pyroclastic flows are both weighted ten times higher than lava flows, for example). The weightings used in this project are different to those in the Ewert et al. method, aiming to better represent the differing threat levels posed by each of the hazard factors; Ewert et al. (2005) weight lahars, pyroclastic flows, and lava flows equally, for example. The full list of scored elements is:

- Volcano type
- Crater lake or ice/ snow cap presence
- Pyroclastic flow hazard
- Lahar hazard
- Lava flow hazard
- Number of subfeatures
- Maximum VEI
- Eruption frequency

The availability and quality of volcano data covering the GFDRR priority countries are very varied; all except two of these factors, crater lake or ice/snow cap presence and number of subfeatures, are given an uncertainty score to incorporate this. The uncertainty score is a completely original addition to the Ewert et al. (2005) method, reflecting the lesser state of knowledge in the GFDRR priority countries compared to the U.S. (the study area of Ewert et al. (2005)). Similarly to the hazard elements, the six uncertainty scores are summed and then assigned to one of three Uncertainty Levels. Again, the scores are weighted to reflect the relative importance of uncertainty surrounding one hazard aspect compared to another. In most cases, four levels of uncertainty are used and, broadly, these represent:

- Listed with certainty on the Smithsonian Institution website
- Listed on the Smithsonian Institution website, but with some uncertainty
- Assumed or inferred, fairly sure
- Assumed or inferred, unsure

The precise algorithm is outlined below. Where relevant, it is applied in the order in which it is written.

B3.1 Volcano Type

Score **1:**

Given for more explosive edifice types, termed "Type 1". These are: caldera, complex volcano, compound volcano, explosive crater, lava cone, lava dome, maar, pyroclastic shield, stratovolcano.

Uncertainty **0**: The Holocene volcano type is definitely Type 1; mention of explosive activity and/ or Type 1 features, in the summary text.

Uncertainty **0.13**: The Holocene volcano type is written as Type 1, but followed by a question mark, unless the volcanic status (a separate field) is fumarolic, in which case give 0.27 uncertainty.

Uncertainty **0.27**: The Holocene volcano type is written as Type 1 but the volcano status (a separate field) is fumarolic.

Uncertainty **0.4**: No mention of Type 1 features, or only mentions lava flows in the summary text.

Score **0:**

Given for more effusive edifice types, termed "Type 0". These are: cinder cone, fissure vent, fumaroles field, hydrothermal field, pumice cone, pyroclastic cone, scoria cone, shield volcano, submarine volcano, tuff cone, volcanic field.

Uncertainty **0**: The Holocene volcano type is definitely Type 0; no mention of explosive activity, or Type 1 features, or non-basaltic compositions, in the summary text

Uncertainty **0.13**: The Holocene volcano type is written as Type 0, but followed by a question mark

Uncertainty: **0.4**: Mention of explosive activity, or Type 1 features, or non-basaltic compositions, in the summary text.

B3.2 Crater lake or ice/ snow cap presence

Score **0:**

No crater lake or ice/ snow cap in any text or pictures.

Score **1:**

Crater lake or ice/ snow cap in any text or pictures.

B3.3 Pyroclastic flow hazard

Score **2**,

Uncertainty **0**: Pyroclastic flows are listed in the eruptive history

Uncertainty **0.23**: Pyroclastic flows are listed in the eruptive history, but with a question mark

Uncertainty **0.47**: Pyroclastic flows are not listed in the eruptive history, but are mentioned in the summary text.

Score **1**,

Uncertainty **0.47**: The volcano is Type 1, has no pyroclastic flows listed in the eruptive history or mentioned in the summary text, but does have explosive eruptions or central vent eruptions listed in the eruptive history

Uncertainty **0.7**: The volcano is Type 1 but has no eruptive history or an eruptive history with only uncertain eruptions, unless the volcano status is fumarolic or hydrothermal, in which case give hazard score 0, uncertainty 0.

Score **0**,

Uncertainty **0**: The volcano is Type 1 with 3+ certain eruptions in the eruptive history and no pyroclastic flows listed; or the volcano is submarine; or the volcano is Type 0 of basaltic composition; or the volcano status is fumarolic or hydrothermal

Uncertainty **0.23**: The volcano is Type 1 with 1-2 certain eruptions in the eruptive history and no pyroclastic flows listed

Uncertainty **0.47**: The volcano is Type 0, with no eruptive history and predominately lava flows in the text; or the volcano is Type 0 with no compositional information

Uncertainty **0.7**: The volcano is Type 0 and has non-basaltic compositions listed; or the volcano is Type 0 and has uncertainty in its volcano type listing for some other reason.

B3.4 Lahar hazard

Score **2**,

Uncertainty **0**: Lahars are listed in the eruptive history

Uncertainty: **0.23**: Lahars are listed in the eruptive history, but with a question mark

Uncertainty: **047**: Lahars are not listed in the eruptive history, but are mentioned in the summary text.

Score **1**,

Uncertainty **0.47**: Pyroclastic flows, listed with certainty, have occurred within the last fifty years (1960 onwards); or the volcano has a crater lake or ice/ snow cap

Uncertainty **0.7**: Pyroclastic flows listed with uncertainty (followed by a question mark) have occurred within the last fifty years (1960 onwards).

Score **0**,

Uncertainty **0**: The volcano is Type 1 with 3+ certain eruptions in the eruptive history and no lahars listed; or the volcano has hazard score 0, uncertainty 0 for pyroclastic flows

Uncertainty **0.23**: The volcano is Type 1 with 1-2 certain eruptions in the eruptive history and no lahars listed

Uncertainty **0.47**: The volcano has hazard score 0, uncertainty 0.47, or hazard score 0, uncertainty 0.7, for pyroclastic flows (i.e. Type 0 volcano)

Uncertainty **0.7**: The volcano has hazard score 1, uncertainty 0.47, or hazard score 1, uncertainty 0.7, for pyroclastic flows; or the volcano has hazard score 2, uncertainty 0.47.

B3.5 Lava flow hazard

Score **0.2**,

Uncertainty **0**: Lava flows are listed in the eruptive history

Uncertainty **0.13**: Lava flows are listed in the eruptive history, but with a question mark

Uncertainty **0.27**: Lava flows are not listed in the eruptive history, but are mentioned in the summary text

Uncertainty **0.4**: Lava flows are not listed in the eruptive history and are not mentioned in the summary text, but are inferred from the volcano type and composition (e.g. basaltic volcanic field).

Score **0**,

Uncertainty **0.0**: The volcano is Type 0 with 3+ certain eruptions in the eruptive history and no lava flows listed; or the volcano status is fumarolic or hydrothermal

Uncertainty **0.13**: The volcano is Type 0 with 1-2 certain eruptions in the eruptive history and no lava flows listed

Uncertainty **0.27**: The volcano is Type 1 with no lava flows listed in the eruptive history or mentioned in the summary text; or the volcano is Type 1 with no eruptive history

Uncertainty **0.4**: The volcano is Type 0 with no eruptive history and no mention of lava flows in the summary text.

B3.6 Number of subfeatures

Score **0.1** for the first fifteen subfeatures, **0.05** for each subfeature thereafter.

Subfeatures are counted as those listed on the synonyms and subfeatures page.

B3.7 Maximum VEI

Score **1:**
The volcano's maximum VEI is 0, 1, or 2.

Score **2:**
The volcano's maximum VEI is 3 or 4.

Score **3:**
The volcano's maximum VEI is 5 or 6.
or
The volcano's maximum VEI is P (Plinian) or C (caldera-forming).

Score **4:**
The volcano's maximum VEI is 7+

Uncertainty **0**: The volcano's maximum VEI is taken from a certain eruption in the eruptive history, with no question mark for the VEI
Uncertainty **0.13**: The volcano's maximum VEI is taken from a certain eruption in the eruptive history, but with a question mark for the VEI
Uncertainty **0.27**: The volcano's maximum VEI is taken from an uncertain eruption in the eruptive history, with or without a question mark for the VEI
Uncertainty **0.4**: The volcano has an eruptive history but with no VEI values so the maximum VEI is estimated from the available information; or the volcano has no eruptive history so the maximum VEI is estimated from the available information; or the maximum VEI is P (Plinian) of C (caldera-forming).

B3.8 Eruption frequency

Score **1:**
The volcano has 1 or 2 Holocene eruptions listed in the eruptive history.

Score **2:**
The volcano has 3 to 10 Holocene eruptions listed in the eruptive history.
or

The volcano is a volcanic field, and has no eruptive history and no information relating to number of eruptions; or the volcano has no eruptive history and no information relating to number of eruptions, but the text refers to a "group" or "series".

Score **3:**
The volcano has 11 to 20 Holocene eruptions listed in the eruptive history.

Score **4:**
The volcano has 21+ Holocene eruptions listed in the eruptive history.

Uncertainty **0**: The number of eruptions listed as uncertain in the eruptive history is less than half of the number of total eruptions
Uncertainty **0.15**: The number of eruptions listed as uncertain in the eruptive history is greater than or equal to half of the number of total eruptions
Uncertainty **0.45**: The volcano has no eruptive history so the number of eruptions is estimated from the available information.

Eruptions listed as uncertain are included in the count, but those listed as discredited are not.

Table 2 gives a summary of the eight hazard and six uncertainty factors and their scorings.

Table 2: Hazard and Uncertainty Score ranges

Hazard Factor	Hazard Score Range	Uncertainty Score Range
Volcanotype	0, 1	0, 0.13, 0.27, 0.4
Crater lake, ice/snow cap	0, 1	N/A
Pyroclastic flow	0, 1, 2	0, 0.23, 0.47, 0.7
Lahar	0, 1, 2	0, 0.23, 0.47, 0.7
Lava flow	0, 0.2	0, 0.13, 0.27, 0.4
Number of subfeatures	0.1 for first 15 subfeatures, 0.05 for each thereafter	N/A
Maximum VEI	1, 2, 3, 4	0, 0.13, 0.27, 0.4
Eruption frequency	1, 2, 3, 4	0, 0.15, 0.45
Total	**2 to 14.55**	**0 to 3.05**

The eight hazard scores and six uncertainty scores are summed and assigned to Levels 1 to 3 (Level 1 lowest hazard or uncertainty, Level 3 highest) as shown in Tables 3A and 3B. Divisions into Hazard and Uncertainty Levels are arbitrary and simply split the score range into three equal cohorts.

Table 3A: Hazard Scores and Levels.

Summed Hazard Score	**Hazard Level**
0 – 5	1
5 – 9	2
9+	3

Table 3b: Uncertainty Scores and Levels

Summed Uncertainty Score	**Uncertainty Level**
0 – 1	1
1 – 2	2
2 – 3	3

Results are displayed as scatter plots of hazard against uncertainty, with background colouring used to show Hazard Levels and background colour intensity used to show Uncertainty Levels. Individual volcanoes are identified only by their Hazard Level and Uncertainty Level, rather than the more specific scores. The division of volcanoes into just three Hazard and Uncertainty Levels reflects the intrinsic limitations of available data, the simplicity of the method and the generalizations inherent in defining hazard as a combination of only eight factors. Note that Uncertainty Score is not an error margin pertaining to the Hazard Score; the numbering used in calculating both scores is arbitrary.

One particularly noteworthy caveat is the apparent low hazard ranking of many volcanoes, combined with high uncertainty. In such cases, it is likely that low Hazard Scores are a result of a lack of information, rather than actual low physical threat. For example, a volcano may have produced high VEI eruptions with pyroclastic flows and lahars, but if no eruption records exist, the Hazard Score cannot reflect such occurrences and is thus “artificially” low (and the Uncertainty Score high). It is therefore imperative that volcanoes’ Hazard and Uncertainty Scores and Levels are reported together. Geological studies may help to better constrain the Hazard Levels of high uncertainty volcanoes; evidence of a volcano’s previous eruptions and hazardous flows may be discovered as a result of such work, increasing the volcano’s Hazard Score and reducing the Uncertainty Score,

B4 Population Exposure Index

A method for measuring the number of people threatened by each volcano was developed to give an indicator of population vulnerability. This can be combined with the hazard level of each volcano to quantify population risk.

The method used develops the idea of the Volcano Population Index (see Ewert and Harpel, 2004). The 2009 LandScan population database and volcano geographic coordinates were used to calculate estimates of the numbers of people living within 10 km and 30 km of each volcano. The populations were then multiplied by weightings, and summed.

The weightings are used to account for two factors that influence the relative threat to populations at different extents:

- Decrease in proximity to the volcano when moving from the 10 km to 30 km radius circle
- Increase in area when moving from the 10 km to 30 km radius circle

The weighting necessary to reflect differing proximity to the volcano was derived empirically. A database of fatal volcanic eruptions, available from the Smithsonian Institution, was used to count the number of events in which fatalities occurred within 10 km of the volcano, and the number for which fatalities occurred between 10 km and 30 km from the volcano. There were 25 events for the former and 15 for the latter; weightings of 0.625 for the 10 km circle and 0.375 for the 30 km circle were used to reflect this.

The increase in area when moving from the 10 km to 30 km radius circle is nine-fold, and thus additional area-based weightings were adopted: 0.9 for the former and 0.1 for the latter.

The two sets of weightings were combined to give a final weighting of 0.9375 for the 10 km radius circle, and 0.0625 for the 30 km radius circle. Total weighted population exposures at each volcano were calculated by multiplying the two area population figures by their respective weightings, then summing. The weighted summed population was then assigned one of seven Scores, as detailed in Table 4. The Scores are referred to as the Population Exposure Index.

Table 4: Population Exposure Index

Weighted summed population	Population Exposure Index
0	0
< 3,000	0.5
3,000 – 9,999	1
10,000 – 29,999	1.5
30,000 – 99,999	2
100,000 – 300,000	2.5
> 300,000	3

The Population Exposure Index is further grouped into three Levels as shown in Table 5.

Table 5: Population Exposure Index levels

Population Exposure Index	Population Exposure Index Level
0, 0.5	1
1, 1.5	2
2, 2.5, 3	3

The uncertainty in the Population Exposure Index data is associated with the uncertainties associated with the LandScan data and inaccuracies in volcano locations, though these are not quantified.

B5 Risk to Populations

A simple estimate of population risk for each volcano was computed by taking the product of the Hazard Level and Population Exposure Index. The numerical product is assigned to one of three Population Risk Levels as shown in Table 6.

Table 6: Population Risk Level cohorts

	Volcano Hazard Level		
Population Exposure Index	**1**	**2**	**3**
0, 0.5	1	1	1
1	1	2	2
1.5	1	2	3
2	2	2	3
2.5, 3	2	3	3

The Population Risk Levels have uncertainties as described in the hazard assessment, as well as those present in the Population Exposure Index methodology. Only the Uncertainty Level ascribed during the hazard assessment is quantified, however.

B6 Ash Hazard and Risk

Ash hazard is addressed in this study in a very simple way and only addresses the first order question of identifying areas that might be adversely affected by suspended ash and ash fall. The main control on ash hazard is the wind direction and the eruption column height which itself is related to eruption intensity. Here we have taken the view that eruptions of magnitude 3 and 4 (equivalent to VEI 3 and 4) will be quite a frequent hazard in most of the study countries. Return periods are presented for most countries. Further these eruptions commonly transport ash in the atmosphere at heights of 8 to 16 km at which much commercial aviation is concentrated. The main prevailing wind directions at atmospheric pressures of 250-100 mbar are displayed as a guide to ash hazard.

There are important caveats. The analysis here is not a substitute for a full stochastic and probabilistic modeling assessment of ash hazard that takes account of the frequency of eruptions of different magnitude and intensity winds at all altitudes and complexities of ash transport processes. The method will also not capture ash hazard for low frequency, high magnitude events. Characteristics of the eruption (plume height, duration, pulsatory behaviour etc.) are also critical factors that will affect how and where particles are released from the plume. We use reanalysis data (over a relatively coarse global grid) and not direct local weather observations. The reanalysis data has been generated using models and data assimilation with a range of inputs including rawinsonde (upper air soundings) and pilot balloon data, and observations from surface, ship, aircraft and satellites. For purposes of this study reanalysis data provide a good overview of trends in wind speed and direction on a global scale, but the data do exhibit some discrepancies with direct observations.

B6.1 Data sources

The data set used was NCEP/NCAR Reanalysis 1 (2.5 degree global grid) provided by NOAA/OAR/ESRL PSD (Kalnay et al., 1996) and obtained from http://www.esrl.noaa.gov/psd. Daily average data were extracted for zonal ("u wind") and meridional winds ("v winds") at pressures of 250, 200, 150 and 100 mbar for the period 1/1/1990 - 31/12/2010. Each component was averaged over the range of pressures to produce a daily series of wind speed and direction for each location. The rose diagrams were produced in R (R Development Core Team, 2011), using ncdf4 (Pierce, 2010) and a version of the rose2 function from the heR.Misc package (Klepeis, 2004) modified to show the direction of transport rather than the direction the wind is coming from (the meteorological convention). The rose diagram is a radial histogram (of 8 sectors). The total length of the bar in each sector shows the percentage of days the wind travelled in that direction (see dashed rings on each diagram for scale). The average daily wind speed is indicated by colour (speed in m/s, see map legend) - the length of a single colour bar indicates the percentage of days at a given speed and direction.

B7 Assessment of National Capacity for Coping with Volcanic Risk

A monitoring index was created in order to compare each of the GFDRR priority countries' capabilities in monitoring each of their volcanoes.

Volcanoes are scored using two indices:

- Frequency of monitoring

- Existence and proximity of seismic networks.

Each volcano is assigned a score between 0 and 3 for each index. These scores are then summed and assigned to one of three Monitoring Levels. Further, an uncertainty score is given to account for differences in the credibility and accuracy of the sources used (websites and personal communication). The uncertainty scores for each country's volcanoes are averaged to give a country-wide average monitoring level uncertainty. More specifically, monitoring and uncertainty scores are assigned as follows:

B7.1 Frequency of monitoring

Score **0**:
The volcano is not monitored

Score **1**:
The volcano is monitored yearly, or less often

Score **2**:
The volcano is monitored weekly or monthly

Score **3**:
The volcano is monitored continuously

Score **1.5**:
There is no data pertaining to the frequency of monitoring at the volcano

Uncertainty **0:** Data is taken from a strong source, such as a contact at a relevant institution or a recently updated website
Uncertainty **0.5**: Data is taken from a weaker source, such as a potentially out-of-date website or a secondary source
Uncertainty **1**: Unknown, or not confirmed

B7.2 Existence and proximity of seismic networks

Score **0**:
The volcano is not covered by a regional seismic network and has no seismometers within 15 km

Score **2**:
The volcano is covered by a regional or temporary seismic network situated within 15 km

Score **3**:

The volcano is covered by a dedicated permanent seismic network situated within 15 km

Score **1.5**:

There is no data pertaining to the existence or proximity of seismic networks at the volcano

Uncertainty **0:** Data is taken from a strong source, such as a contact at a relevant institution or a recently updated website
Uncertainty **0.5**: Data is taken from a weaker source, such as a potentially out-of-date website or a secondary source
Uncertainty **1**: Unknown, or not confirmed

Each volcano's two monitoring scores are summed and assigned to one of three Monitoring Levels as shown in Table 7A. The country-averaged uncertainty is classified as either low, low-medium, medium-high, or high, as in Table 7B.

Table 7A: Monitoring Scores and Levels

Summed Monitoring Level Score	Monitoring Level
0	0
1, 1.5, 2	1
2.5, 3, 3.5	2
4, 4.5, 5, 6	3

Table 7B: Country-averaged Monitoring Level uncertainties

Country-averaged uncertainty score	Monitoring Level Uncertainty
0 – 0.5	Low
0.5 – 1	Low-medium
1 – 1.5	Medium-high
1.5 – 2	High

A bar chart is used to depict the distribution of each country's volcanoes across the four monitoring levels, with colouring used to indicate risk level (1, 2 or 3). The country-averaged uncertainty level is shown above the plot.

B8 GIS analyses

The GIS analyses of the study were performed in ArcGIS version 10, and all results were stored in file geodatabases. The analyses were constructed as models in ArcGIS ModelBuilder.

B8.1 GIS models overview

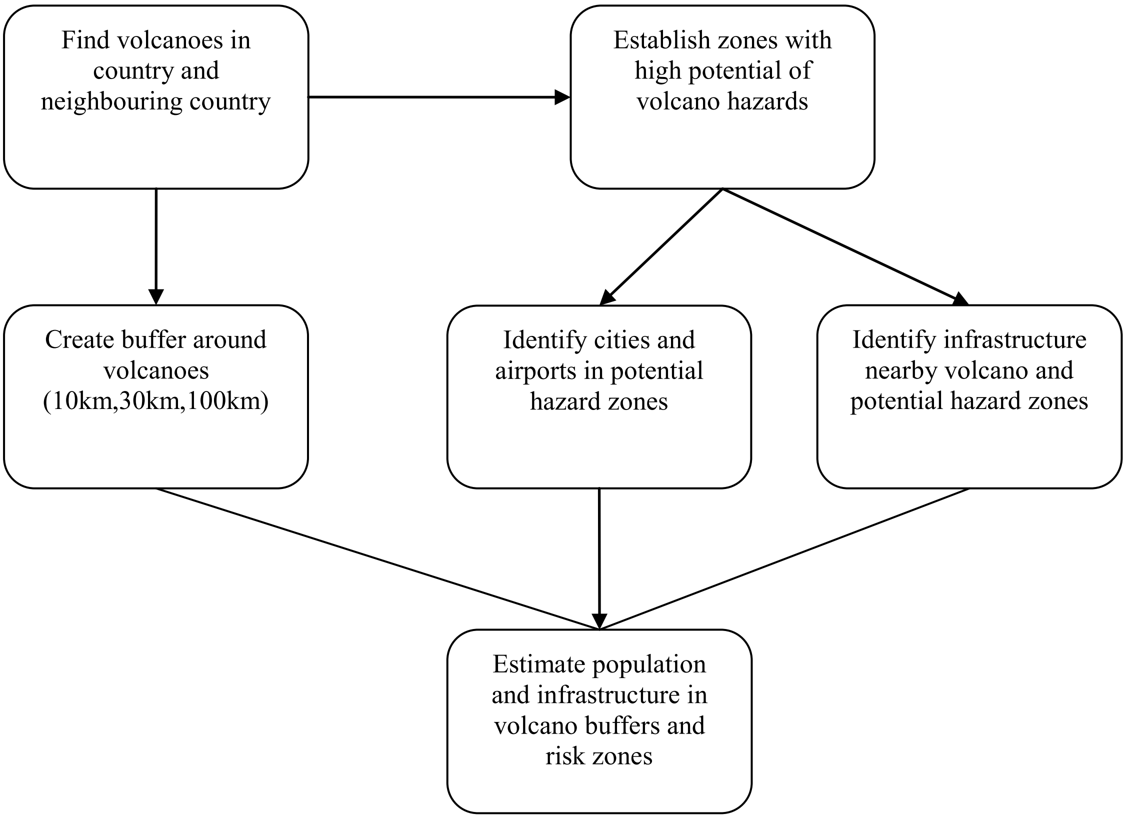


Figure 1 Overview of different GIS model.

B8.2 Model explanation

The figures in the following chapters use the standard ArcGIS ModelBuilder symbology, as shown in Figure 2. Some of the tools have preconditions, i.e. they will start after the execution of other tools, as shown in Figure 3.

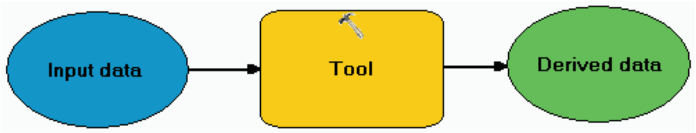


Figure 2 Legend to models: Input data source, tool and derived data

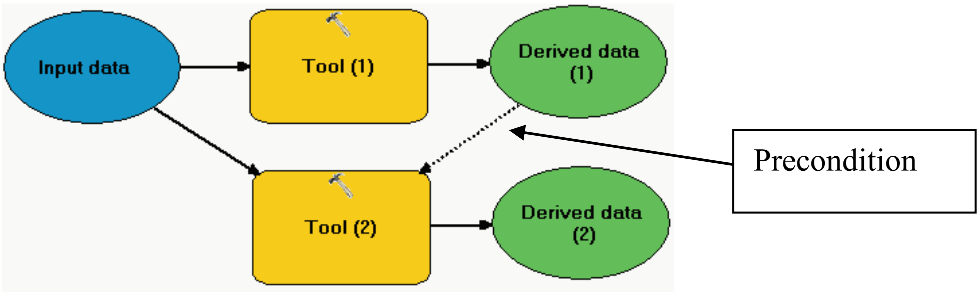


Figure 3 Preconditions

Several of the models make use of iterators, which allow the preceding tools to run multiple for several features or datasets as shown in Figure 4.

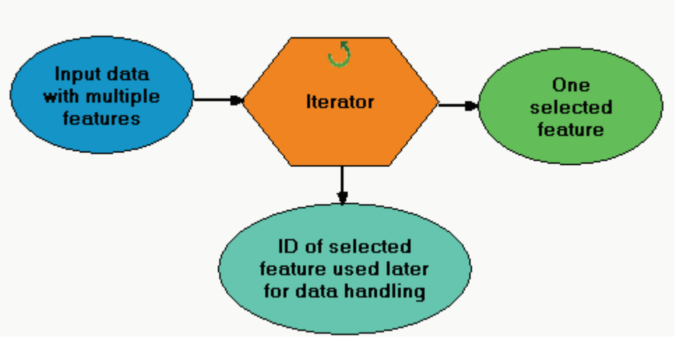


Figure 4 Example of an iterator

B8.3 Finding volcanoes in country and neighbouring country

The volcanoes present in and nearby a GFDRR priority country were identified by creating a point dataset for all volcanoes, and intersecting them with each country and a buffer of 200 km around the country's border, as shown in Figure 5.

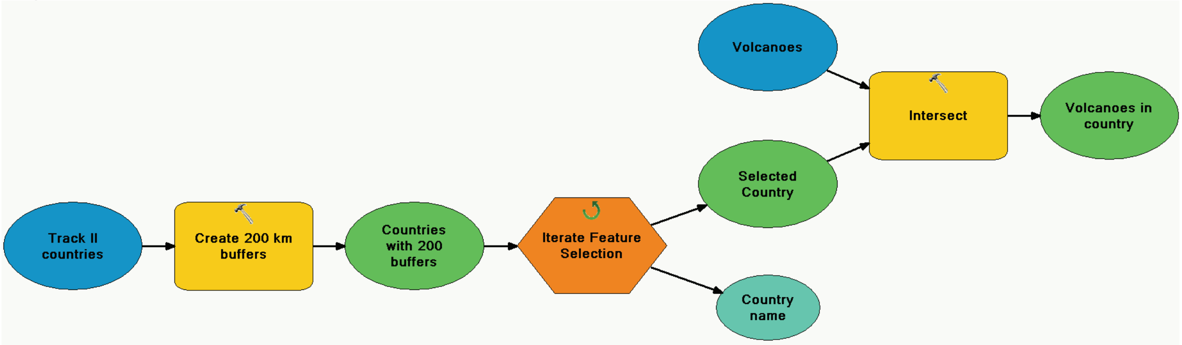


Figure 5 Model for identifying volcanoes in and nearby country.

B8.4 Creating buffers around volcanoes

To assess the number of people and important infrastructure affected by a volcanic eruption, buffers of different radii around the volcanoes were created.

The buffers were created using an advance buffer tool ("Buffer Wizard"). This tool makes buffers around the volcano based on a local coordinate system, a "Buffer Processing Coordinate System", around each volcano location. Buffers were made for 10, 30 and 100 km radial distances around each volcano. As these buffers could overlap, the buffers were dissolved into non-overlapping features. For more information about the Buffer Wizard, see http://blogs.esri.com/Support/blogs/mappingcenter/archive/2009/07/15/The-Buffer-Wizard-in-ArcMap.aspx .

B8.5 Establishing zones with high potential for volcano hazards

Potential hazard areas for pyroclastic flows and lahars were based on a drainage basin analysis in ArcGIS. Hydrological drainage basins were made based on a terrain model (DTM). Only areas out to a fixed distance from the volcano, "the Outer Buffer", were included in the analysis, cf. figure 6 below. Drainage basins intersecting the Inner Buffer, within a certain distance from the volcano, were regarded as potentially hazard areas. Areas entirely outside the Inner Buffer were considered safe. For the lahar hazard, the distance of the Inner Buffer was 10 km and Outer Buffer 100 km, while for pyroclastic flow the distances were 3 km and 30 km.

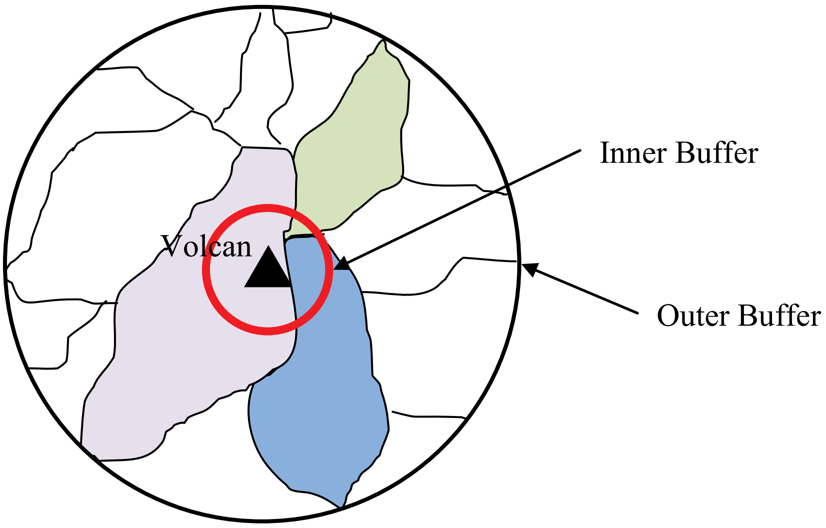


Figure 6 The principles of drainage basin analysis. The basin are indicated with a black line, and the coloured areas are the potential hazard zones.

To avoid areas outside the Outer Buffer being included, the DTM was clipped to the Outer Buffer. The clipped DTM was thereafter resampled from 90 m to 450 meters in order to avoid the analysis being influenced by minor variations in the terrain. Lakes was removed by excluding completely flat areas (slope = 0°). However, care was taken not to exclude land with flat topography. Sinks in the DTM were filled to ensure no dead ends in the flow analysis. The filled DTM with lakes excluded was then used for Flow analysis and the subsequent Drainage Basin analysis. The results were darinage basins in a raster format. The raster results were converted to vector/polygon features, enabling the intersection analysis with the inner buffer, hence producing potential hazard areas. Figure 7 below shows the model for creating potential lahar hazard zones.

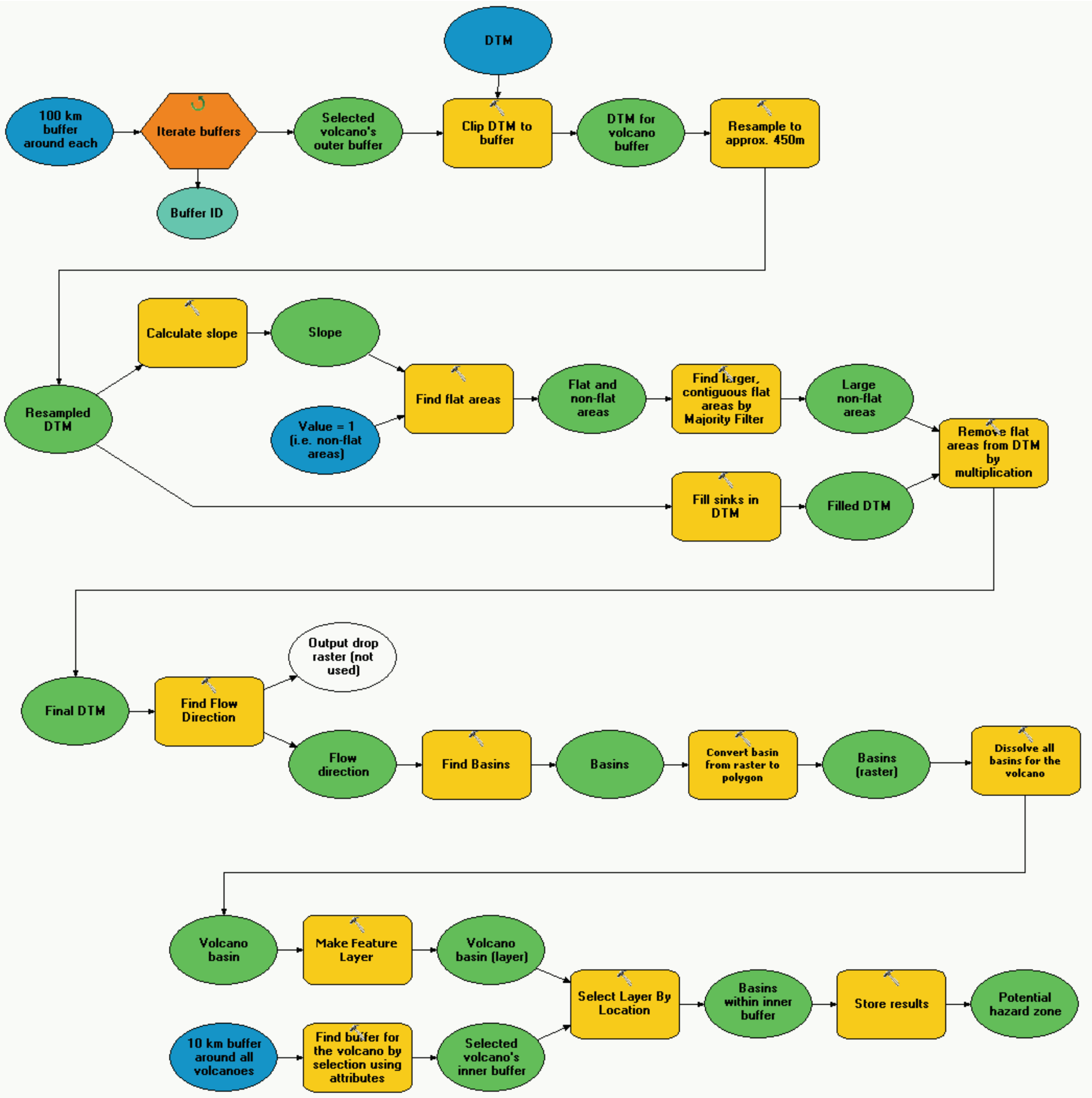


Figure 7 Model for creating potential lahar hazard zones.

B8.6 Identification of infrastructure line data near volcanoes and potential hazard zones

Infrastructure inside a hazard zone or a volcano buffer was identified by clipping the infrastructure features to the zones and buffers, and then running a summary statistics of the features. To ensure more accurate results, all infrastructure data was projected to the local UTM zone of the country. Since the quality and the source of the data varied, features could erroneously appear offshore a country's coast, for instance. Therefore a buffer was created around the country to ensure coastal infrastructure was fully included. The final results were statistics, i.e. the total length of infrastructure, both in total within the country and within each of the potential hazard zones. Figure 8 shows an example of the analysis for railways.

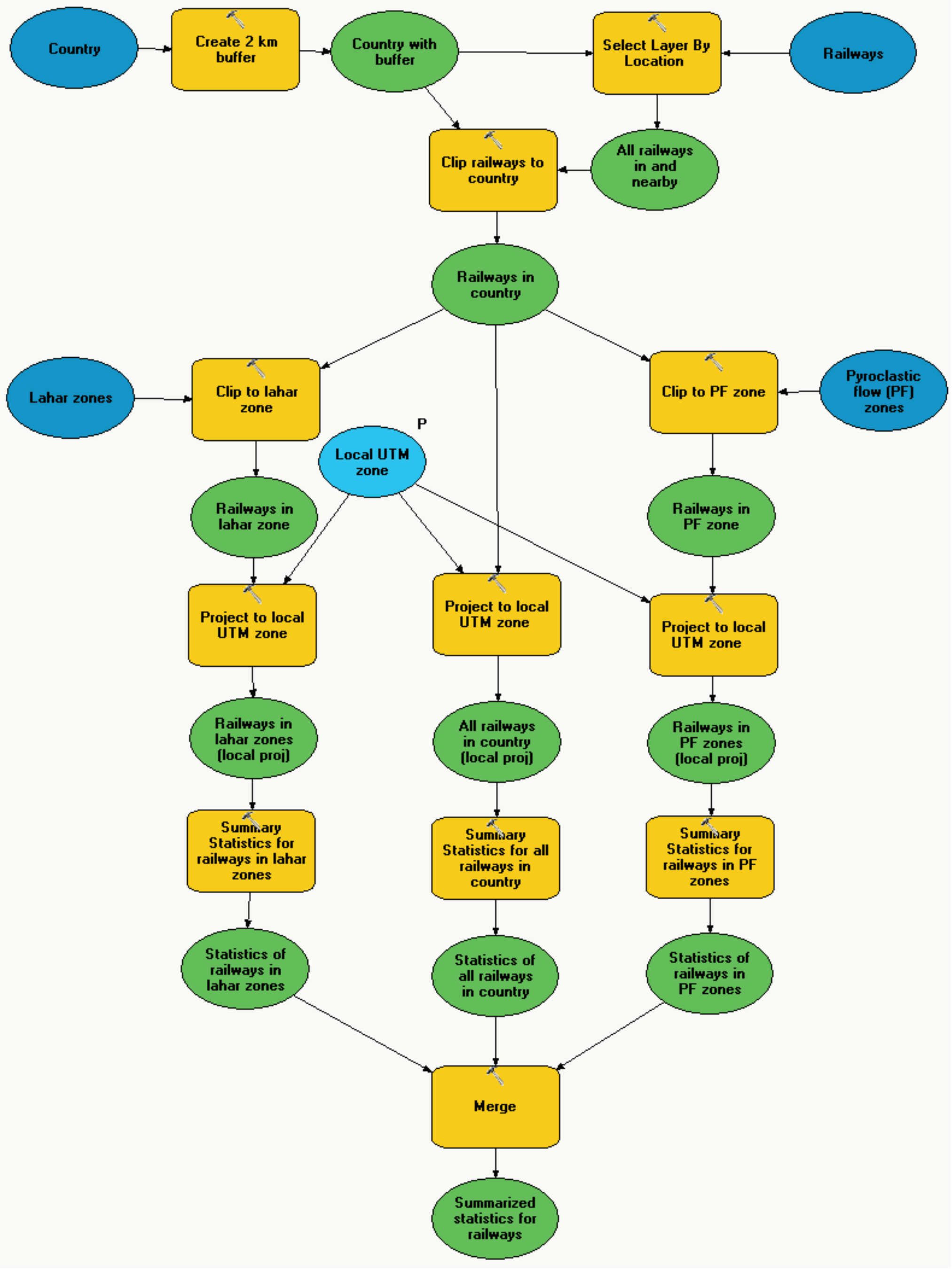


Figure 8 Model for estimating length of railways in total and within potential hazard zones.

B8.7 Identification of cities, airports and ports in potential hazard zones

Cities and airports within hazard zones and volcano buffers were identified using selection models. Similar to the infrastructure line data mentioned above, the selection included a buffer of 2 kilometres around the country's coasts to ensure that coastal cities, airports and ports were correctly included. An example of the identification of cities within a potential lahar hazard zone is shown in Figure 9 below.

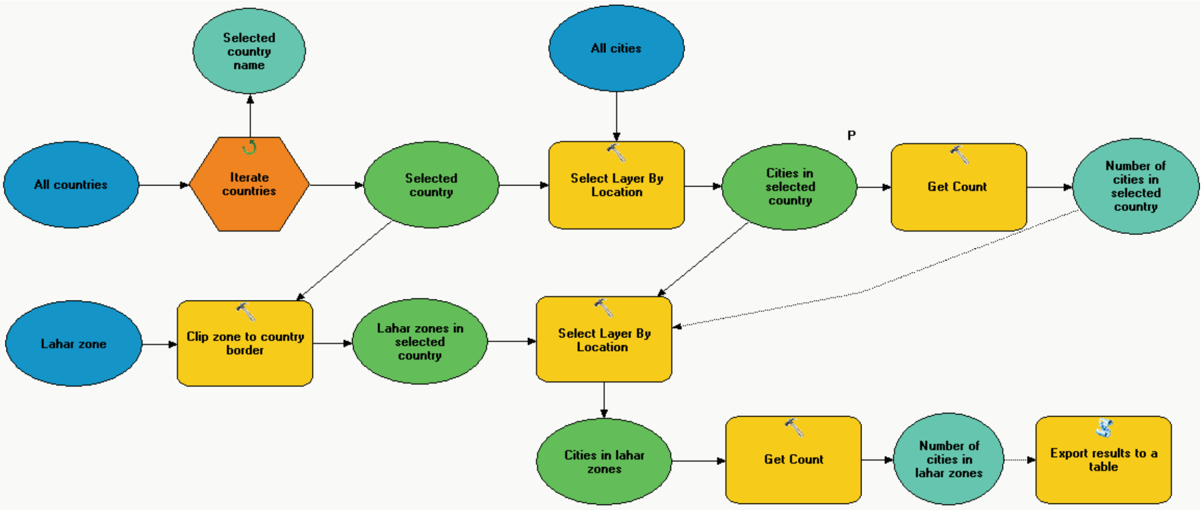


Figure 9 Model for identifying cities within a potential lahar hazard zone.

B8.8 Estimation of population near a volcano and in hazard zones

The population within a volcano buffer and in a potential hazard zone was calculated by clipping the population dataset (Landscan) to the buffer, and using Zonal Statistics tools to find the total population within the zone. All results were stored in tables. Figure 10 shows an example of a model for estimating the population count within a volcano buffer.

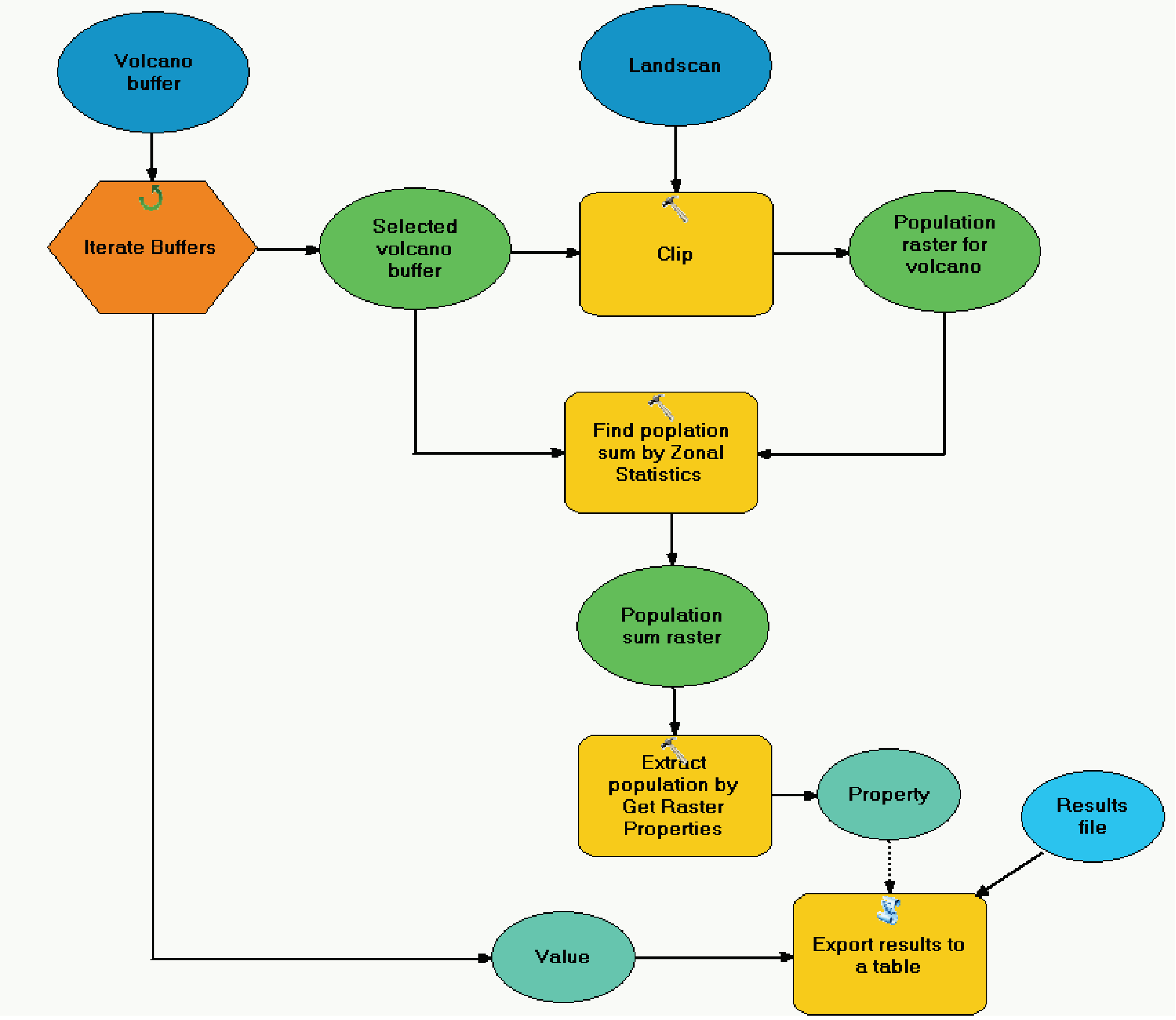


Figure 10 Model for estimating population within a volcano buffer.

B8.9 Examples from GIS analysis

Figures 11 – 18 show the map examples from various stages of the GIS analysis. The examples show the modelling of potential hazard areas for pyroclastic flows for the Santa María volcano in Guatemala. The modelling of potential hazard areas for lahars is identical, but with larger buffer distances.

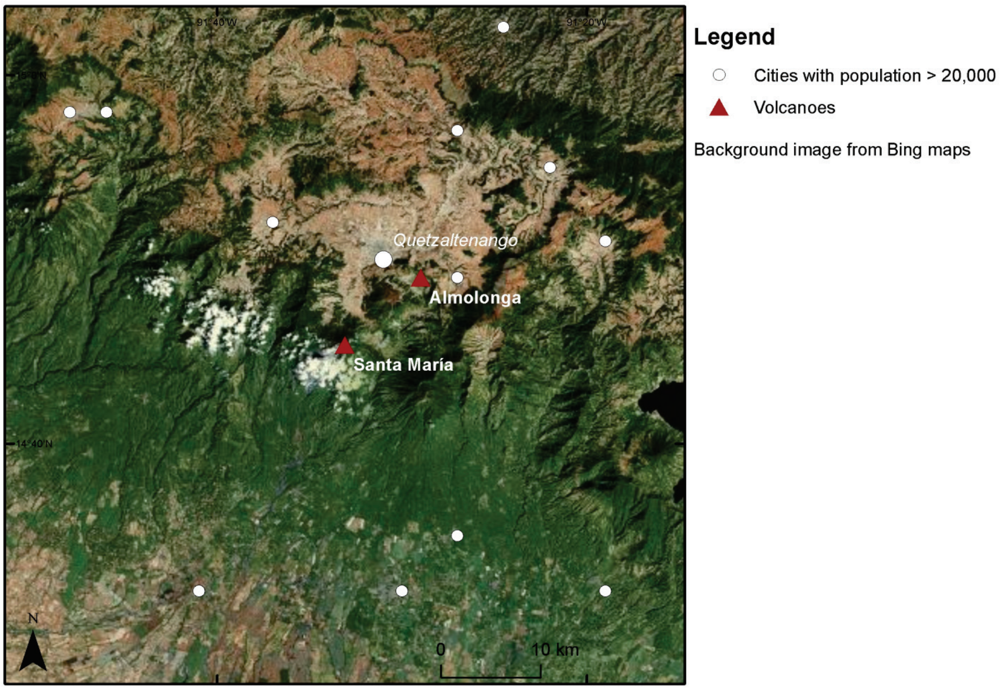


Figure 11 Overview map. Satellite imagery from Bing maps of the vicinity of the Santa María volcano.

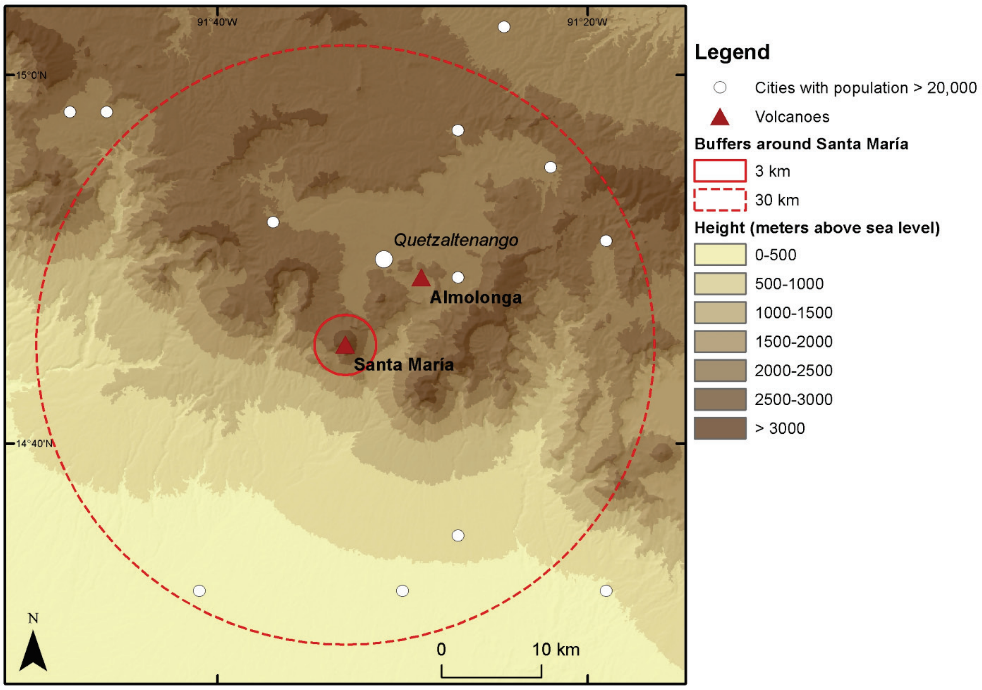


Figure 12 The terrain model (SRTM) for the area and the buffers around the volcano. 3 km and 30 km were used for pyroclastic flow analysis.

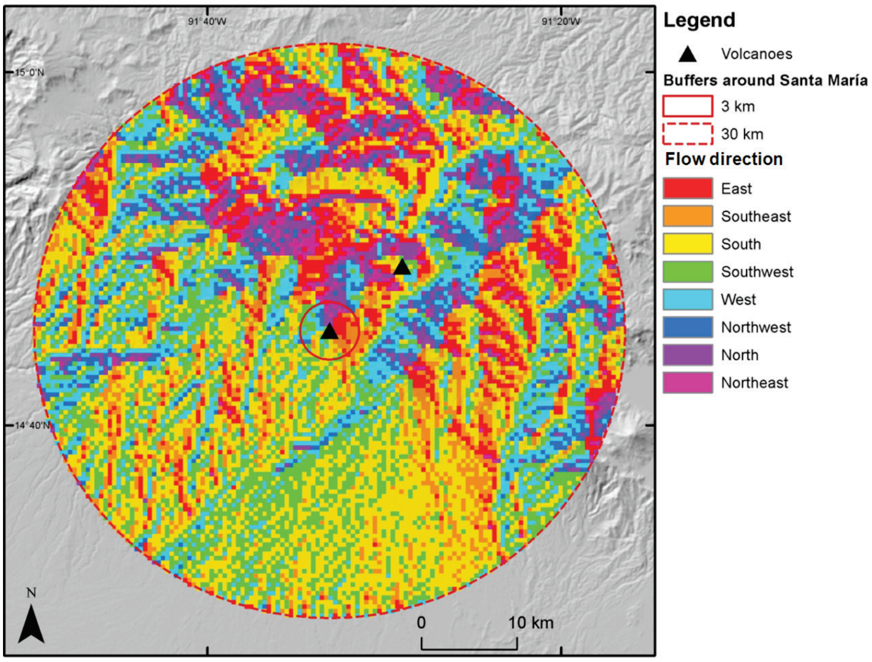


Figure 13 The flow direction analysis determined the direction of the flow for each individual spot / grid cell, and was used as input to the drainage basin analysis.

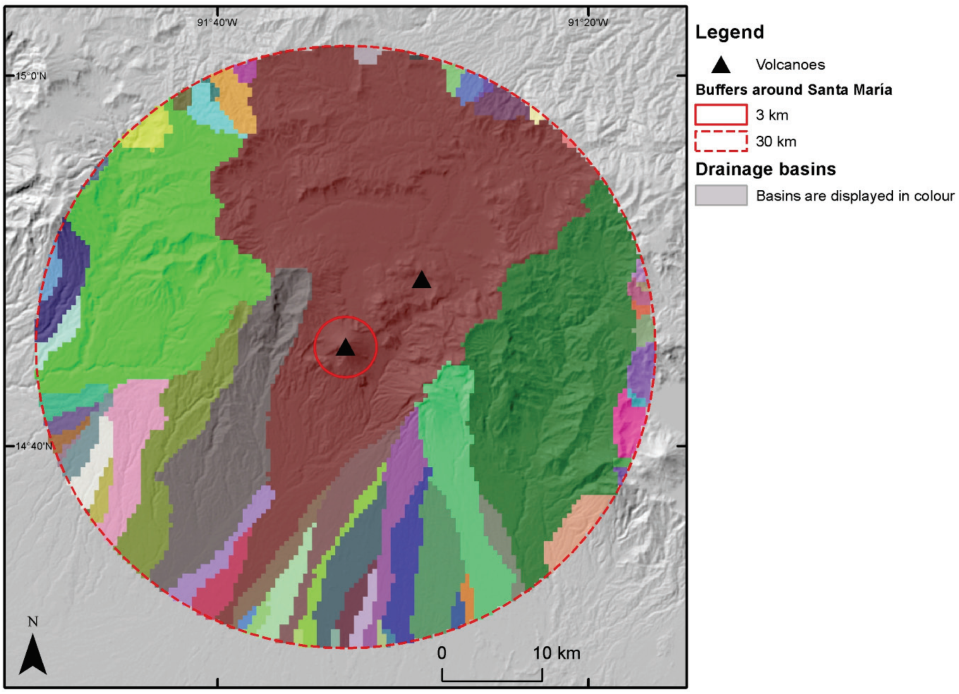


Figure 14 The drainage basin analysis created a raster in which each basin was given a unique value.

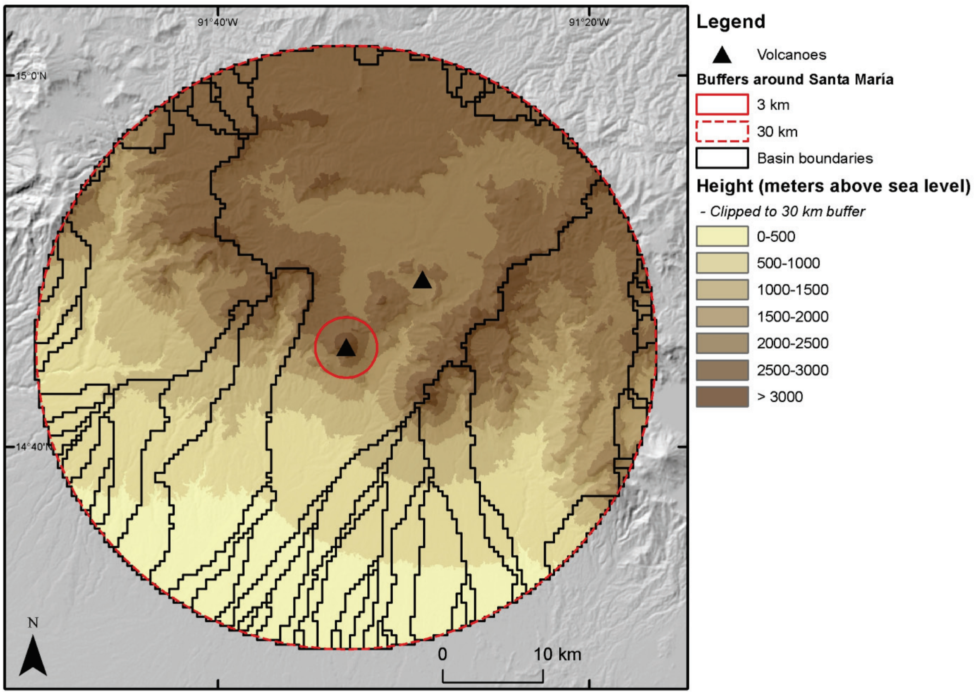


Figure 15 The drainage basin raster was converted into polygons (vectors). The polygons were used for later intersection analysis.

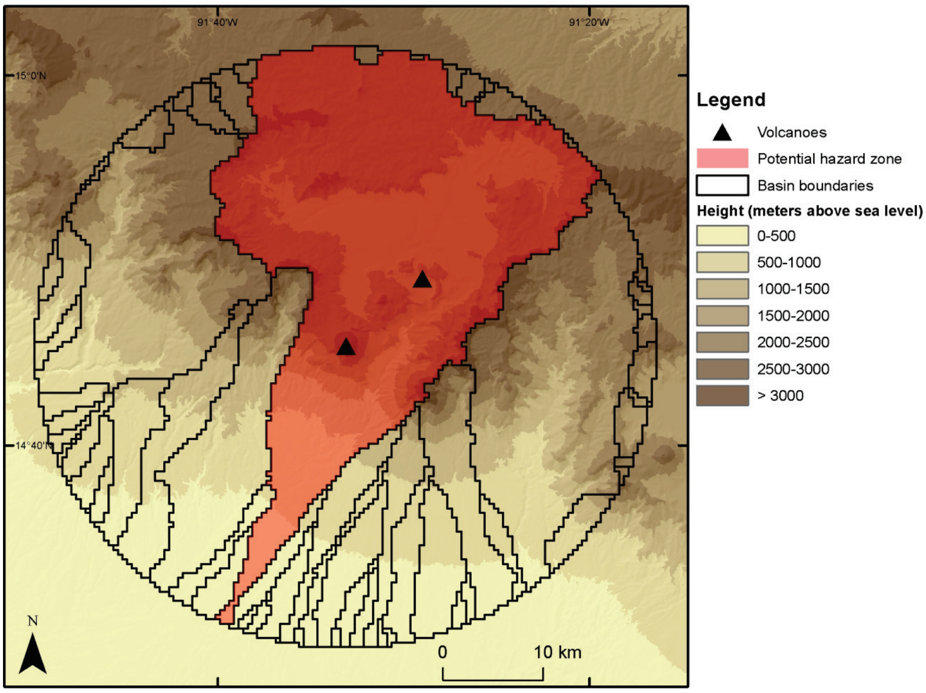


Figure 16 The potential hazard zone was found by selecting the drainage basins which intersected the inner buffer. In this example, one drainage basin intersected the inner buffer.

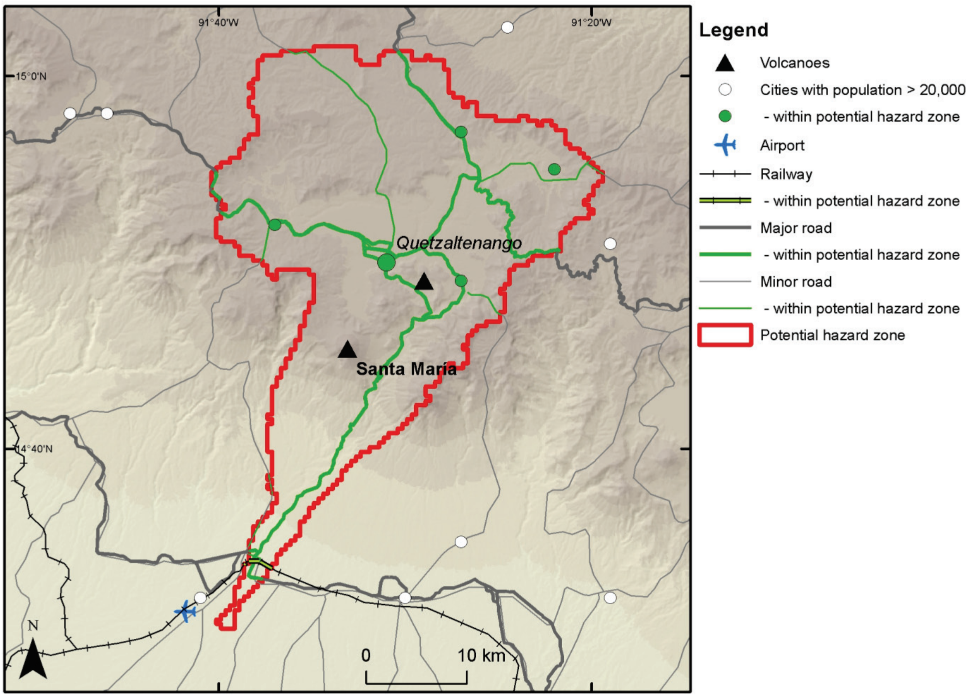


Figure 17 Infrastructure and cities within potential hazard zones were found by intersection with the potential hazard zone. The results were used to calculate statistics for country profiles. In this example, cities, roads and railways intersected the potential hazard zone. The airport was outside of the zone. No ports were present in the area.

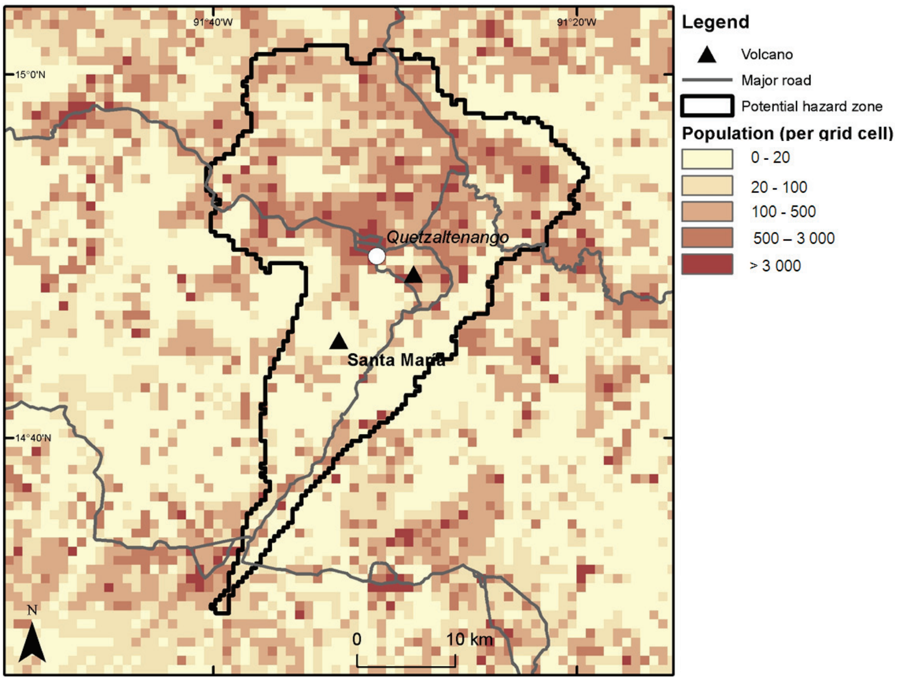


Figure 18 The Landscan population grid was clipped to the potential hazard zone. The resulting data was used to calculate population statistics for the country profiles.

B8.10 Examples of potential hazard zones

The following maps show the resulting potential hazard zones for selected volcanoes of Hazard Level 2 and 3. Figures 19 and 20 show the results for Marapi, Sumatra, Indonesia, with Hazard Level 3.

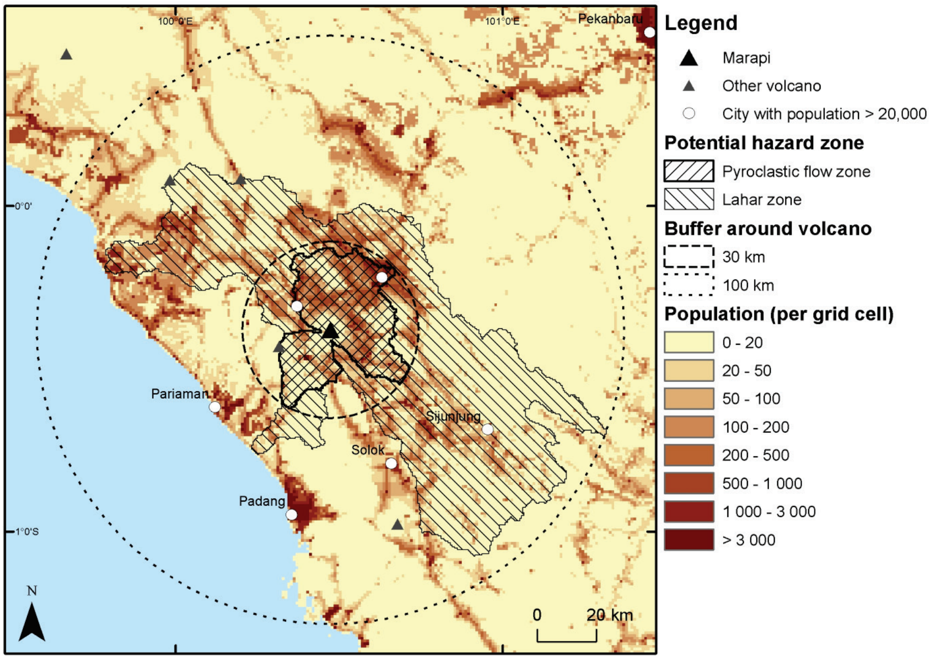


Figure 19 Potential hazard zones of Marapi overlayed on population grid.

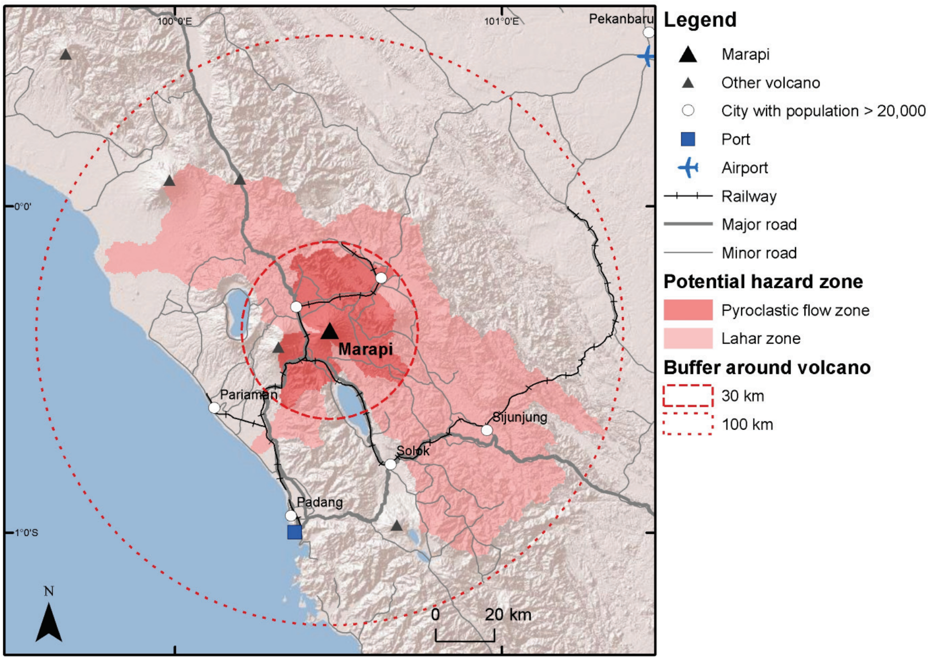


Figure 20 Potential hazard zones of Marapi overlayed on infrastructure.

Figures 21 and 22 show results for Kone, Ethiopia, with Hazard Level 2. Only the pyroclastic flow hazard was considered for Kone.

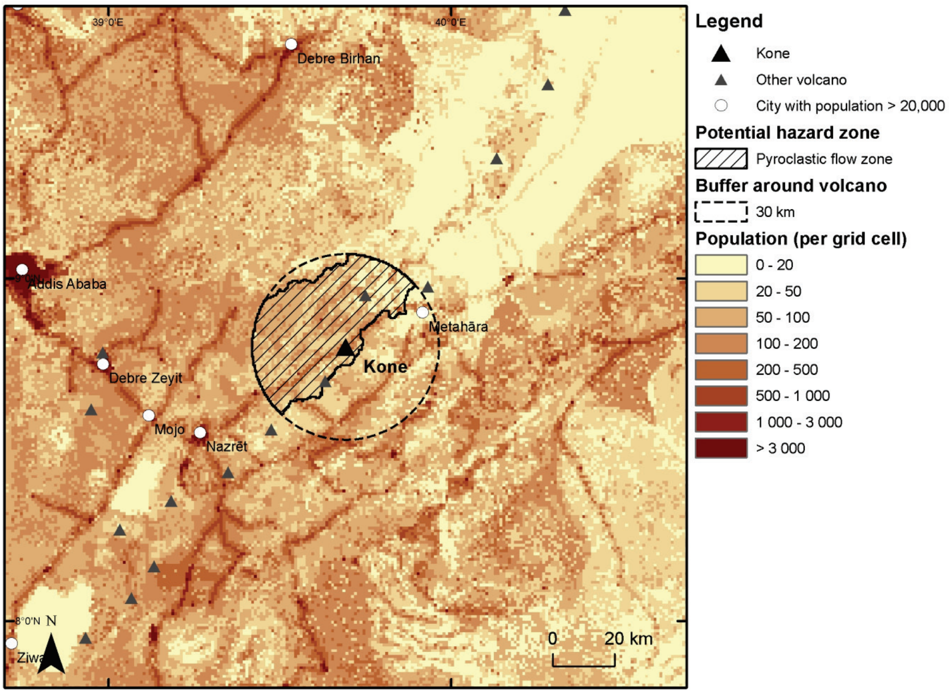


Figure 21 Potential hazard zones of Kone overlayed on population grid.

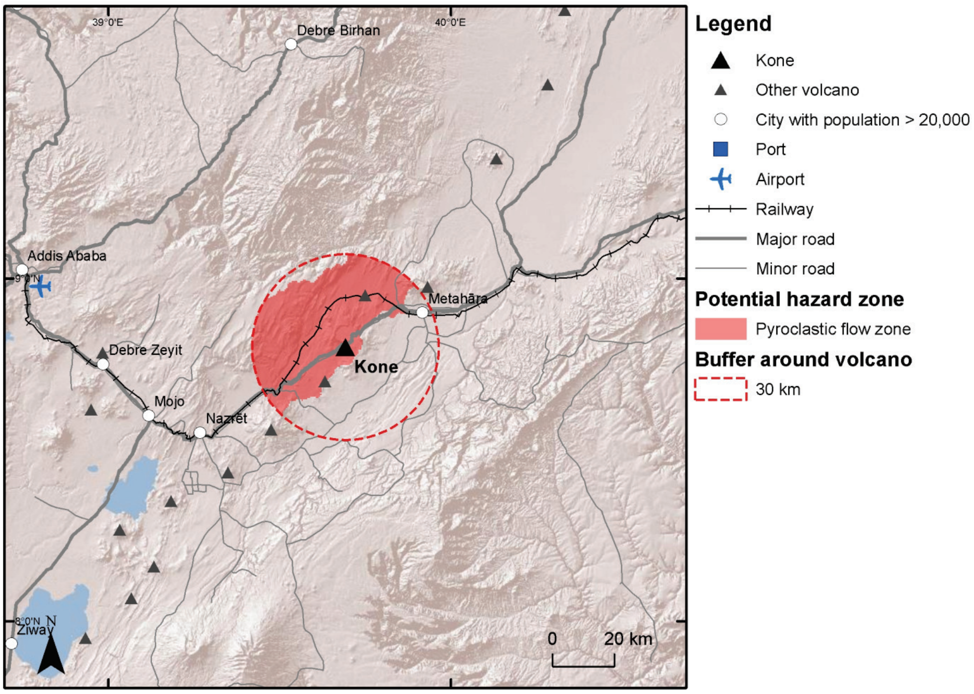


Figure 22 Potential hazard zones of Kone overlayed on infrastructure.

Figures 23 and 24 show results for Azufral, Colombia, with Hazard Level 3.

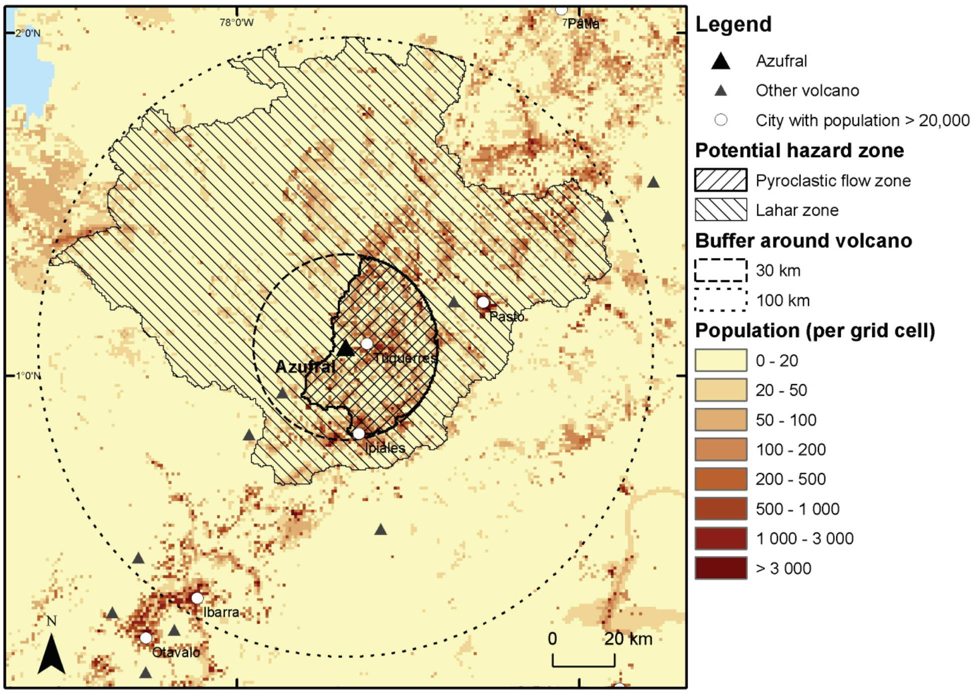


Figure 23 Potential hazard zones of Azufral overlayed on population grid.

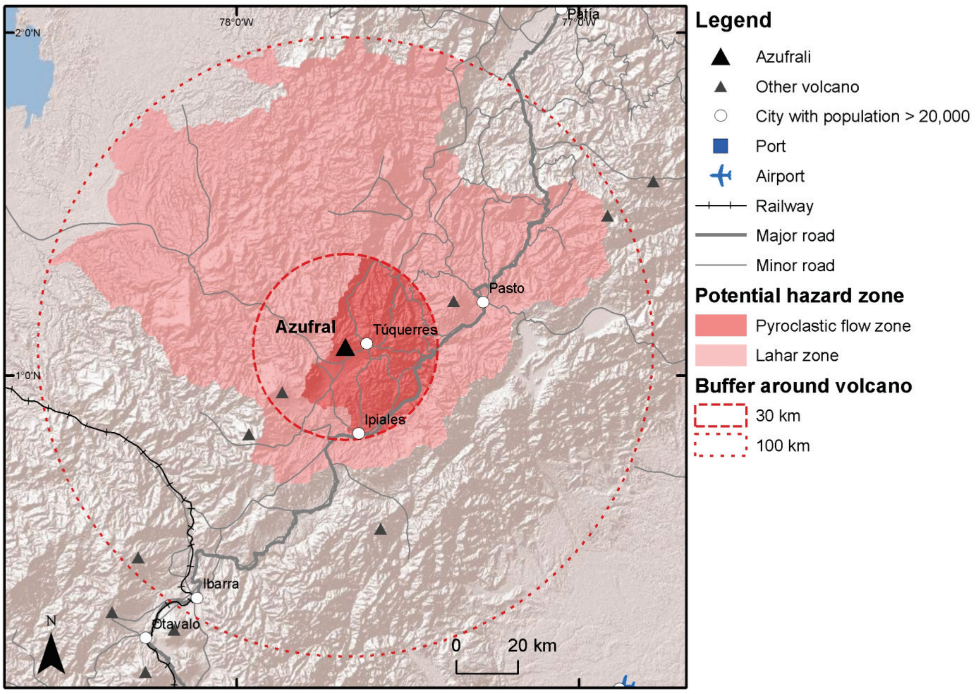


Figure 24 Potential hazard zones of Azufral overlayed on infrastructure.

Figures 25 and 26 show results for Santa Isabel, Colombia, with Hazard Level 2. Only the lahar hazard was considered for Santa Isabel.

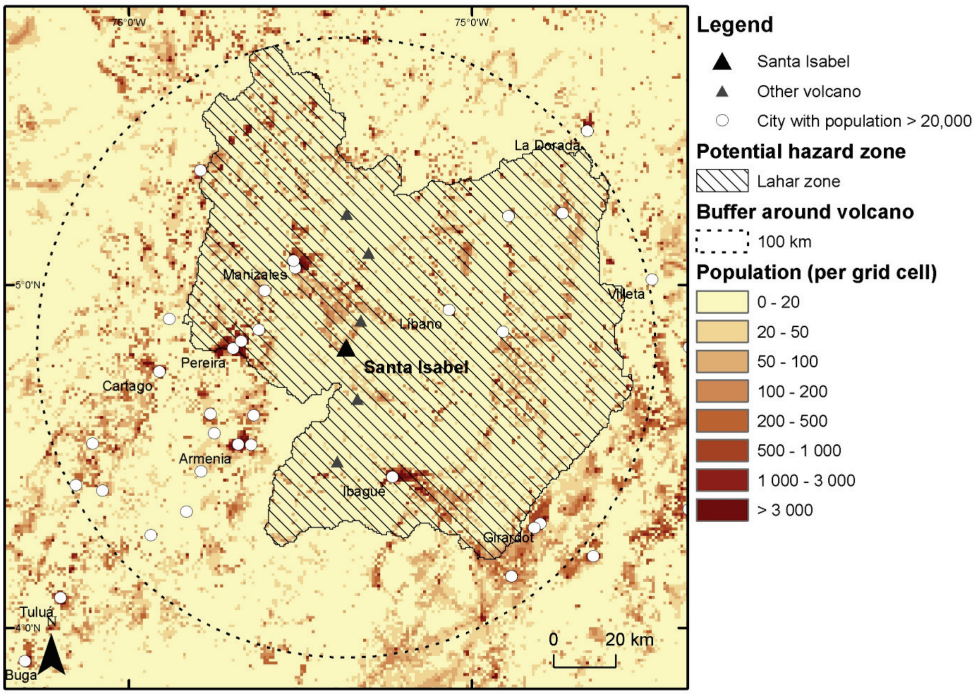


Figure 25 Potential hazard zones of Santa Isabel overlayed on population grid.

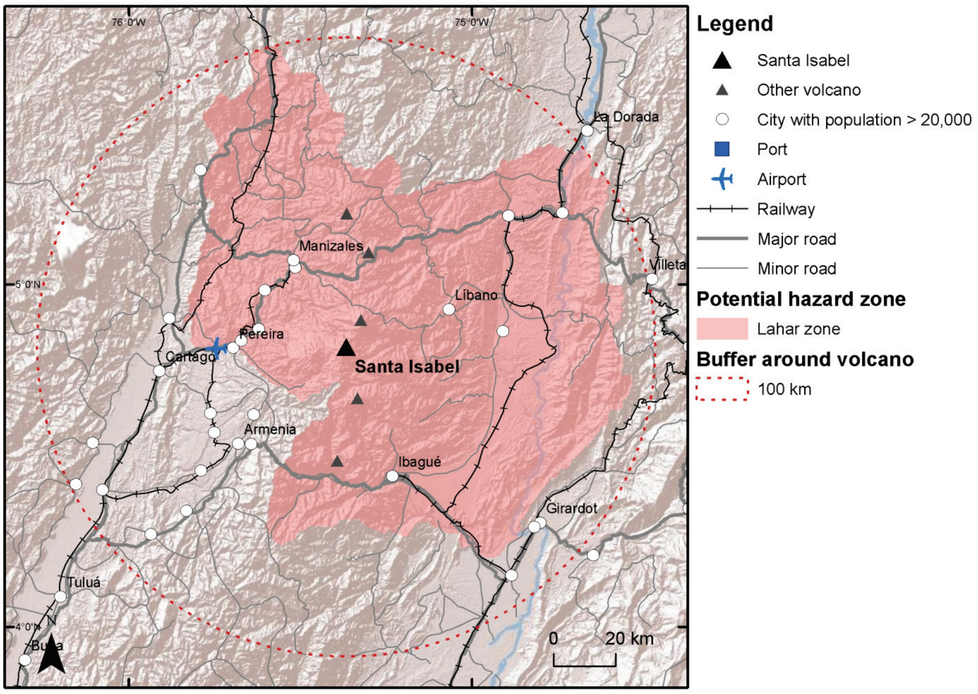


Figure 26 Potential hazard zones of Santa Isabel overlayed on infrastructure.

Figures 27 and 28 show results for Dukono, Philippines, with Hazard Level 3.

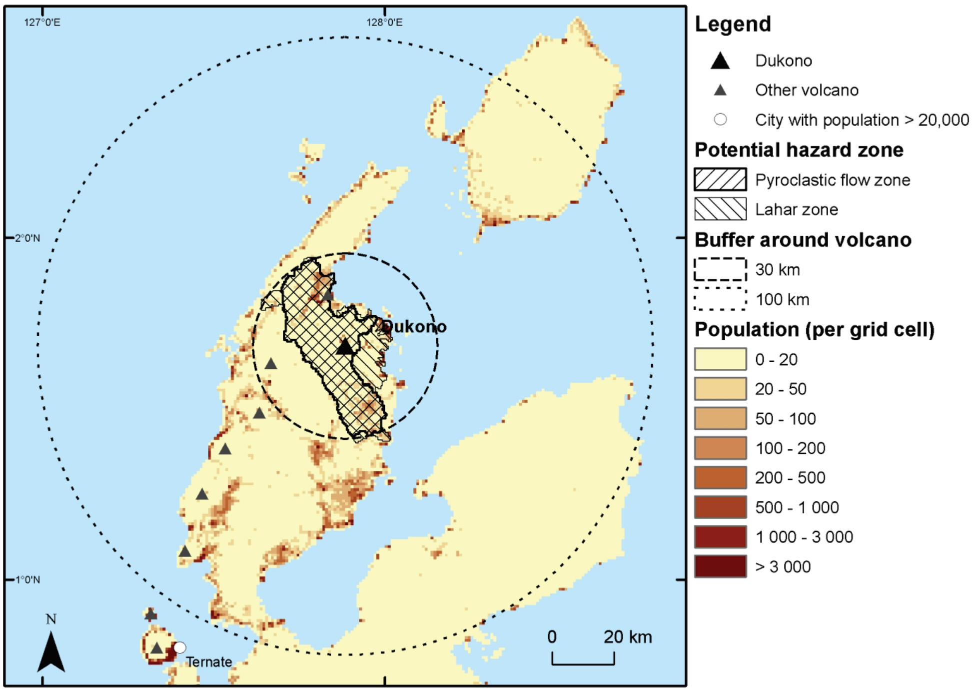


Figure 27 Potential hazard zones of Dukono overlayed on population grid.

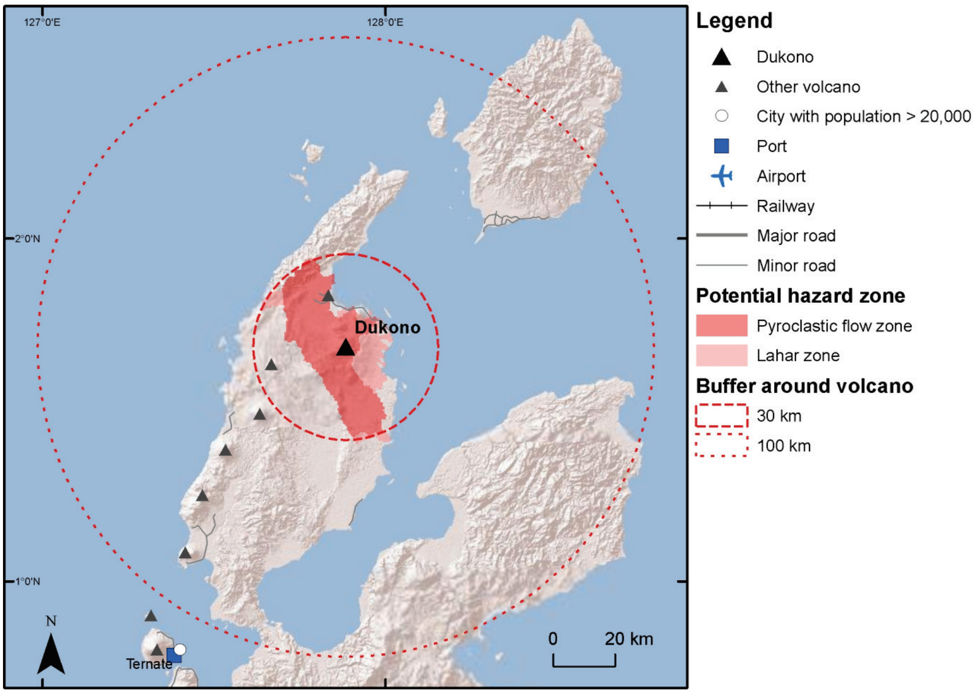


Figure 28 Potential hazard zones of Dukono overlayed on infrastructure.

Figures 29 and 30 show results for Kanlaon, Philippines, with Hazard Level 3.

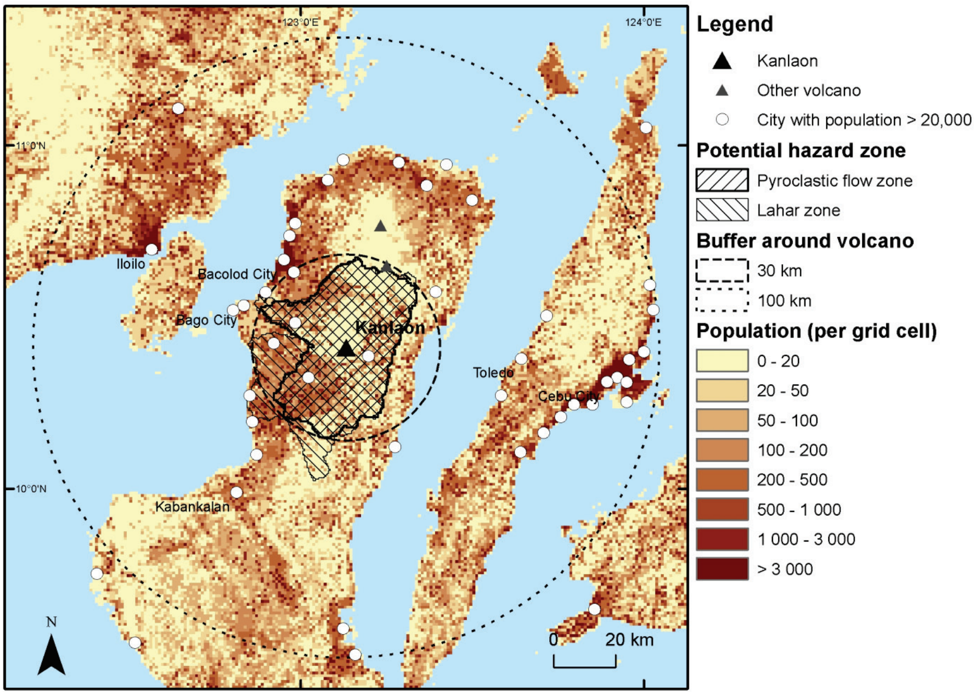


Figure 29 Potential hazard zones of Kanlaon overlayed on population grid.

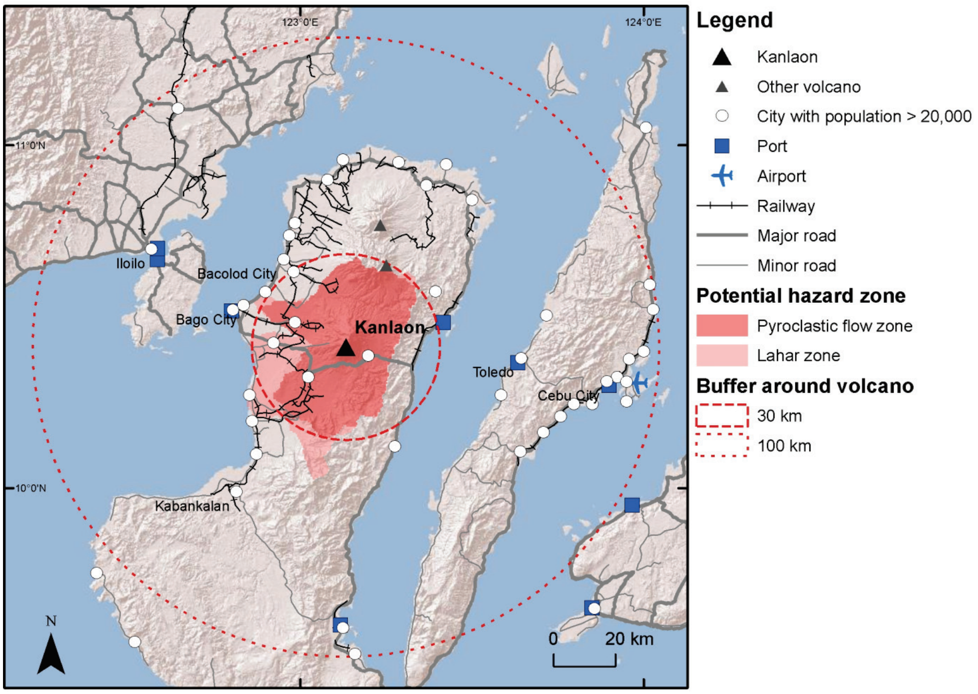


Figure 30 Potential hazard zones of Kanlaon overlayed on infrastructure.

B9 Datasets used in the GIS analyses

Landscan
By Oak Ridge National Laboratory

Full name: LandScan (2009)^{TM} High Resolution global Population Data Set

Usage:
- Population density data

Year of publication: 2009

Spatial resolution: 30" X 30" (approximately 1kmx1km at the Equator)

Comments:
- The population analysis was made utilizing the.

More information:
- http://www.ornl.gov/sci/landscan/

SRTM
By National Aeronautics and Space Administration (NASA)

Full name: The Shuttle Radar Topography Mission

Usage:
- Digital Terrain Model

Year of publication: 2000

Spatial resolution: 3 arc-seconds (approximately 90 meters)

Accuracy:
- Relative vertical height accuracy <= 10 meter (from http://www2.jpl.nasa.gov/srtm/statistics.html)

More information:
- http://www2.jpl.nasa.gov/srtm/

ESRI Data & Maps for ArcGIS 10, World data
By ESRI

Usage:
- ESRI World Roads
- ESRI World Airports

Version: ArcGIS 10

Year of publication: 2010

Accuracy:
- "The level of detail for each feature is generally better than what is traditionally utilized in a 1:500,000 scale product. The positional accuracy is typical of a 1:100,000 scale map, or +/-50 meters 95% of the time." From dataset metadata.

More information:
- http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/What_is_ESRI_Data_and_Maps/001z00000002000000/

Digital Chart of the World
Provider: National Geospatial-Intelligence Agency

Usage:
- Railways
- Minor roads

Year of publication: 1993

Comments:
- The dataset was used for minor roads and for railways despite its age because of it had full coverage of the GFDRR priority countries at a fairly detailed and apparently consistent level.

More information:
- http://earth-info.nga.mil/publications/specs/printed/89009/89009_DCW.pdf

Geonames Largest Cities
By Geonames.org

Usage:
- Largest Cities

Year of publication: 2010

More information:
- http://www.geonames.org/

World port index

By National Geospatial-Intelligence Agency

Usage:

- Ports

Version: 2010

Year of publication: 2010

More information:

- http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015

Globcover

By European Space Agency

Usage:

- Agricultural land cover (i.e. land cover codes “Post-flooding or irrigated croplands”, “Rainfed croplands”, “mosaic cropland/vegetation” and “mosaic vegetation/cropland”).

Version: 2009

Year of publication: 2010

Spatial resolution: 10 arc-seconds (approximately 300 meters)

More information:

- http://ionia1.esrin.esa.int/

B10 Magnitude frequency analysis

The recurrence rates of explosive volcanism in the study countries were estimated based on analysis of a global database of large magnitude explosive volcanic eruptions (LaMEVE). The LaMEVE dataset consists of information on magnitudes and ages of explosive eruptions for M > 4. There are several features of the data that need to be addressed in for analysis.

1. The dataset consists of a mixture of data where the age has been determined by different methodologies and can be usefully classified into historic dates, radiocarbon ages and a variety of other radiometric systems and dating methods. Historic data are largely confined to ages less than 500 years ago, while most ages from 500 years up to 40 ka ago are radiocarbon, and ages greater than 40 ka are mostly by the other

methods. Ages between 500 and 2000 years BP are from radiocarbon but include some historic ages.

2. The data show marked under-recording with increases back in time. The under-recording is strongly affected by the dating method as shown by the analyses of Coles and Sparks (2006), Deligne et al. (2010) and Furian (2010).
3. The time series of global volcanic events may not be stationary. There are for example some researchers who think that explosive volcanism may be reduced during glaciations and anomalously high during deglaciations. They also claim to be able to detect these changes in the data (Huybers and Langmuir, 2009).
4. Under-recording may reflect sampling biases and preservation potential of the deposits. In particular the geology, in particular the Holocene tephra records, of about two-thirds of the World's volcanoes have not been studied. These parameters may also be affected by environmental change. For example high latitude eruptions are less likely to be in the dataset for glacial periods because they are more easily eroded away and there is no carbon to date. There may also be different processes that control tephra preservation rate operating on different time scales.
5. For age data based on geological studies there are reasons to infer that the catalogue is incomplete because a large number of the World's volcanoes have not been studied. For large magnitude eruptions (likely M > 6.5 and certainly M > 7) the historic record (mostly the last 500 years) is too short to sample eruptions with magnitude return periods of 50 years or more, so these data will be mostly based on analysis of incomplete geological data.

A major conclusion from the above considerations is that analysis methods need to take all these factors into account. We have inspected the datasets to see to what extent the various complications above can be identified, analysed quantitatively to assess under-recording, biases, incompleteness, preservation potential and evidence for non-stationarity.

First of all below find the Log of event rate data for M = 4 to 5 against time (Figure 31a) going back to 100 ka. The data define a curve, so the data cannot be described by a simple exponential law. I have also distinguished the 500 year rate, based largely on historic data, which I will argue should not be mixed up with the geological data (red points) based on the analysis of Furian (2010). Note that the 12 to 14 ka data point is anomalously high and is possible evidence for a last glacial surge in volcanism suggested by Huybers and Langmuir (2009). In Figure 31b the same data going back 10 ka years is shown. Here the data can be described by an exponential but excluding the 500 year data. The intercept rate is 0.129 events per year compared to 0.334 events per year in the 500 year data. The ratio of these rates is gives a parameter which I will describe as the geological recording rate index of 0.38. Based on the analysis of Furian (2010) the 500 year data may itself show under-recording because of improvements in global recording of volcanism after 1900 AD. She estimated about 0.8. Although this analysis needs to be re-done for the LaMEVE data, a preliminary estimate is that the geological under-recording index is reduced to 0.3. I interpret this to mean that the geological record in LaMEVE is based on studies of about a third of the world's volcanoes, a result consistent with the unpublished results of Delinge (Masters thesis) on the volcanic records where 326 out of 1100 volcanoes had a "very good" Holocene record.

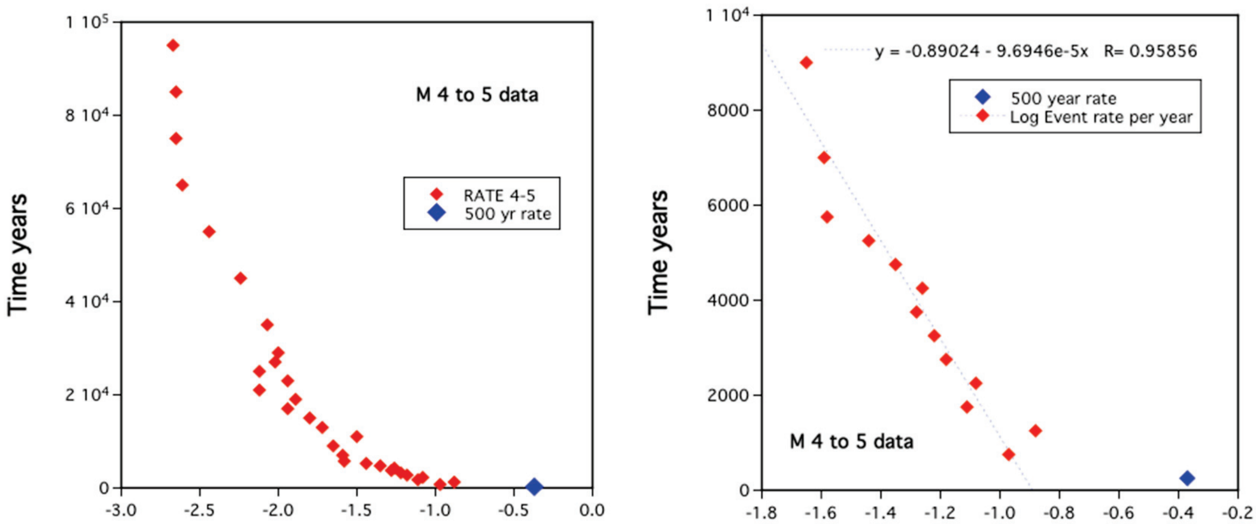
The the same analysis was applied to the M>4, M = 5 to 6, M >5, M 6 to 7 and M > 6 datasets. Broadly the same features can be seen in the plots with curving Log event rate versus time. A time scale can be identified where, after excluding the 500 year data, a log plot looks reasonable. Applying the same approach the geological under-recording index is 0.38 (M ~ 5 to 6) and 0.33 (M ~ 6 to 7). When uncertainties are taken into account (see below) there values are indistinguishable.

The historic data gives return periods as follows with comparisons to the Delinge et al analysis of exceedance return rates (rhs):

M 4 – 5 2.99 years	M > 4 2.34 years	M > 4.5 (D et al) 4.4 years
M 5 – 6 13.5 years	M > 5 10.4 years	M > 5 (D et al) 7.9 years
M 6 – 7 49.0 years	M > 6 49.0 years	M > 6 (D et al) 42 years

These results are not corrected for the improvement in recording after 1900 AD. Note that the agreement is in fact very good if the new analyses are changed by a factor of 0.8. This is not too surprising as most of the historical data analysed by Delinge et al (2010) and Furian (2010) will be the same as in the analysis of the LaMEVE database. 2σ uncertainties are estimated using the results of Delinge et al (2010).

The M > 7 data provides different challenges reflecting that there are no historic data that definitively exceed M >7, although the Tambora 1815 eruption is borderline (M 6.9) with enough uncertainty that it could well have exceeded M = 7. Thus we cannot use historic data to provide any benchmark rate, which is thought to be representative of the true rate. Figure 32 shows the data. Here an exponential fit was put through the last three points to generate an event rate at the zero time intercept of 0.000657, which gives a return period of 1520 years, compared to 370 years from the analysis of Deligne at al. If the geological under-recording is the same as for other magnitudes (about 0.3) then the return period increases to 490 years. There are large uncertainties of course in both these estimates and we no longer have historic data for eruptions of these large magnitudes that allows the under-recording index to be calculated.



(a) (b)

Figure 31 Assessment of magnitude-frequency relationships.

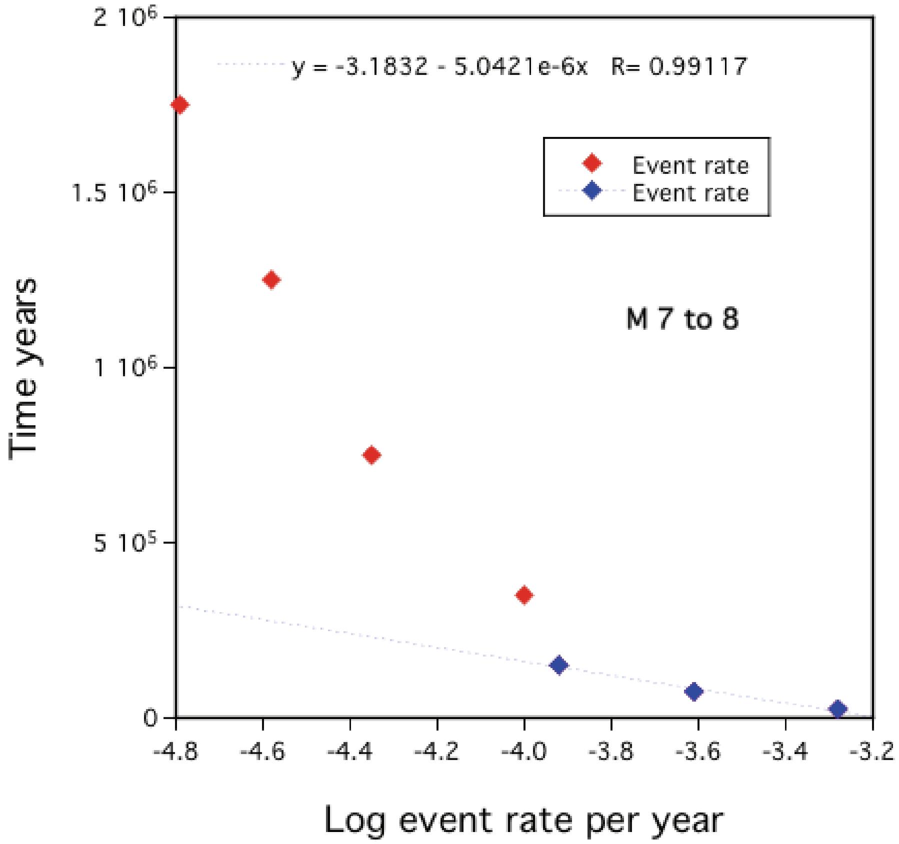


Figure 32 Assessment of magnitude-frequency relationships for magnitudes greater than 7.

B11 References

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Appendix C - Country Profiles

Contents

C1 Introduction

The following country profiles detail the full results attained for the sixteen Category A countries (those with volcanoes within their borders). These countries are:

- Colombia
- Costa Rica
- Djibouti
- Ecuador
- Ethiopia
- Guatemala
- Indonesia
- Madagascar
- Mali
- Panama
- Papua New Guinea
- Philippines
- Solomon Islands
- Vanuatu
- Vietnam
- Yemen

Explanations of the data sources and brief overviews of the methods used are given here. For more detailed methodologies, see Appendix B.

C1.1 Volcanic Facts

The volcanic facts section gives the number of Holocene volcanoes, the number of each type (as defined in the hazard ranking methodology), the number with potential for key hazards, and the number of fatalities caused by volcanic eruptions. All the data used in generating these counts is available from the Smithsonian Institution (SI). The number of volcanoes, number of each type of volcano, and number of volcanoes generating pyroclastic flows, lava flows, and lahars is calculated using the Global Volcanism Program (GVP) database, and the eruptive history[1] of each volcano, available on the SI website.

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[1] Volcanoes are counted as having generated pyroclastic flows, lahars, or lava flows if they are given a 2 for the former two, or a 0.2 for the latter, in the hazard ranking assessment (see Appendix B). These scores mean that the volcano has the hazard listed in its eruptive history, or the hazard is mentioned in its summary page. The count does not imply that volcanoes without any record of these hazards cannot manifest these hazards, because both the historical and geological records of many of the volcanoes are incomplete and commonly poor.

The number of fatalities is counted using a database of fatal eruptions, available on request from the SI. The coverage of the database varies between countries and over time; there are also uncertain records, such as those for which only a qualitative description of the number of fatalities is available. The number quoted in the country profile is therefore quoted with these underlying uncertainties, though is nevertheless a useful estimate.

C1.2 Socio-Economic Facts

Explanations of and sources for the information given in the socio-economic facts section are as follows:

- Total population: "The de facto population in a country," as of 1st July 2010.

  Source: International Human Development Indicators, United Nations Development Programme 2010.

- Gross domestic product (GDP) per capita, 2008 purchasing power parity (PPP) US$: "Sum of value added by all resident producers in the economy plus any product taxes (less subsidies) not included in the valuation of output, calculated without making deductions for depreciation of fabricated capital assets or for depletion and degradation of natural resources, divided by population. Value added is the net output of an industry after adding up all outputs and subtracting intermediate inputs. When expressed in purchasing power parity (PPP) US$ terms, it is converted to international dollars using PPP rates; an international dollar has the same purchasing power over GDP that the U.S. dollar has in the United States."

  Source: International Human Development Indicators, United Nations Development Programme 2010.

- Human Development Index (HDI): "A composite index measuring average achievement in three basic dimensions of human development – a long and healthy life, knowledge, and a decent standard of living." Figures quoted in the country profiles are for 2010. Each country's HDI is categorised as either Very High, High, Medium, or Low. As of 2010, these categories are relative and based on quartiles, with a country classed as Very High HDI if its HDI is in percentiles 76 – 100, classed as High HDI if its HDI is in percentiles 51 – 75, and so on.

  Source: International Human Development Indicators, United Nations Development Programme 2010.

- Ten largest cities, as measured by population ("Key Cities"): The ten most populous cities. Cities are arbitrarily defined as settlements with populations over 20,000, though a minimum of three cities must be listed for each country. These two criteria are relevant for only Djibouti and Papua New Guinea (which have only three and eight settlements with populations over 20,000, respectively), and the Solomon Islands and Vanuatu (both of which have only one settlement with a population over 20,000, meaning the next two largest cities are also used). The cities in the list are thus referred to and mapped as the Key Cities.

  Source: Geonames (for city names, populations, and geographic coordinates).

- Distance from capital city to nearest volcano: The distance between a country's capital city and its nearest volcano. The distance, given in kilometres, is calculated by inputting city and volcano coordinates into an online calculator based on a spherical earth. Distances are rounded to two significant digits.

  Sources: SI GVP (volcano geographic coordinates), Geonames (city geographic coordinates), and Movable-Type (distance calculator).

- Number (percentage) of cities (population over 20,000) within 100 km of a volcano[2]: The number (and percentage) of settlements with populations over 20,000 located within 100 km of a volcano. Each country's volcanoes, plus those in other countries sufficiently close to its borders, are included in this count; for example, some cities in Guatemala are within 100 km of volcanoes located in El Salvador. The computation is carried out using buffer analysis in ArcGIS. Population numbers are rounded to two significant digits; percentages are given as whole numbers.

  Source: SI GVP (volcano geographic coordinates), Geonames (city geographic coordinates).

- Number (percentage) of people living within 10, 30, and 100 km of a volcano[3]: The number (and percentage) of people living within 10, 30, and 100 km of a volcano. Populations living proximate to multiple

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[2] For Vanuatu and the Solomon Islands, the Key Cities rather than those with populations over 20,000 are used.

[3] For some countries, there is a discrepancy between the total population given or implied in this statistic, and that quoted in the volcanic facts section. This discrepancy arises because of the different datasets used (LandScan 2009 for the former, and UNDP 2010 for the latter).

volcanoes are only counted once. Each country's volcanoes, plus those in other countries sufficiently close to its borders, are included in this count; for example, some populations in Guatemala are within 10, 30, and 100 km of volcanoes located in El Salvador. The computation is carried out using buffer analysis and zonal analysis in ArcGIS. Population numbers are rounded to two significant digits, and percentages are given as whole numbers; population numbers below 1,000 are listed as "<1,000" to reflect data resolution.

Source: Oak Ridge National Laboratory LandScan 2009 (population distribution), SI GVP (volcano geographic coordinates).

C1.3 Hazard and Uncertainty Assessments

A method based on Ewert et al., 2005 was derived to measure volcanic hazard; it scores eight hazard-related elements for each volcano, sums these eight scores, and assigns the score to one of three Hazard Levels. Level 1 is lowest hazard, level 2 higher, and level 3 highest.

The availability and quality of volcano data varies drastically. An uncertainty measure was derived to incorporate this fact. Six of the eight hazard elements are also assigned a separate uncertainty score; as with the hazard score, these six scores are summed and assigned to one of three levels. All the data used in the hazard and uncertainty assessments are available on the SI website.

Each volcano thus has a hazard and uncertainty score, and level. A scatter plot is used to depict the hazard and uncertainty scores for each country's volcanoes, with background colouring and colour intensity used to show the three Hazard Levels and Uncertainty Levels, respectively. A table then identifies the volcanoes in each Hazard-Uncertainty cohort.

Source: SI GVP

C1.4 Exposure Assessments – Population Exposure Index

A Population Exposure Index (PEI) was used as a preliminary measure of population vulnerability to quantify population exposure to volcanic hazards. The number of people living within 10 km and 30 km of each volcano was computed using LandScan 2009 population data in ArcGIS. These population numbers were then weighted and summed; the 10 km circle population was weighted fifteen times more than the 30 km circle population, to account for differences in area and proximity to the volcano. For further details on the derivations of these weightings, see Appendix B. The weighted, summed population was then assigned to one of seven PEI scores, and the seven scores further grouped into three levels.

A scatter plot is used to depict PEI against hazard score for each country's volcanoes, with background colouring used to show the three Risk Levels, with red for Risk Level 3, orange for Risk Level 2, and green for Risk Level 1 (see below); vertical lines indicate the three PEI Levels. A table then identifies the volcanoes in each Hazard-PEI cohort.

Source: Oak Ridge National Laboratory LandScan 2009 (population distribution).

C1.5 Exposure Assessments – Risk Levels

The scatter plot of hazard score against PEI is a basic measure of volcano Risk Level. Volcanoes classed as Hazard Level 3 that have large surrounding populations (high PEI) pose the highest risk, and vice versa. This relationship is quantified to give three Risk Levels; the hazard score is multiplied by the PEI score for each volcano, and the result assigned to one of three Risk Levels. A list of volcanoes by Risk Level, sorted alphabetically, is given for each country. These are quoted with the Uncertainty Level ascribed during the hazard assessment; though possible further uncertainties may be introduced during the PEI calculations, their quantification is difficult and they are thus unaccounted for.

C1.6 Exposure Assessments – Hazard Specific

C1.6.1 Pyroclastic flows and lahars

Areas potentially affected by pyroclastic flows and lahars were modelled at volcanoes at which such hazards had previously occurred, or were deemed probable[4]. These models were run in ArcGIS, and use various datasets to calculate levels of exposure of cities, populations (from Landscan), ports, roads, railways, and airports to pyroclastic flow and lahar hazards. As with previous counts, both volcanoes located inside each country, as well as those in other countries but sufficiently close to the border, are included in these counts. Results are rounded to two significant digits.

Sources: SRTM Digital Terrain Model 2000, World Port Index 2010 (ports), ESRI World Roads 2010 and Digital Chart of the World 1993 (roads), Digital Chart of the World 1993 (railways), ESRI World Airports 2010 (airports), Landscan population distribution. Other datasets as described above.

C1.6.2 Ash

Measurement of exposure to ash hazards was carried out by overlaying wind roses on maps indicating airports, agricultural areas, and key cities. Calculated

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[4] Volcanoes are counted as having generated pyroclastic flows or lahar if they are given a 2 for these hazards in the hazard ranking assessment. Pyroclastic flows and lahars are counted as “probable” if they are given a 1 for these hazards in the hazard ranking assessment. Full explanation of these scores is available in Appendix B.

at pressures of 250 – 100 mbar (approximately 10 – 16 km altitude), each wind rose separates winds into eight directions, showing the percentage of winds blowing and average wind speed in each. Note that winds at other altitudes, as well as eruption characteristics (such as plume height and duration) will also affect the transport of ash; these factors are unaccounted for here. Wind roses were generated for coordinate locations near volcanoes producing VEI 3+ eruptions, with the wind roses required to show wind patterns across the whole country shown. Qualitative assessments of the level of exposure can then be made.

Sources: NCEP/NCAR Reanalysis Dataset (Kalnay et al., 1996) (wind roses), Globcover 2010 (agriculture). Other datasets as described above.

C1.7 Frequency of Explosive Eruptions

Estimates of recurrence rates of explosive volcanism in the study countries were computed based on analysis of a global database of large magnitude explosive volcanic eruptions (LaMEVE). Magnitude is defined as the Log of mass of magma erupted minus 7. Not all volcanoes in the study countries are explosive. The return rate of eruptions above a given magnitude is estimated by multiplying the global rate (return period in years) by the ratio of number of the explosive volcanoes in the region to the global number of explosive volcanoes in the GVP database (440). The numbers of volcanoes in several of the countries are too few for the down-scaling to be done for every country, thus rates are presented for Indonesia, the Philippines, Ethiopia and Yemen (African Region), Colombia and Ecuador (South American Region), Costa Rica, Panama and Guatemala (Central American Region), and Papua New Guinea, The Solomon Islands, and Vanuatu (Pacific region). For further details, see Appendix B.

Sources: LaMEVE, University of Bristol 2011.

C1.8 National Capacity for Coping with Volcanic Risk

A monitoring index was created to give an indication of each country’s capabilities in monitoring each of their volcanoes. Volcanoes are scored based on frequency of monitoring, and existence and proximity of seismic networks; scores are then assigned to levels zero (unmonitored) to three (established, comprehensive monitoring). The information used to apply the monitoring index comes from various sources, namely websites and personal communication. These sources differ in their credibility and accuracy; as such, an Uncertainty Level of low, low-medium, medium-high, or high, is given for each country (rather than each volcano).

A bar chart is used to depict the distribution of each country's volcanoes across the four Monitoring Levels, with colouring used to indicate Risk Level (1, 2 or 3). The country-averaged Uncertainty Level is shown above the plot.

C2 Colombia

Description

Colombia has fifteen Holocene volcanoes listed in the GVP database; all are located along a well-defined line, parallel to and between 150 km and 200 km inland of the country's Pacific coastline. The volcanoes are related to the subduction of the Nazca Plate below the South American Plate.

All except one of Colombia's volcanoes are stratovolcanoes or similarly dominantly-explosive types. Despite eight of Colombia's volcanoes having produced pyroclastic flows and six having caused lahars, the risks they pose are restricted because the majority of the country's most-populous cities are located on or towards the northern coast, well away from volcanoes. Exceptions are the cities of Ibagué, Pasto and Pereira, all with populations of roughly 400,000, which are overlooked by Machín, Galeras, and the Ruiz-Tolima Chain, respectively. Moreover, less densely populated rural areas surround many of Colombia's volcanoes, highlighted by thirteen volcanoes each having over 100,000 people living with 30 km of their summits.

Both Galeras and Nevado del Ruiz have caused loss of life. Machín has not caused any fatalities but has shown recent unrest, and its geological record indicates the potential for violent and destructive explosive eruptions. In 1993, a sudden intense but small magnitude explosive eruption of Galeras killed nine people, including six volcanologists who were in the inner crater or on its rim. A far larger disaster, the largest in South America's history, was the 1985 eruption of Nevado del Ruiz. Though only VEI 3, the eruption generated pyroclastic flows that melted the volcano's glacier cap and caused lahars. The mudflows descended the western flanks, flowing along the Río Lagunillas valley. The town of Armero, located on the banks of Río Lagunillas 48 km from the volcano, was completely buried. Though the death toll is uncertain, it is estimated that 21,000 of the 29,000 residents of Armero were killed, along with others elsewhere bringing the total loss of life to between 23,000 and 26,000.

Following the 1985 Nevado del Ruiz tragedy, the Colombian Government took steps to strengthen the monitoring and response mechanisms for Colombian volcanoes. These measures included making INGEOMINAS responsible for the monitoring of volcanoes and provision of scientific advice.

Further eruptions with human impacts have occurred very recently at Galeras volcano. An eruption starting on 25th August 2010 spread ash as far as 30 km to the northwest; 7,000 people were advised to evacuate though few left their homes. On 25th January 2011, seismic patterns similar to those detected prior to previous eruptions were seen, and the alert level was raised to II ("eruption likely in the next few days or weeks").

Location of Colombia’s Volcanoes and Key Cities

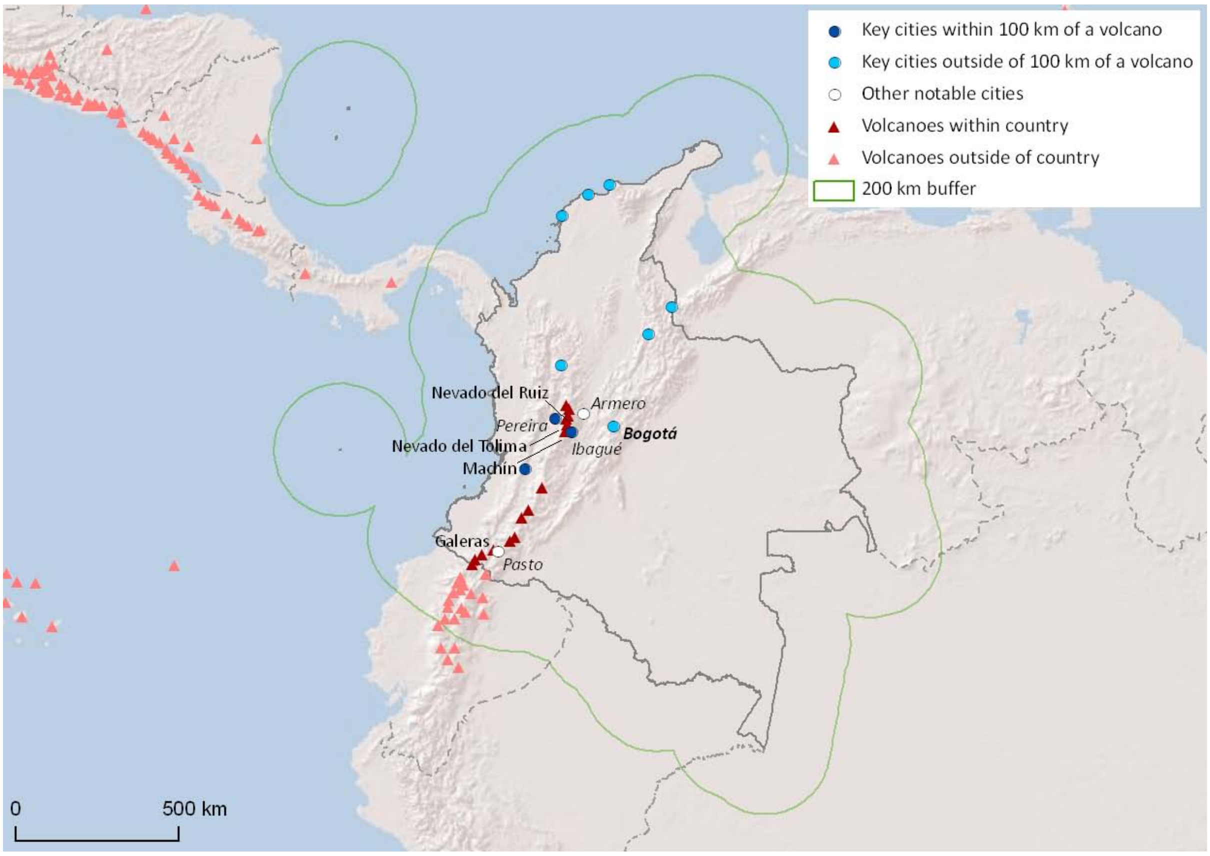


Figure 2.1: Locations of Colombia's volcanoes, ten largest cities, and other notable cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Colombia.

Volcanic Facts

Number of Holocene volcanoes:	15
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	14 and 1 respectively
Number of volcanoes generating pyroclastic flows:	8
Number of volcanoes generating lahars:	6
Number of volcanoes generating lava flows:	6
Number of fatalities caused by volcanic eruptions:	25,785

Socio-Economic Facts

Total population:	46,300,200
GDP per capita, 2008 PPP US$:	8,959
HDI:	0.689 – High

Ten largest cities, as measured by population ("Key Cities"), and populations:

- Bogotá (capital city)	Population:	7,102,602
- Cali	Population:	2,392,877
- Medellín	Population:	1,999,979
- Barranquilla	Population:	1,380,425
- Cartagena	Population:	952,024
- Cúcuta	Population:	721,398
- Bucaramanga	Population:	571,820
- Pereira	Population :	440,118
- Santa Marta	Population :	431,781
- Ibagué	Population :	421,685

Distance from capital city to nearest volcano:	140 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	56 (32%)
Number (percentage) of people living within 10 km of a volcano:	360,000 (1%)
Number (percentage) of people living within 30 km of a volcano:	2,800,000 (6%)
Number (percentage) of people living within 100 km of a volcano:	12,000,000 (28%)

Hazard and Uncertainty Assessments

The plot in Figure 2.2 shows the classifications of Colombia's fifteen volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 2.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

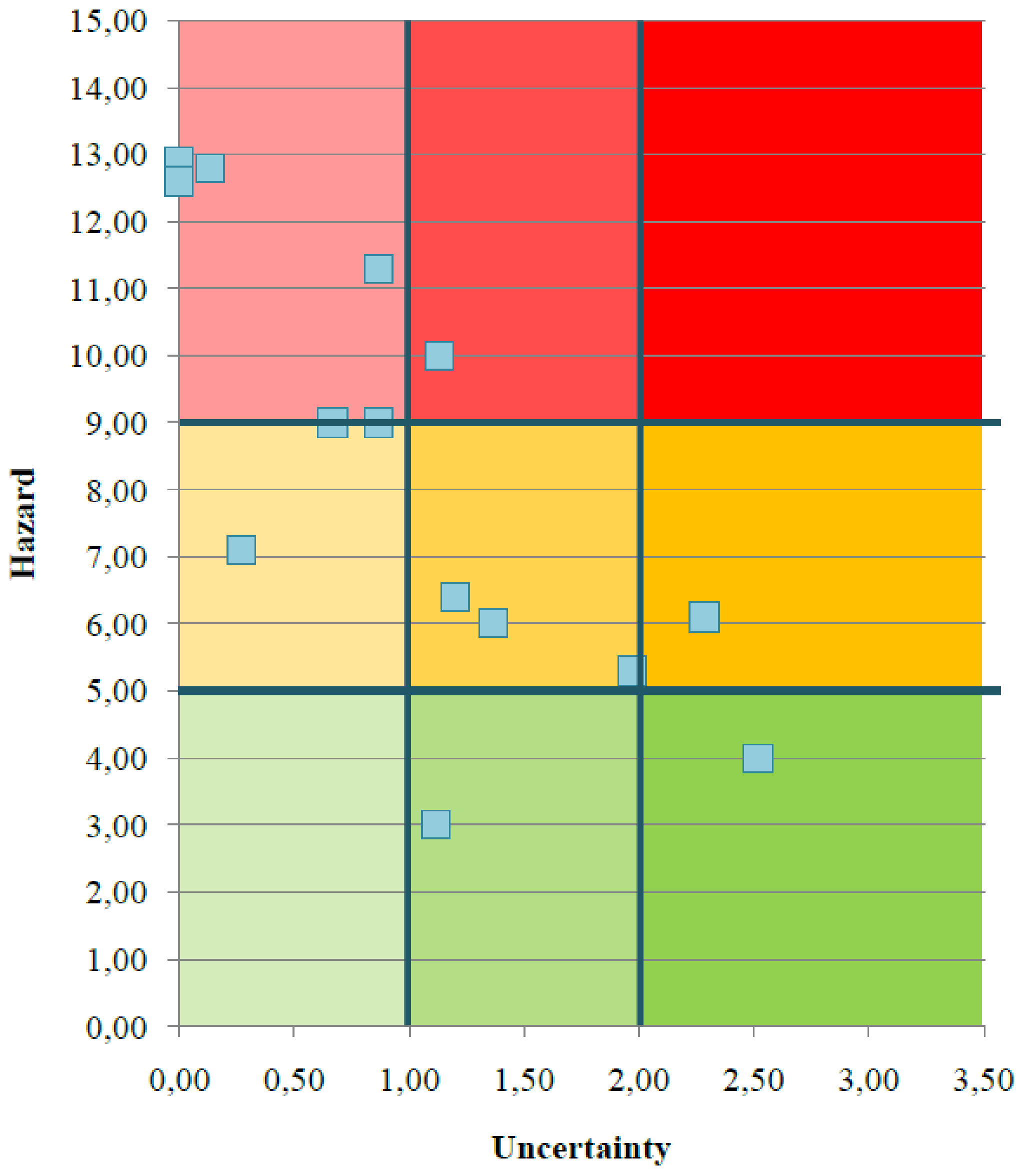


Figure 2.2: Distribution of Colombia's volcanoes across Hazard and Uncertainty Levels.

Table 2.1 Identities of Colombia's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Doña Juana Galeras Machín Nevado del Huila Nevado del Ruiz Nevado del Tolima Puracé	Azufral	
Hazard Level 2	Cerro Bravo	Cumbal Romeral Santa Isabel	Cerro Negro de Mayasquer
Hazard Level 1		Sotará	Petecas
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Colombia's volcanoes are mostly classed as Hazard Level 2 or 3. As is the case with many other GFDRR priority countries, Colombia's highest hazard volcanoes generally have lowest uncertainty, and vice versa. Of note are Azufral and Cerro Negro de Mayasquer; both have somewhat higher Uncertainty Levels than would be expected for their respective Hazard Levels.

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 2.3 shows the classifications of Colombia's fifteen volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 2.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

The correlation between the Hazard Levels and PEI Levels of Colombia's volcanoes is positive and fairly strong; seven volcanoes are subsequently classed as Risk Level 3, and all except one of these are of Uncertainty Level 1.

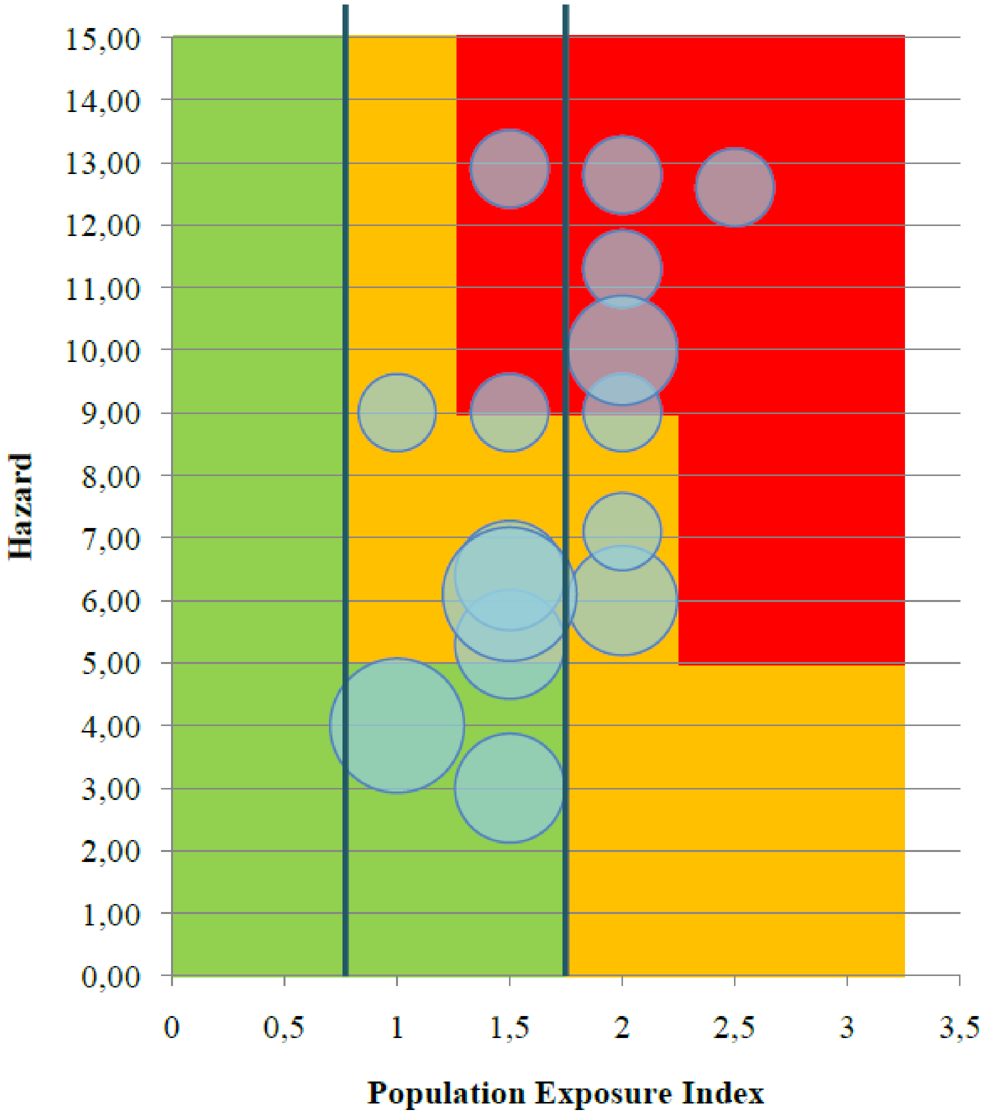


Figure 2.3: Distribution of Colombia's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Basic results – Risk assessments

The list below gives the Risk Levels of Colombia’s volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 2.1 and Figure 2.2.

Risk Level 3:

Azufral	Uncertainty Level 2
Doña Juana	Uncertainty Level 1
Galeras	Uncertainty Level 1
Machín	Uncertainty Level 1
Nevado del Ruiz	Uncertainty Level 1
Nevado del Tolima	Uncertainty Level 1
Puracé	Uncertainty Level 1

Risk Level 2:

Cerro Bravo	Uncertainty Level 1
Cerro Negro de Mayasquer	Uncertainty Level 3
Cumbal	Uncertainty Level 2
Nevado del Huila	Uncertainty Level 1
Romeral	Uncertainty Level 2
Santa Isabel	Uncertainty Level 2

Risk Level 1:

Petecas	Uncertainty Level 3
Sotara	Uncertainty Level 2

Of Colombia’s fifteen volcanoes, seven are Risk Level 3, six are Risk Level 2, and two are Risk Level 1.

Table 2.2 Identities of Colombia's volcanoes in each Hazard-PEI cohort.

Hazard Level 3		Doña Juana Nevado del Huila Puracé	Azufral Galeras Machín Nevado del Ruiz Nevado del Tolima
Hazard Level 2		Cerro Negro de Mayasquer Cumbal Santa Isabel	Cerro Bravo Romeral
Hazard Level 1		Petecas Sotará	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Hazard-specific exposure assessments

Table 2.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 2.3 Extent of infrastructure exposure to lahars and pyroclastic flows in Colombia.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	49 28%	Number of cities: Percentage of total number of cities:	9 5%
Population	Number of people: Percentage of total number of people:	10,000,000 23%	Number of people: Percentage of total number of people:	1,900,000 4%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	7,600 15%	Length (km): Percentage of total length:	1,400 3%
Main Roads	Length (km): Percentage of total length:	2,300 24%	Length (km): Percentage of total length:	490 5%
All Railways	Length (km): Percentage of total length:	1,000 29%	Length (km): Percentage of total length:	21 1%
Airports	Number of airports: Percentage of all airports:	31 23%	Number of airports: Percentage of all airports:	8 6%

Figure 2.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Colombia.

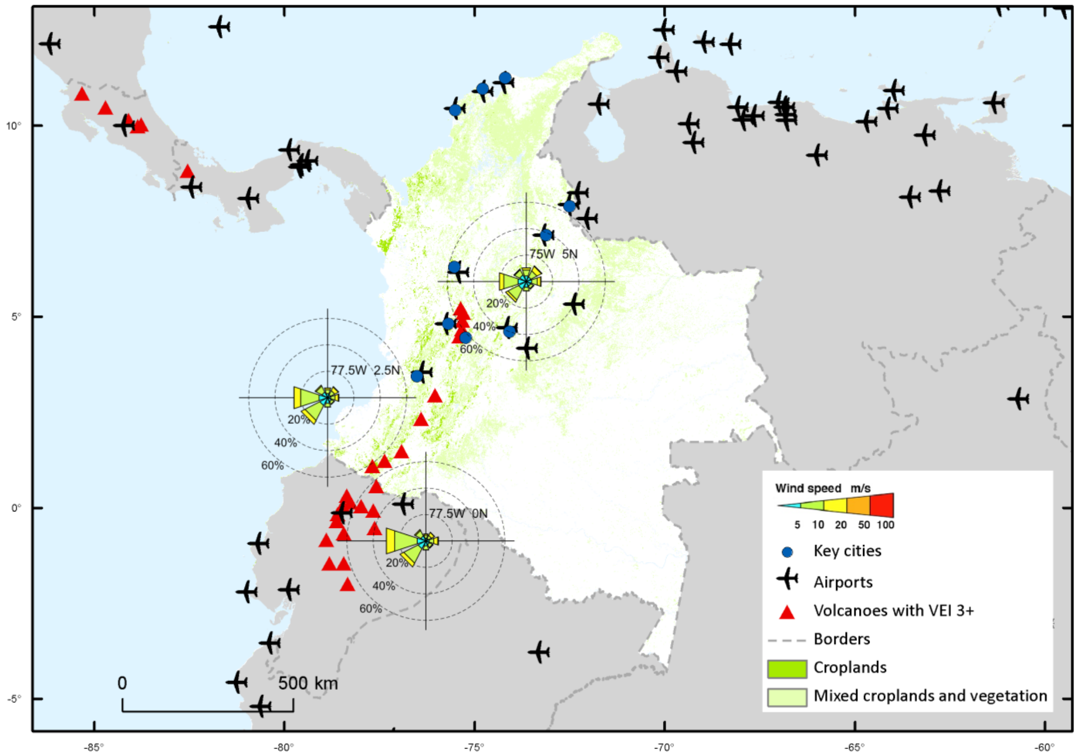


Figure 2.4 Map showing elements exposed to ash hazards in Colombia, with wind roses indicating dominant wind directions and speeds.

The predominant winds in Colombia are easterly and north-easterly, and do not typically exceed 20 m/s. However, the rose diagrams show wind varies significantly and ash could potentially be transported in any direction (with a minimum probability of approximately 5% in the 'least likely' sectors towards the south or southeast). The major city and international airport of Bogotá lies approximately 150 – 200 km to the east of the Ruiz-Tolima volcanic chain (including Romeral, Cerro Bravo, Nevado del Ruiz, Machín and Nevado del Tolima volcanoes). Wind is expected to travel in this direction approximately 10% of the time. The city of Ibagué lies approximately 20 km east of Machín volcano and 60 km south of Nevado del Ruiz, and could be significantly affected by ash fall. Pereira (city and airport) lies approximately 60 km to the west of Nevado del Ruiz in the primary downwind direction (approximately 20% probability of wind in this direction), and ashfall from Romeral and Cerro Bravo to the north-east is also likely to cause a significant impact. Agriculture in Colombia is scattered and largely comprised of mixed croplands. Agricultural lands to the west of the Ruiz-Tolima volcanic chain, and in close proximity to volcanoes are most likely to be affected by ashfall.

Frequency of Explosive Volcanism

Table 2.4 gives the estimated return periods for different magnitude eruptions in the South American region, which comprises Colombia and Ecuador in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 2.4 Return periods for different magnitude eruptions in Colombia.

Magnitude	Return Period (years)
3	0.6
3.5	1.1
4	2.3
4.5	4.4
5	8
5.5	20
6	42
6.5	110
7	490
8	30,000

National Capacity for Coping with Volcanic Risk

Figure 2.5 depicts the numbers of Colombia's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

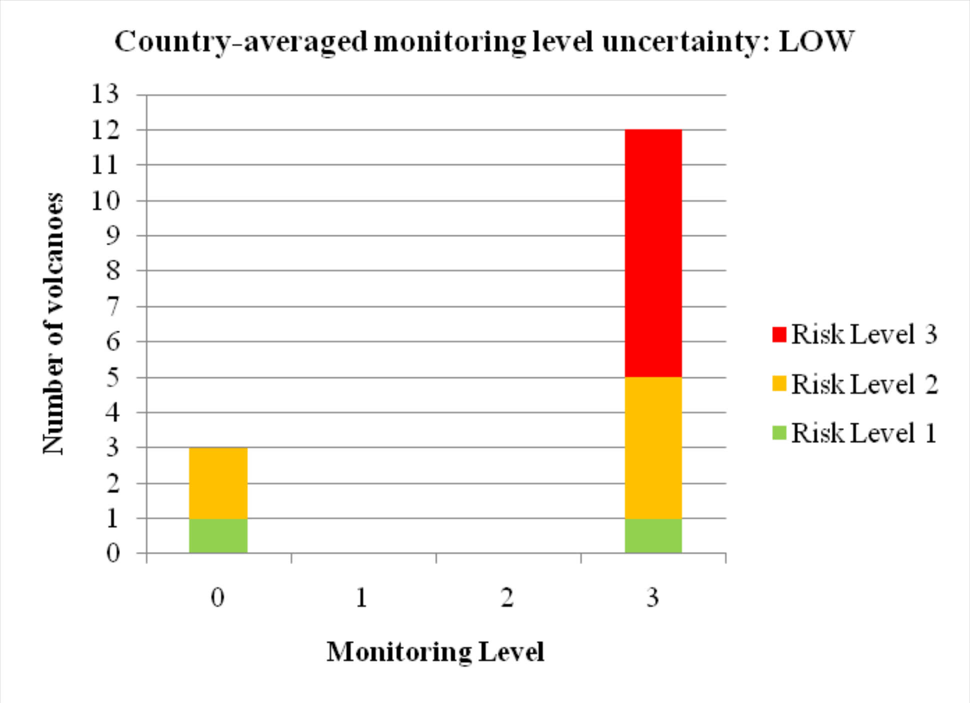


Figure 2.5 Distribution of Colombia's volcanoes across Monitoring and Risk Levels.

Twelve of the fifteen Colombian Holocene volcanoes have a Monitoring Level of 3, meaning they are continuously monitored through a well-established and facilitated institution. These twelve include all seven of the Risk Level 3 volcanoes. The three volcanoes with a Monitoring Level of 0 include one Risk Level 1 and two Risk Level 2 volcanoes; these volcanoes are not monitored by INGEOMINAS.

Summary

Volcanic risk is significant in Colombia, with several Risk Level 3 volcanoes. Knowledge of those volcanoes which have shown recent eruptions and unrest is mostly high, but there are a significant number of volcanoes where Hazard Levels are uncertain and baseline geological knowledge is poor. All the Risk Level 3 and some Risk Level 2 volcanoes are well monitored.

C3 Costa Rica

Description

Ten Holocene volcanoes are listed in the GVP database for Costa Rica. These volcanoes arise as a result of the subduction of the Cocos Plate beneath the Caribbean Plate, giving a line of stratovolcanoes and complex volcanoes that lies parallel to the country's Pacific coastline, roughly 50 km inland.

Some of Costa Rica's largest population centres could be threatened by volcanic activity. Liberia, located towards the border with Nicaragua, is about 25 km from Rincón de la Vieja, and the city of Alajuela is situated 70 km southeast of Arenal. Five of Costa Rica's volcanoes each have over 100,000 people living with 30 km of their summits. Further, Costa Rica's tallest two volcanoes overlook the capital, San José, along with a third smaller volcano. The latter of these three, Barva, has only scarce details regarding dates and resultant impacts of eruptions, though lava flows blanket its south side and descend nearly to the city of Heredia. The larger two volcanoes, Irazú and Turrialba, have well documented eruptions. Irazú is one of Costa Rica's most active volcanoes, with frequent explosive eruptions documented since 1723. An eruption in 1963 – 1965, one of Irazú's largest at VEI 3, caused ash fall that led to significant disruption of San José and surrounding areas. Five major explosive eruptions have occurred at Turrialba during the past 3,500 years, with a series of pyroclastic flow-generating events in the 19th century.

In terms of fatalities, the most destructive eruption in Costa Rica's history is that of Arenal in August 1968. Situated towards the middle of Costa Rica's southeast to northwest trending line of volcanoes and roughly 70 km from the border with Nicaragua, Arenal is one of Costa Rica's most active volcanoes. The 1968 eruption initiated persistent activity which still continues; roughly 100 people were killed in the first three days, mostly by pyroclastic flows but also by ballistic bombs. The village of Tabacon, 3.5 km northwest of the volcano, was almost totally obliterated. Other destructive eruptions include the 1963 – 1965 eruption of Irazú, which led to approximately fifty fatalities.

Location of Costa Rica’s Volcanoes and Key Cities

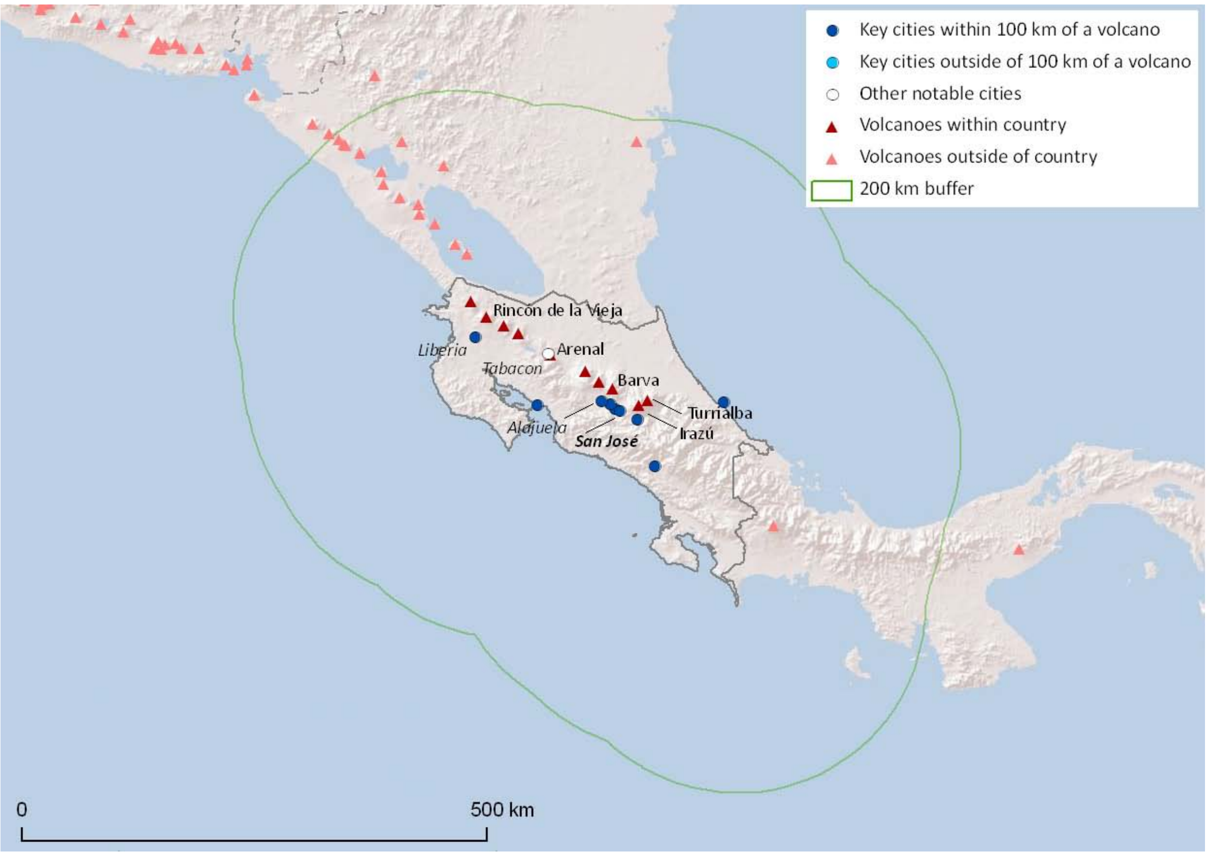


Figure 3.6: Locations of Costa Rica's volcanoes, ten largest cities, and other notable cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Costa Rica.

Volcanic Facts

Number of Holocene volcanoes:	10
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	10 and 0 respectively
Number of volcanoes generating pyroclastic flows:	5
Number of volcanoes generating lahars:	6
Number of volcanoes generating lava flows:	6
Number of fatalities caused by volcanic eruptions:	140

Socio-Economic Facts

Total population:	4,639,000
GDP per capita, 2008 PPP US$:	11,143
HDI:	0.725 – High

Ten largest cities, as measured by population (“Key Cities”), and populations:

- San José (capital city)	Population:	335,007
- Puerto Limón	Population:	63,081
- San Francisco	Population:	55,923
- Alajuela	Population:	47,494
- Liberia	Population:	45,380
- Paraíso	Population:	39,702
- Puntarenas	Population:	35,650
- San Isidro	Population :	34,877
- Curridabat	Population :	34,586
- San Vicente de Moravia	Population :	34,447

Distance from capital city to nearest volcano:	23 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	33 (100%)
Number (percentage) of people living within 10 km of a volcano:	120,000 (3%)
Number (percentage) of people living within 30 km of a volcano:	3,100,000 (72%)
Number (percentage) of people living within 100 km of a volcano:	4,200,000 (99%)

Hazard and Uncertainty Assessments

The plot in Figure 3.2 shows the classifications of Costa Rica's ten volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 3.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

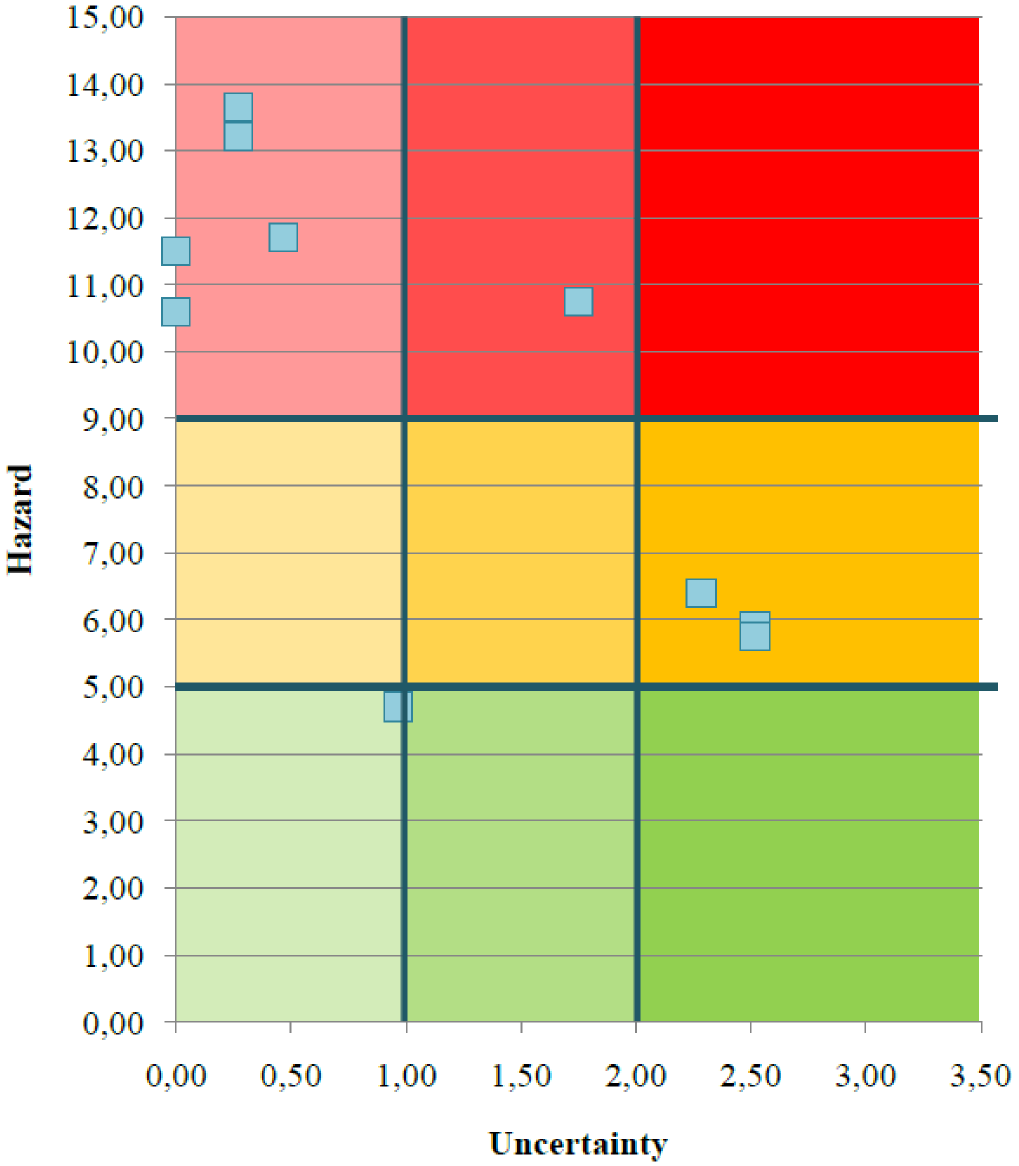


Figure 3.7: Distribution of Costa Rica's volcanoes across Hazard and Uncertainty Levels.

Table 3.5 Identities of Costa Rica's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Arenal Irazú Poás Rincón de la Vieja Turrialba	Barva	
Hazard Level 2			Orosí, Platanar, Tenorio
Hazard Level 1	Miravalles		
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Costa Rica’s volcanoes are mostly classed as Hazard Level 2 or 3. Barva is notable for having a higher Uncertainty Level than the other Hazard Level 3 volcanoes. Orosí, Platanar, and Tenorio are all Level 2 Hazard, but are also Level 3 Uncertainty.

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 3.3 shows the classifications of Costa Rica’s ten volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 3.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Many of Costa Rica’s volcanoes have both high Hazard and high PEI Levels, and subsequently have high Risk Levels. Greatest uncertainty surrounds Costa Rica’s Risk Level 2 volcanoes.

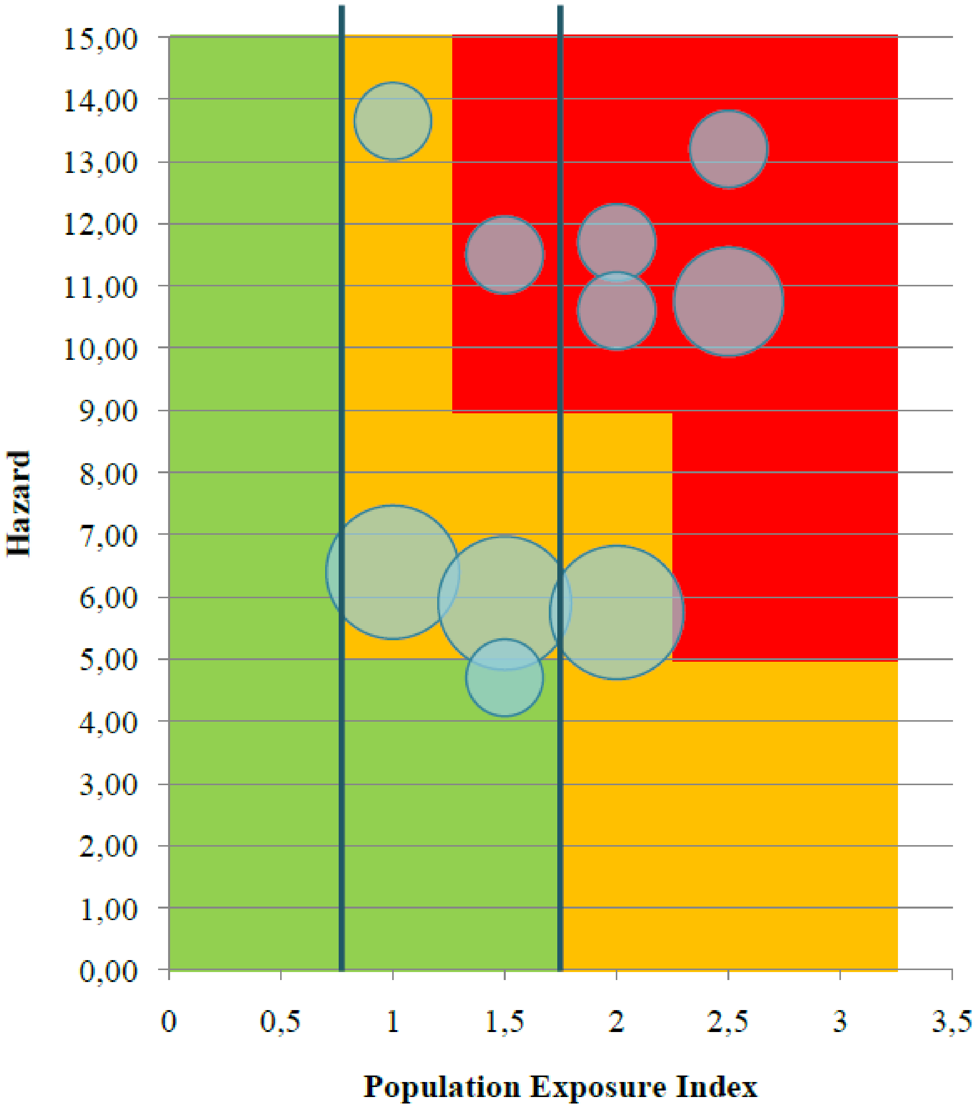


Figure 3.8: Distribution of Costa Rica's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Basic results – Risk assessments

The list below gives the Risk Levels of Costa Rica's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 3.1 and Figure 3.2.

Risk Level 3:

Volcano	Uncertainty
• Arenal	Uncertainty Level 1
• Barva	Uncertainty Level 2
• Irazú	Uncertainty Level 1
• Poás	Uncertainty Level 1
• Turrialba	Uncertainty Level 1

Risk Level 2:

• Orosí	Uncertainty Level 3
• Platanar	Uncertainty Level 3
• Rincón de la Vieja	Uncertainty Level 1
• Tenorio	Uncertainty Level 3

Risk Level 1:

• Miravalles	Uncertainty Level 1

Of Costa Rica's ten volcanoes, five are Risk Level 3, four are Risk Level 2, and one is Risk Level 1.

Table 3.6 Identities of Costa Rica's volcanoes in each Hazard-PEI cohort.

Hazard Level 3		Arenal Rincón de la Vieja	Barva Irazú Poás Turrialba
Hazard Level 2		Orosí Tenorio	Platanar
Hazard Level 1		Miravalles	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Hazard-specific exposure assessments

Table 3.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 3.7 Extent of infrastructure exposure to lahars and pyroclastic flows in Costa Rica.

Exposed Elements	**Lahars**	**Pyroclastic Flows**
Cities (population > 20,000)	Number of cities: 27 Percentage of total number of cities: 82%	Number of cities: 27 Percentage of total number of cities: 82%
Population	Number of people: 3,400,000 Percentage of total number of people: 79%	Number of people: 2,800,000 Percentage of total number of people: 65%
Ports	Number of ports: 0 Percentage of total number of ports: 0%	Number of ports: 0 Percentage of total number of ports: 0%
All Roads	Length (km): 2,100 Percentage of total length: 46%	Length (km): 1,100 Percentage of total length: 24%
Main Roads	Length (km): 1,400 Percentage of total length: 53%	Length (km): 890 Percentage of total length: 33%
All Railways	Length (km): 420 Percentage of total length: 56%	Length (km): 150 Percentage of total length: 20%
Airports	Number of airports: 15 Percentage of all airports: 42%	Number of airports: 4 Percentage of all airports: 11%

Figure 3.4 shows agriculture and infrastructure elements exposed to ash hazards, and a wind rose indicating prevalent conditions for Costa Rica.

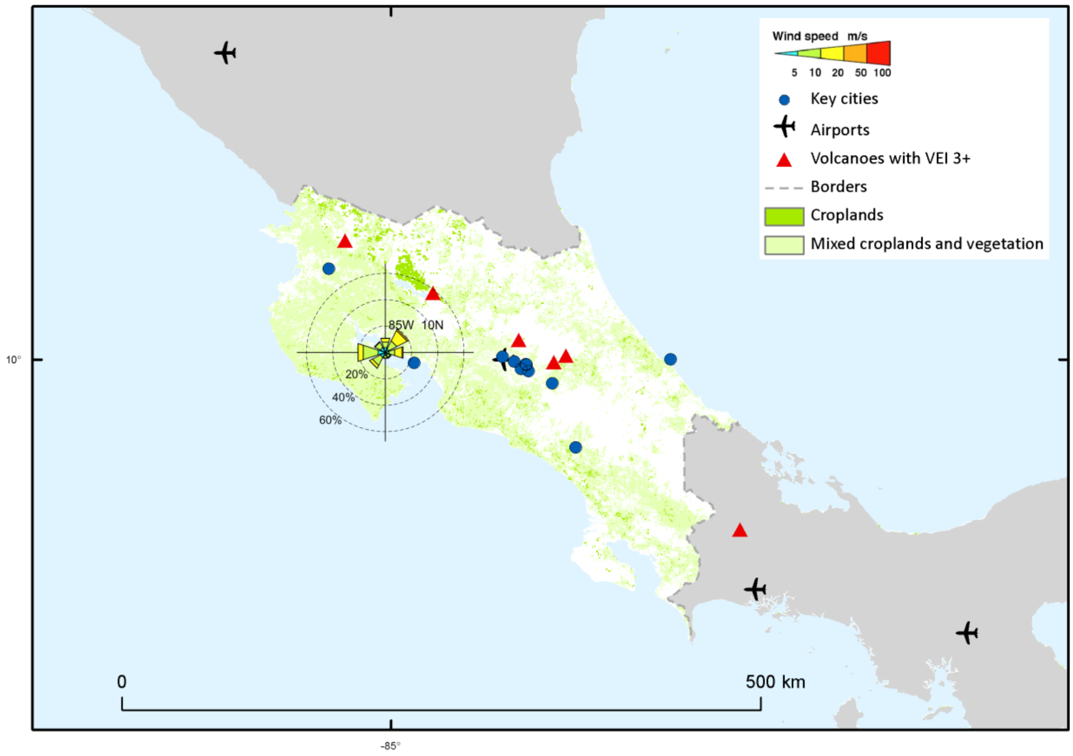


Figure 3.9: Map showing elements exposed to ash hazards in Costa Rica, with wind rose indicating dominant wind directions and speeds.

Winds are predominantly from the east (over 20%) and southwest (just under 20 %), with wind speeds over 10 m/s being dominantly south-westerly/ westerly, and lower velocity winds predominantly easterly/ south-easterly. The cities to the west of Irazu volcano (San José, Alajuela and Curriabat) and Juan Santamaría International Airport (Alajuela) are likely to be impacted by ash fall from volcanoes in the Cordillera Central. The expanse of agricultural land (largely mixed croplands) to the west of the Cordillera Central and Rincón de la Vieja in the northwest could be impacted by ash. Although not in a dominantly downwind direction, the area of dedicated cropland to the north west of Arenal may also be vulnerable to ash fall due to proximity to the volcano (approximately 10 km). Irazu is the most active volcano in Costa Rica (last erupted in 1994) and ashfall from the last major eruption in 1963-65 is reported to have caused significant disruption in the San José region. Future activity would likely affect the Juan Santamaría International Airport (Alajuela).

Frequency of Explosive Volcanism

Table 3.4 gives estimated return periods for different magnitude eruptions in the Central American region, which comprises Costa Rica, Panama, and Guatemala in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 3.8 Return periods for different magnitude eruptions in Costa Rica.

Magnitude	**Return Period (years)**
3	8.8
3.5	17
4	35
4.5	67
5	120
5.5	300
6	640
6.5	1,700
7	7,400
8	460,000

National Capacity for Coping with Volcanic Risk

Figure 3.5 depicts the numbers of Costa Rica's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

Six of the ten Holocene volcanoes in Costa Rica have been allocated a Monitoring Level of 2, as they are monitored at regular intervals by both a well-established institution and the local university, and they have permanent seismic networks; two-thirds of these volcanoes are Risk Level 3. One Risk Level 3 volcano has a Monitoring Level of 1 as it has no recorded seismic monitoring facilities. Two volcanoes have no recorded monitoring facilities and are Risk Level 2.

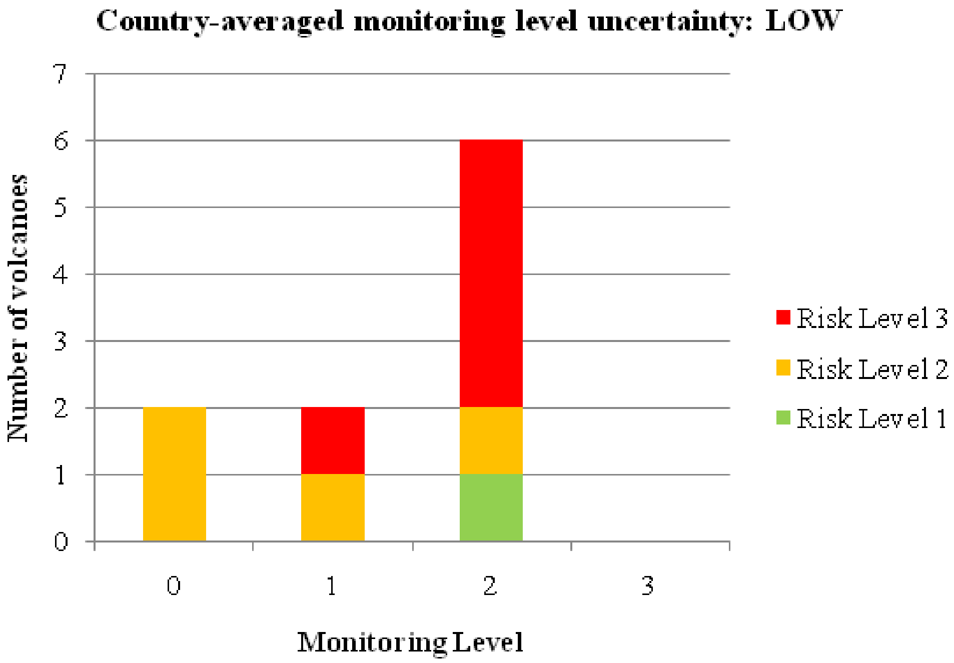


Figure 3.10: Distribution of Costa Rica's volcanoes across Monitoring and Risk Levels.

Summary

Costa Rica has several Risk Level 3 volcanoes, most of which are Monitoring Level 2 but not level 3. Barva has only Monitoring Level 1, but has both Hazard and Risk Levels of 3. There are several volcanoes with high Uncertainty Levels that likely reflect the lack of geological knowledge.

C4 Djibouti

Description

Only one Holocene volcano, Ardoukôba, is detailed in the Global Volcanism Program (GVP) database for Djibouti. The Ardoukôba Rift contains a broad area of youthful fissure vents, trends northwest from the Red Sea, and is exposed over a distance of 12 km.

One eruption is recorded in Ardoukôba's history; the VEI 1 event occurred in November 1978, producing lava flows with a volume of over 1.2 x 10^7 m^3. No damage or fatalities were recorded.

Location of Djibouti's Volcano and Key Cities

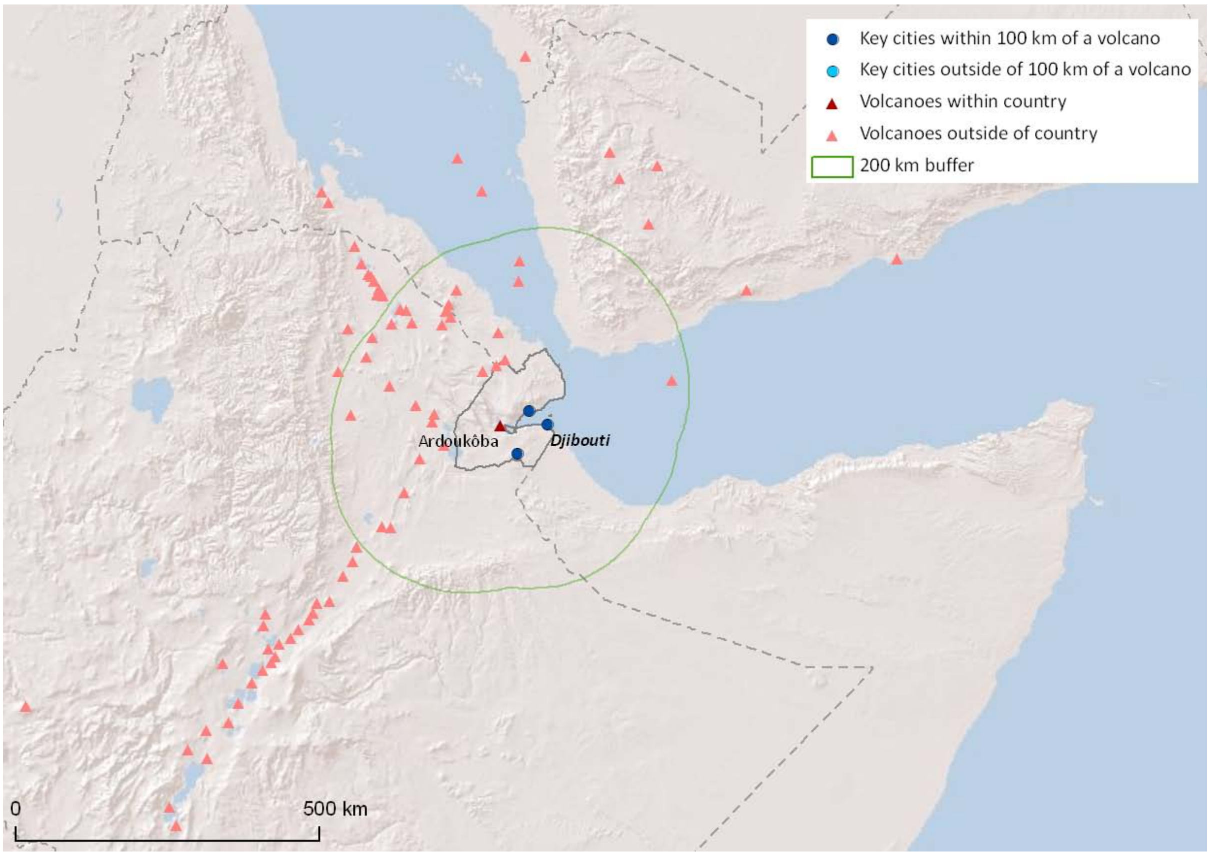


Figure 4.11: Locations of Djibouti's volcano, and three largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Djibouti.

Volcanic Facts

Number of Holocene volcanoes:	1
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	0 and 1 respectively
Number of volcanoes generating pyroclastic flows:	0
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	1
Number of fatalities caused by volcanic eruptions:	0

Socio-Economic Facts

Total population:	879,100
GDP per capita, 2008 PPP US$:	2,274
HDI:	0.402 – Low

Three largest cities, as measured by population (“Key Cities”), and populations:

- Djibouti (capital city)	Population:	623,891
- ‘Ali Sabieh	Population:	40,074
- Tadjoura	Population:	22,193

Distance from capital city to nearest volcano:	76 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	3 (100%)
Number (percentage) of people living within 10 km of a volcano:	2,300 (~ 0%)
Number (percentage) of people living within 30 km of a volcano:	22,000 (3%)
Number (percentage) of people living within 100 km of a volcano:	720,000 (100%)

Hazard and Uncertainty Assessments

The plot in Figure 4.2 shows classification of Djibouti’s volcano across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 4.1 lists the name of the volcano and the Hazard-Uncertainty class to which it is assigned.

Djiobuti’s volcano is classed as Level 1 for both hazard and uncertainty.

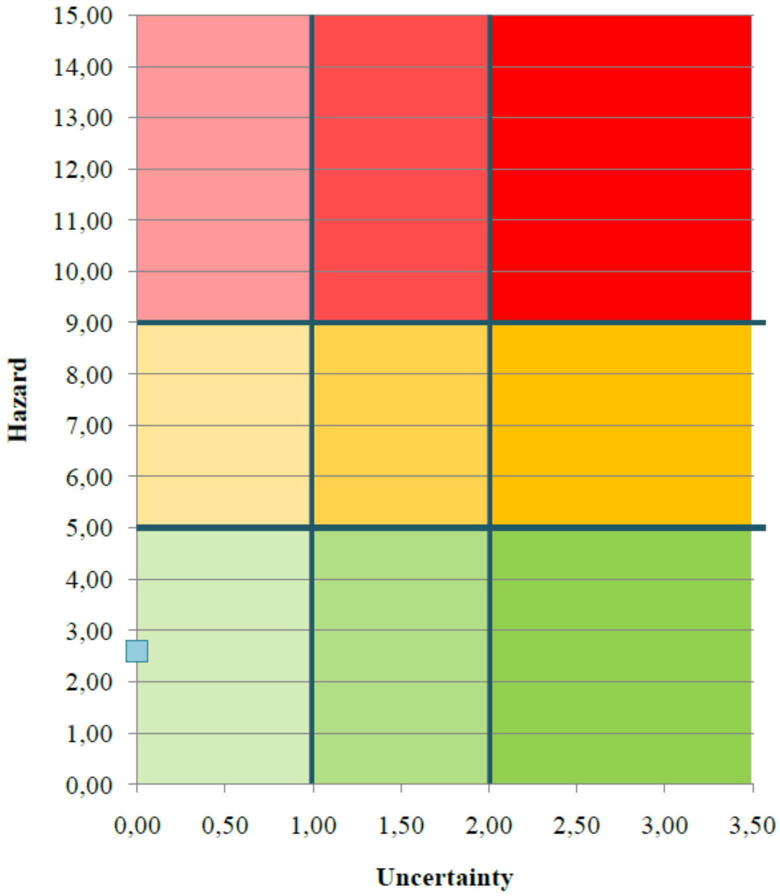


Figure 4.12: Distribution of Djibouti's volcano across Hazard and Uncertainty Levels.

Table 4.9 Identity of Djibouti's volcano in its Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1	Ardoukôba		
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 4.3 shows the classification of Djibouti’s volcano across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 4.2 lists the volcano name and its Hazard-PEI class.

Djibouti’s volcano has a low PEI Level, and is thus classed as Risk Level 1.

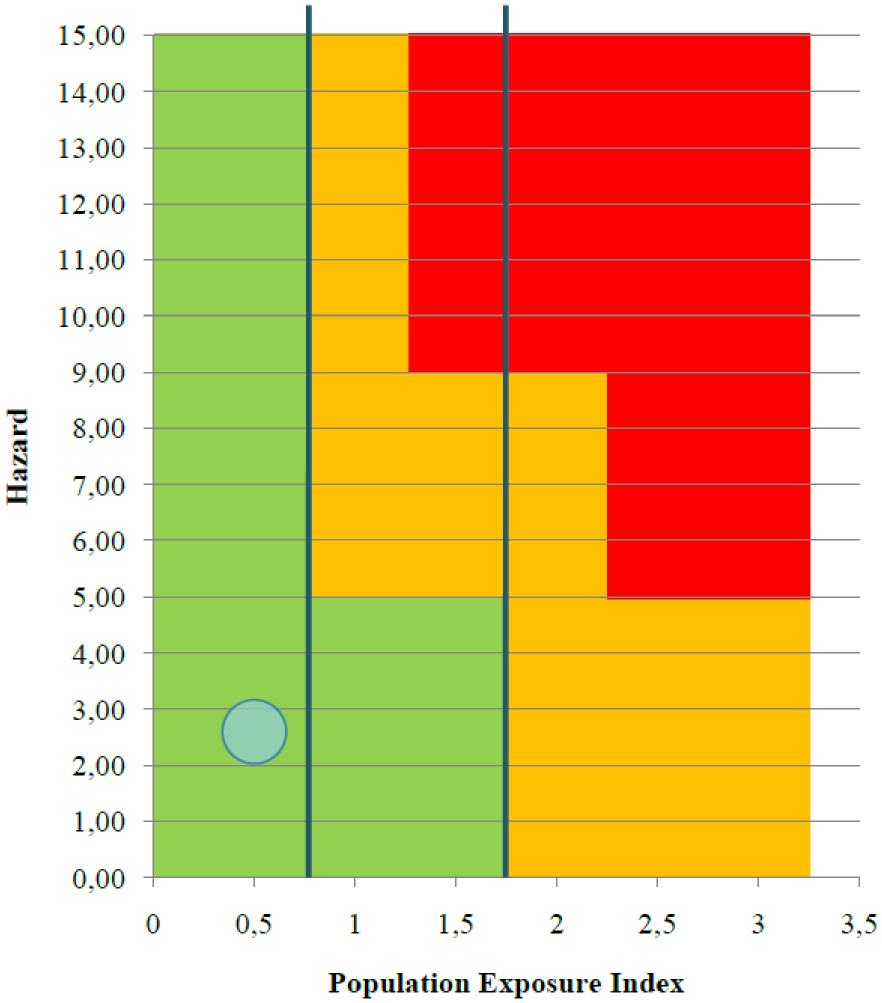


Figure 4.13: Distribution of Djibouti’s volcano across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 4.10 Identity of Djibouti's volcano in its Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1	Ardoukôba		
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Level of Djibouti's volcano, a measure that combines Hazard Level and PEI. The Uncertainty Level quoted is that ascribed during the hazard assessment, as in Table 4.1 and Figure 4.2.

Risk Level 1:

- Ardoukôba Uncertainty Level 1

Djibouti's volcano is Risk Level 1.

Hazard-specific exposure assessments

Table 4.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 4.11 Extent of infrastructure exposure to lahars and pyroclastic flows in Djibouti.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	0 0%	Number of cities: Percentage of total number of cities:	0 0%
Population	Number of people: Percentage of total number of people:	0 0%	Number of people: Percentage of total number of people:	5,800 1%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	0 0%	Length (km): Percentage of total length:	56 4%
Main Roads	Length (km): Percentage of total length:	0 0%	Length (km): Percentage of total length:	0 0%
All Railways	Length (km): Percentage of total length:	0 0%	Length (km): Percentage of total length:	21 1%
Airports	Number of airports: Percentage of all airports:	0 0%	Number of airports: Percentage of all airports:	0 0%

Figure 4.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Djibouti. Note that Djibouti's volcano itself is unlikely to pose any ash hazard, but those nearby in Ethiopia may.

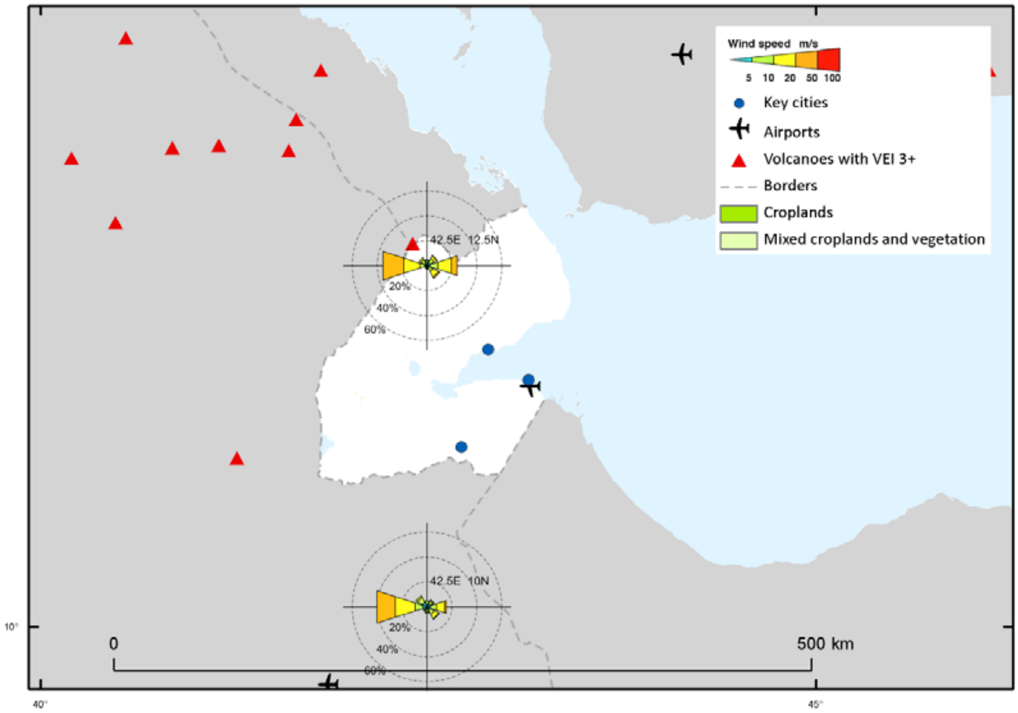


Figure 4.14: Map showing elements exposed to ash hazards in Djibouti, with wind roses indicating dominant wind directions and speeds.

Winds are predominantly easterly (36 - 40%), and as such could direct ash from the most proximal volcanoes in Ethiopia away from Djibouti. The stronger 20-50 m/s winds also dominate in this direction. Westerly winds occur approximately 15-25% of the time and could transport ash from Gabillema towards Ali Sabieh (160 km east), and potentially affect flights into Djibouti international airport (210 km east northeast). Winds from the northwest occur approximately 10% of the time, and could transport ash from Mousa Alli volcano in the direction of Tadjoura (90 km southeast) or Djibouti city (130 km southeast).

National Capacity for Coping with Volcanic Risk

The plot below depicts the Monitoring Level of Djibouti's volcano, with proficiency of monitoring increasing from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

The monitoring facilities around Ardoukôba are highly uncertain although there is a permanent (tectonic) seismic network in place, maintained by the L'Observatoire Géophysique d'Arta.

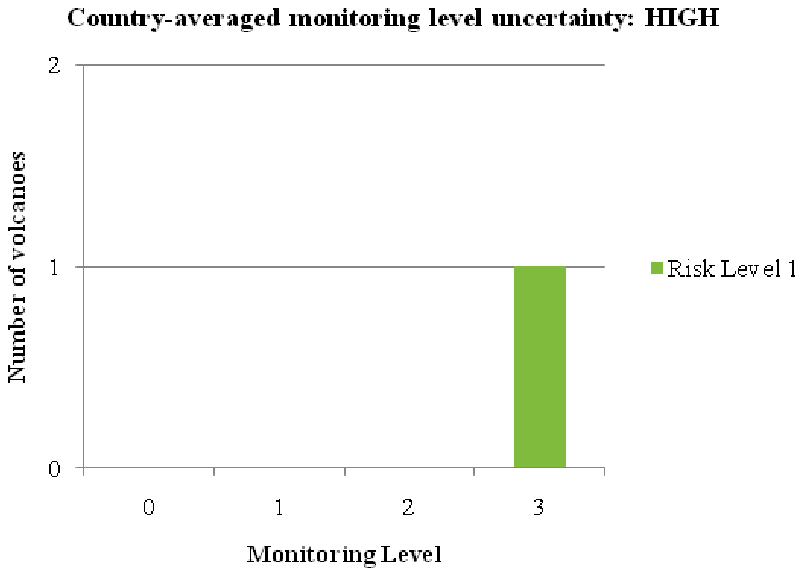


Figure 4.15: Distribution of Djibouti's volcano across Monitoring and Risk Levels.

Summary

Overall volcanic risk in Djibouti is low, with only one historically active volcano that is monitored as part of the country's regional seismic network. Although not explicit in the information above, it seems likely that there are more young volcanic centres in the rift system that goes through the country.

C5 Ecuador

Description

In total, the GVP database currently contains twenty Holocene volcanoes for Ecuador and thirteen for the Galapagos Islands. Subduction of the Nazca Plate beneath the continental South America Plate causes the line of volcanoes that extends along the west coast of South America, including Ecuador; the Galapagos Island volcanoes are a cluster of intra-plate hot spot centres thought to be related to a mantle plume.

Nineteen of the twenty volcanic features on mainland Ecuador are of normally-explosive type, namely compound volcanoes, stratovolcanoes, or calderas. Their propensity to cause hazardous flows is greatly increased by the presence of snow or ice caps on ten of the volcanoes, which raises the likelihood of lahars and floods; twelve of mainland Ecuador's volcanoes have triggered lahars. In terms of proximity to populated areas, Guagua Pichincha threatens Ecuador's capital, Quito. Rising immediately to the west of the city, Guagua Pichincha is one of Ecuador's most active volcanoes, having produced many minor eruptions since the beginning of the Spanish era. The volcano's potential impacts are highlighted by its largest eruption, which occurred in 1660. Ash fell over a 1000 km radius, accumulating to 30 cm depth in Quito, whilst pyroclastic flows travelled to the west (away from Quito) and caused great economic loss through damage to agricultural activity. Though Ecuador's largest population centre, Guayaquil, is about 145 km from its nearest volcano and thus unlikely to be affected by lava flows, lahars, or pyroclastic flows, ash fall from even distant eruptions, such as that of Guagua Pichincha outlined above, could have socio-economic impacts. Further, more rural communities proximate to Ecuador's volcanoes could be severely affected; fifteen of the mainland volcanoes have populations of over 100,000 residing within 30 km of their summits.

The Galapagos Island volcanoes are exclusively shield volcanoes. With a small population of just over 20,000, the main hazard they pose is largely environmental, as a result of lava flows and ash fall. One exception to this is Fernandina, which has erupted explosively on numerous occasions producing pyroclastic flows and debris avalanches. No fatalities are recorded as a result of eruptions of Fernandina.

Greatest loss of life as a result of volcanism in Ecuadorian territories occurred in 1640, following an eruption of Tungurahua. Though some uncertainty surrounds the eruption record, it is believed an approximately VEI 3 eruption caused pyroclastic flows that destroyed a village and its 5,000 inhabitants. Eruptions of Cotopaxi in 1742, 1768, and 1877 have also significantly added to the death toll from volcanoes in Ecuador, with roughly 1,200 deaths as a result of lahars attributable to these three eruptions.

Location of Ecuador’s Volcanoes and Key Cities

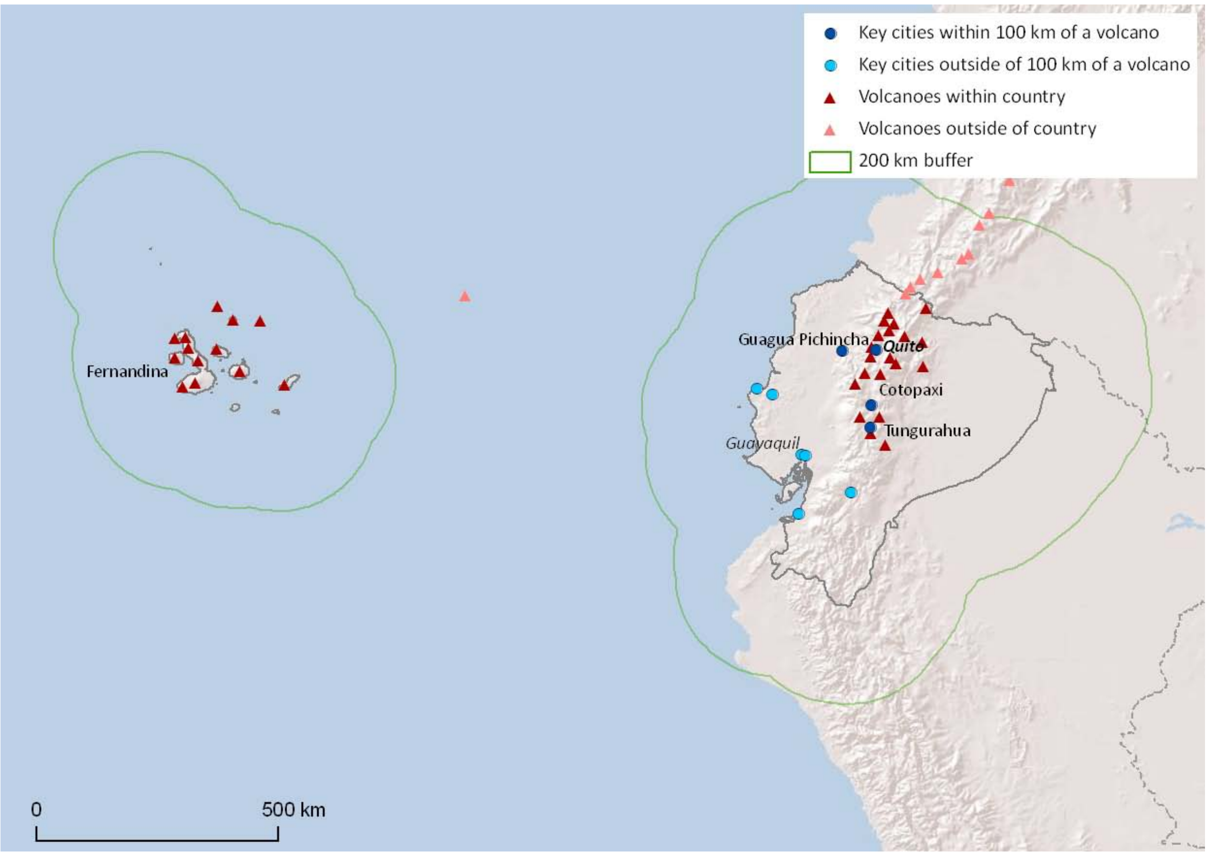


Figure 5.16: Locations of Ecuador's volcanoes and ten largest cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Ecuador.

Volcanic Facts

Number of Holocene volcanoes: 33
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes: 19 and 14 respectively
Number of volcanoes generating pyroclastic flows: 14
Number of volcanoes generating lahars: 9
Number of volcanoes generating lava flows: 21
Number of fatalities caused by volcanic eruptions: 6,761

Socio-Economic Facts

Total population: 13,774,900
GDP per capita, 2008 PPP US$: 8,170
HDI: 0.695 – High

Ten largest cities, as measured by population ("Key Cities"), and populations:

- Guayaquil	Population:	1,952,029
- Quito (capital city)	Population:	1,399,814
- Cuenca	Population:	276,964
- Santo Domingo de los Colorados	Population:	200,421
- Machala	Population:	198,123
- Manta	Population:	183,166
- Portoviejo	Population:	170,326
- Durán	Population :	167,784
- Ambato	Population :	154,369
- Riobamba	Population :	124,478

Distance from capital city to nearest volcano:	10 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	19 (40%)
Number (percentage) of people living within 10 km of a volcano:	590,000 (4%)
Number (percentage) of people living within 30 km of a volcano:	4,000,000 (27%)
Number (percentage) of people living within 100 km of a volcano:	6,800,000 (47%)

Hazard and Uncertainty Assessments

The plot in Figure 5.2 shows the classifications of Ecuador's thirty-three volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 5.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

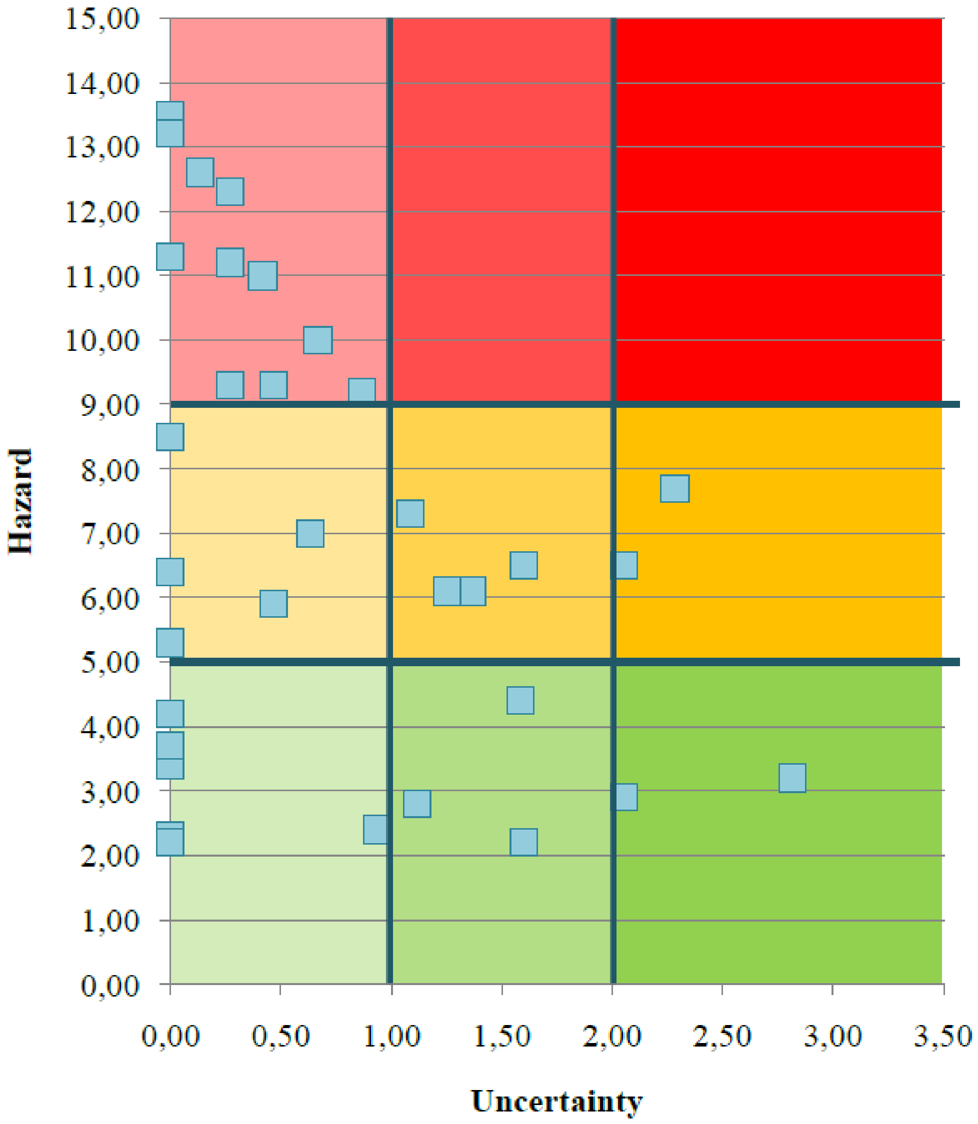


Figure 5.17: Distribution of Ecuador's volcanoes across Hazard and Uncertainty Levels.

Table 5.12 Identities of Ecuador's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Atacazo Cayambe Chimborazo Cotopaxi Cuicocha Fernandina Guagua Pichincha Quilotoa Reventador Sangay Tungurahua		
Hazard Level 2	Azul, Cerro Chacana Negra, Sierra Pululagua Soche	Antisana Chachimbiro Imbabura Sumaco	Illiniza Mojanda
Hazard Level 1	Alcedo Darwin Ecuador Marchena Santiago Wolf	Genovesa Pinta Santa Cruz	Licto San Cristóbal
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Ecuador's volcanoes are spread across the three Hazard and Uncertainty Levels, though all its Hazard Level 3 volcanoes have Uncertainty Level 1. Of note are Illiniza and Mojanda, which are Hazard Level 2, yet high uncertainty at Level 3.

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 5.3 shows the classifications of Ecuador's thirty-three volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 5.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Again, Ecuador's volcanoes are spread; PEI values from the lowest to highest possible are seen. Ecuador's Risk Level 3 volcanoes are all, except one, of Uncertainty Level 1. Some of Ecuador's highest hazard volcanoes, such as Fernandina and Reventador, are in fact Risk Level 1, as a result of low PEI. All the Galapagos Island volcanoes are classed as Risk Level 1, as well as 3 further volcanoes located on mainland Ecuador.

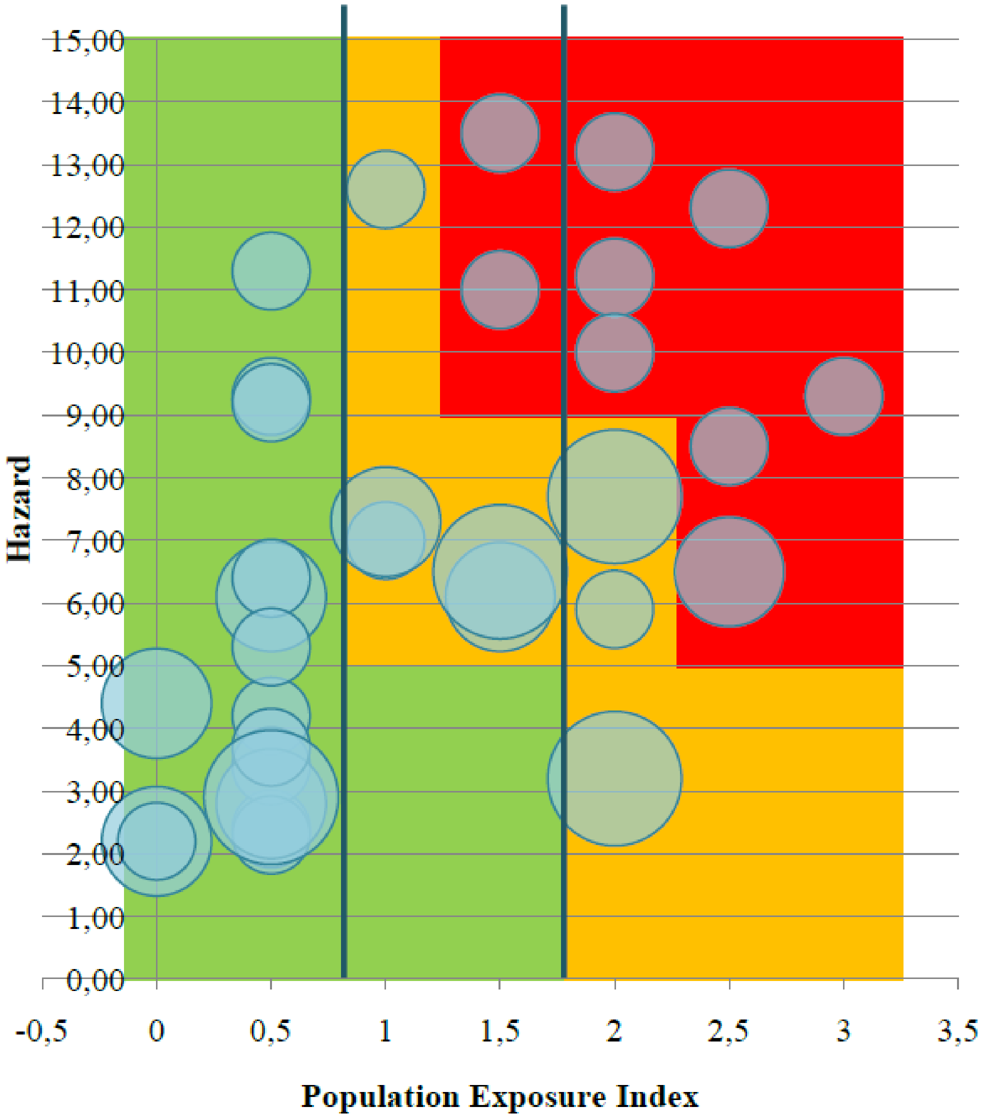


Figure 5.18: Distribution of Ecuador's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 5.2 Identities of Ecuador's volcanoes in each Hazard-PEI cohort.

Hazard Level 3	Fernandina Reventador Sangay	Cayambe Cotopaxi Quilotoa	Atacazo Chimborazo Cuicocha Guagua Pichincha Tungurahua
Hazard Level 2	Azul, Cerro Negra, Sierra Sumaco	Antisana Chachimbiro Illiniza Soche	Chacana Imbabura Mojanda Pululagua
Hazard Level 1	Alcedo Darwin Ecuador Genovesa Marchena Pinta San Cristóbal Santa Cruz Santiago Wolf		Licto
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Ecuador's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 5.1 and Figure 5.2.

Risk Level 3:

• Atacazo	Uncertainty Level 1
• Chimborazo	Uncertainty Level 1
• Cotopaxi	Uncertainty Level 1
• Cuicocha	Uncertainty Level 1
• Guagua Pichincha	Uncertainty Level 1
• Imbabura	Uncertainty Level 2
• Pululagua	Uncertainty Level 1
• Quilotoa	Uncertainty Level 1
• Tungurahua	Uncertainty Level 1

Risk Level 2:

Antisana	Uncertainty Level 2
Cayambe	Uncertainty Level 1
Chacana	Uncertainty Level 1
Chachimbiro	Uncertainty Level 2
Illiniza	Uncertainty Level 3
Licto	Uncertainty Level 3
Mojanda	Uncertainty Level 3
Soche	Uncertainty Level 1

Risk Level 1:

Alcedo	Uncertainty Level 1
Azul, Cerro	Uncertainty Level 1
Darwin	Uncertainty Level 1
Ecuador	Uncertainty Level 1
Fernandina	Uncertainty Level 1
Genovesa	Uncertainty Level 2
Marchena	Uncertainty Level 1
Negra, Sierra	Uncertainty Level 1
Pinta	Uncertainty Level 2
Reventador	Uncertainty Level 1
San Cristóbal	Uncertainty Level 3
Sangay	Uncertainty Level 1
Santa Cruz	Uncertainty Level 2
Santiago	Uncertainty Level 1
Sumaco	Uncertainty Level 2
Wolf	Uncertainty Level 1

Of Ecuador’s thirty-three volcanoes, nine are Risk Level 3, eight are Risk Level 2, and sixteen are Risk Level 1.

Hazard-specific exposure assessments

Table 5.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 5.13 Extent of infrastructure exposure to lahars and pyroclastic flows in Ecuador.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	15 31%	Number of cities: Percentage of total number of cities:	9 5%
Population	Number of people: Percentage of total number of people:	5,300,000 37%	Number of people: Percentage of total number of people:	3,300,000 23%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	3,100 29%	Length (km): Percentage of total length:	1,400 13%
Main Roads	Length (km): Percentage of total length:	3,000 36%	Length (km): Percentage of total length:	1,300 15%
All Railways	Length (km): Percentage of total length:	73 11%	Length (km): Percentage of total length:	150 23%
Airports	Number of airports: Percentage of all airports:	16 37%	Number of airports: Percentage of all airports:	5 12%

Figure 5.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Ecuador.

Winds on the mainland are predominately easterly (about 30%) and north-easterly (about 20%), therefore all major cities are in the dominant down-wind direction of at least one VEI3+ volcano. Particularly proximal cities include Quito, approximately10 km southeast of Guagua Pichincha, and in a primary downwind direction from a number of volcanoes including Reventador (100km) Cayambe (65 km) and Soche (135km); Riobamba, 30 km southwest of Tungurahua; and Santo Domingo de los Colorados, 60 km to the west of Guagua Pichincha. The agricultural lands in the northwest are also likely to be affected by ash fall from a major eruption.

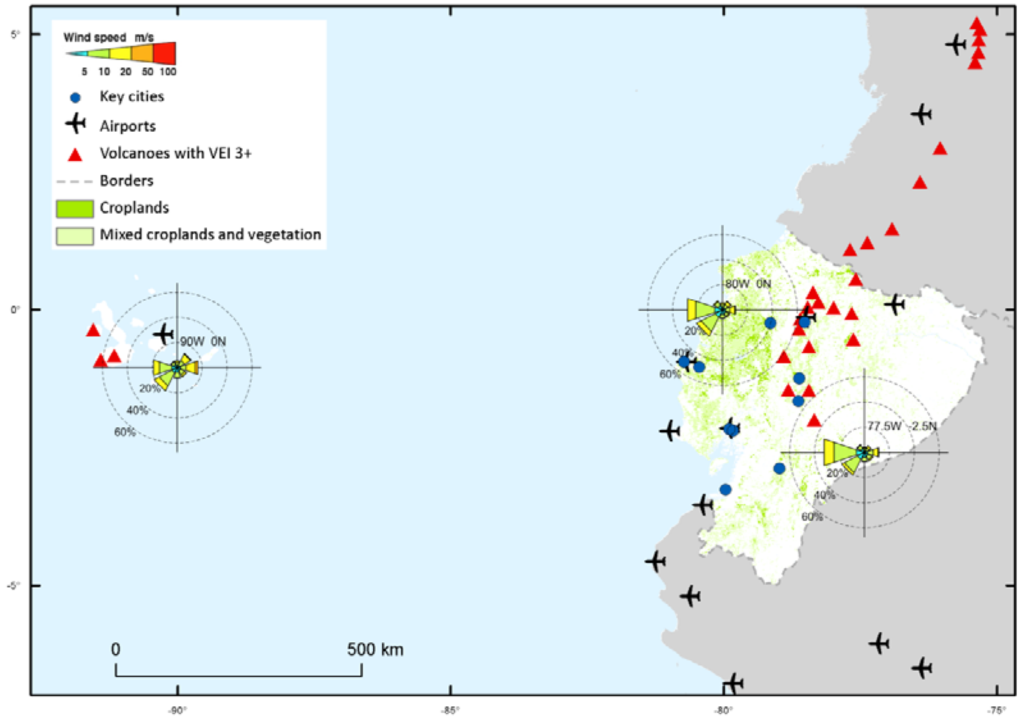


Figure 5.19: Map showing elements exposed to ash hazards in Ecuador, with wind roses indicating dominant wind directions and speeds.

On the Galapagos Islands, wind direction is more variable, although north-easterlies (20 - 21%) and easterlies (18 - 20%) dominate slightly. An eruption of Fernandina, Sierra Negra, or Cerro Azul is likely to affect the airports of Baltra and San Cristobal and would also have a significant impact on the islands' ecology.

Frequency of Explosive Volcanism

Table 5.4 gives the estimated return periods for different magnitude eruptions in the South American region, which comprises Ecuador and Colombia in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 5.14 Return periods for different magnitude eruptions in Ecuador.

Magnitude	**Return Period (years)**
3	0.58
3.5	1.1
4	2.3
4.5	4.4
5	8
5.5	20
6	42
6.5	110
7	490
8	30,000

National Capacity for Coping with Volcanic Risk

Figure 5.5 depicts the numbers of Ecuador's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

One main, established institute, Instituto Geofisico EPN, monitors twenty of the thirty-three Holocene volcanoes in Ecuador and the Galapagos Islands. Six of the nine volcanoes classified as Risk Level 3 are of Monitoring Level 2 or 3, meaning they have at least regular monitoring at monthly intervals and a seismic network within 15 km of each volcano. Ten volcanoes have a Monitoring Level 0, with no recorded regular monitoring or seismic networks, two of which are Risk Level 3.

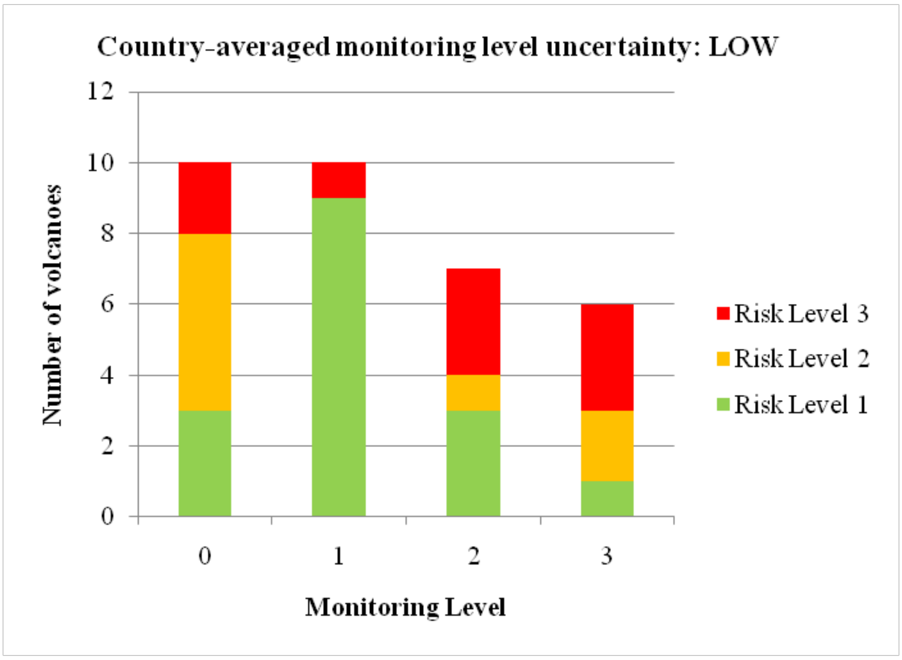


Figure 5.20: Distribution of Ecuador's volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk is significant in Ecuador, with large populations located in the environs of several high hazard volcanoes. Knowledge of many volcanoes is good, though this could be improved for several notable volcanoes with Uncertainty Levels 2 and 3. Correlation between Risk and Monitoring Levels in Ecuador could be of concern; eight Risk Level 2 and 3 volcanoes are poorly- or un-monitored, whilst four Risk Level 1 volcanoes are monitored far more comprehensively, at Level 2 or 3.

C6 Ethiopia

Description

Sixty-five Holocene volcanoes are listed in the GVP database for Ethiopia. They form two distinct lines of volcanoes which can be seen within the extensional East African rift. The first, a northeast trending line that bisects the middle of the country, stretches from the Korath Range in the southwest to the Djibouti border in the northeast, with a second line oriented north northwest nearer the border with Eritrea.

Compared to most other GFDRR priority countries, Ethiopia has a high ratio of effusive to explosive volcano types, with thirty-one of the former and thirty-four of the latter. The single most common edifice type, however, is the stratovolcano. Only seven of Ethiopia's volcanoes have produced pyroclastic flows and none have triggered lahars. Lava flows are common, occurring at fifty-six of the sixty-five volcanoes. The great prevalence of lava flows compared to other hazardous flows in Ethiopia reduces the relative hazard extent and impacts. Further, seven of the country's ten most populous cities are more than 30 km from their nearest volcano; Ethiopia's numerous rural communities, however, mean twenty-five volcanoes have over 100,000 people living with a 30 km radius of their summit.

The distance of the country's main population centres from volcanoes and frequency of lava flows compared to other hazardous flows is reflected in the historic fatalities record; just three eruptions have caused loss of life, with a combined total of 163 casualties. The most devastating of these three eruptions, responsible for nearly a third of Ethiopia's fatalities, occurred at Dubbi in 1861. The eruption's initial explosive phase destroyed two villages and large herds of cattle; the exact cause of the 106 fatalities is unclear but may have been pyroclastic flows.

The volcanic record is particularly poor in Ethiopia. Africa as a region has the highest percentage of volcanoes that are undated but known to be Holocene, and there is no explicit eruptive history for forty-nine of Ethiopia's sixty-five volcanoes. As such, underreporting may downplay the level of hazard posed both in the past and at present.

Location of Ethiopia’s Volcanoes and Key Cities

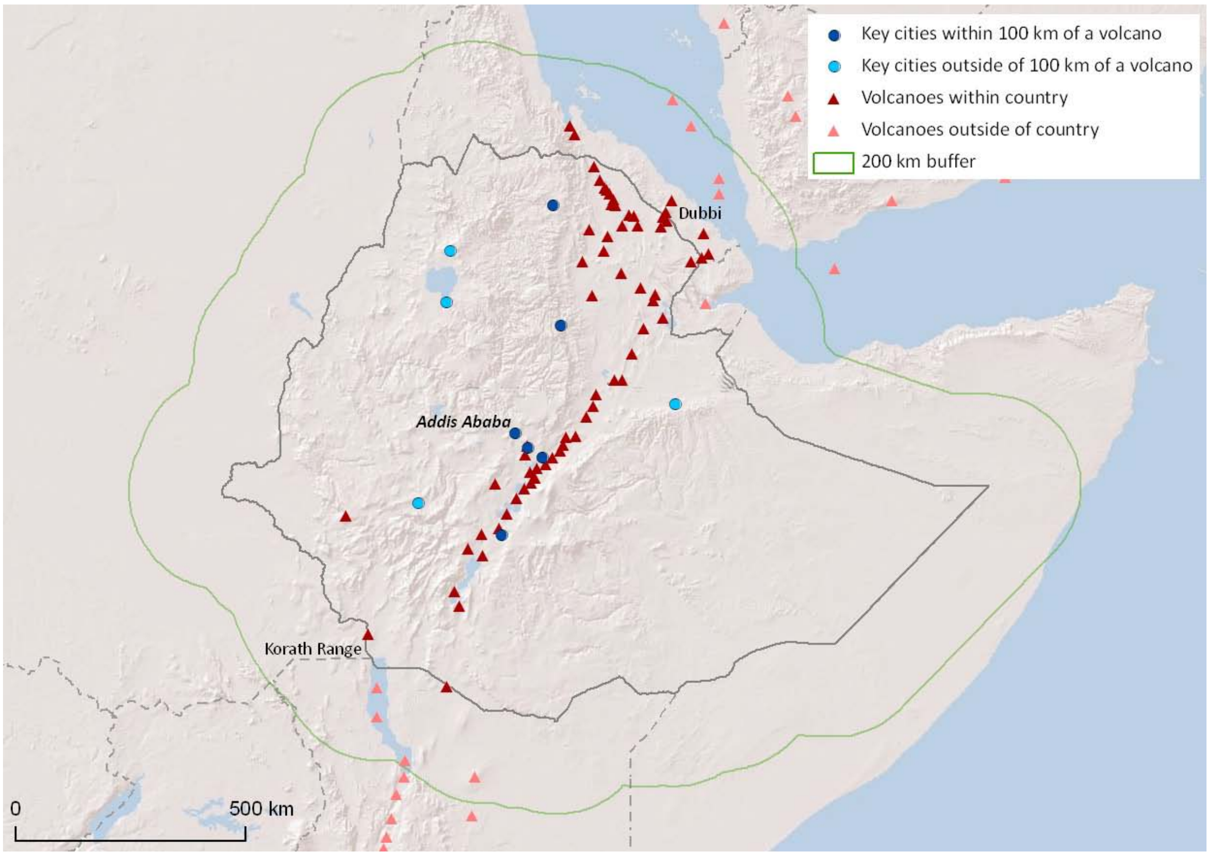


Figure 6.21: Locations of Ethiopia's volcanoes and ten largest cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Ethiopia.

Volcanic Facts

Number of Holocene volcanoes:	65
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	34 and 31 respectively
Number of volcanoes generating pyroclastic flows:	7
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	16
Number of fatalities caused by volcanic eruptions:	156

Socio-Economic Facts

Total population:	84,975,600
GDP per capita, 2008 PPP US$:	991
HDI:	0.328 – Low

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Addis Ababa (capital city)	Population:	2,757,729
- Dirē Dawa	Population:	252,279
- Mek’elē	Population:	215,546
- Nazrēt	Population:	213,995
- Bahir Dar	Population:	168,899
- Gonder	Population:	153,914
- Desē	Population:	136,056
- Āwasa	Population :	133,097
- Jīma	Population :	128,306
- Debre Zeyit	Population :	104,215

Distance from capital city to nearest volcano: 37 km

Number (percentage) of cities (population over 20,000) within 100 km of a volcano: 33 (52%)

Number (percentage) of people living within 10 km of a volcano: 1,300,000 (2%)

Number (percentage) of people living within 30 km of a volcano: 9,500,000 (11%)

Number (percentage) of people living within 100 km of a volcano: 40,000,000 (47%)

Hazard and Uncertainty Assessments

The plot in Figure 6.2 shows the classifications of Ethiopia’s sixty-five volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 6.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Ethiopia’s volcanoes are all of Hazard Level 1 or 2; only five are classed as Uncertainty Level 1. Unlike many other GFDRR priority countries, there seems some positive correlation between hazard and uncertainty; of the Hazard Level 2 volcanoes, twenty-one are Uncertainty Level 3 compared to only seven of Uncertainty Level 2.

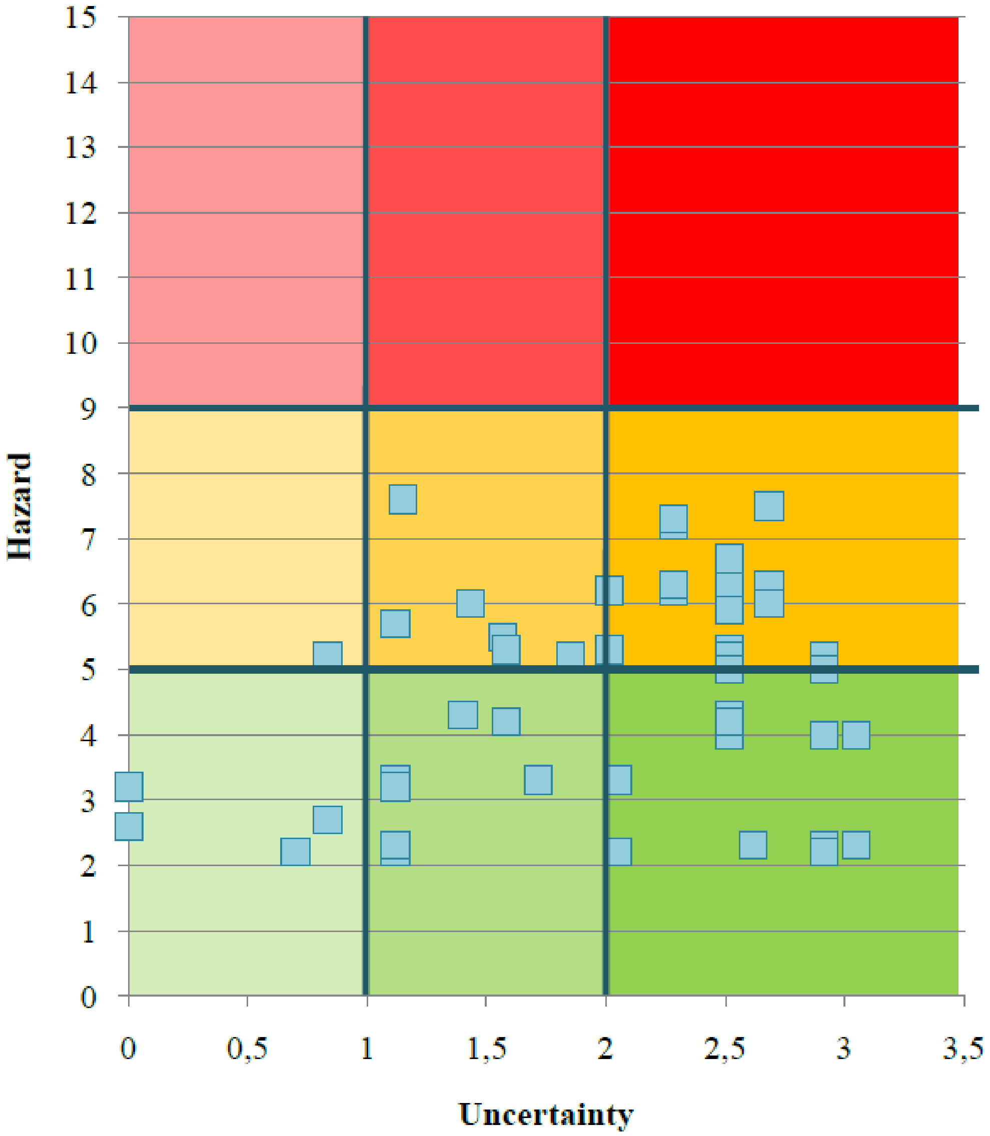


Figure 6.22: Distribution of Ethiopia's volcanoes across Hazard and Uncertainty Levels.

Table 6.15 Identities of Ethiopia's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2	Dalaffilla	Adwa Ayelu Butajiri-Silti Field Dabbahu Dallol Dubbi Mega Basalt Field	Afderà Alid Alutu Asavyo Bilate River Field Bishoftu Volcanic Field Borawli (0201-121) Boset-Bericha Corbetti Caldera Dofen Gabillema Gada Ale Gedamsa Hobicha Caldera Kone Liado Hayk Ma Alalta Mallahle Mousa Alli Nabro O’a Caldera
Hazard Level 1	Alayta Erta Ale Manda Hararo Manda-Inakir	Assab Volcanic Field Beru East Zway Fentale Gufa Sodore Tepi Tosa Sucha Tullu Moje Unnamed (0201-201) Unnamed (0201-221) Unnamed (0201-251) Unnamed (0201-311)	Ale Bagu Alu Bora-Bericcio Borale Ale Borawli (0201-107) Chiracha Dabbayra Dama Ali Groppo Hayli Gubbi Hertali Jalua Korath Range Kurub Manda Gargori Mat Ala Sork Ale Tat Ali Yangudi
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 6.3 shows the classifications of Ethiopia's sixty-five volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 6.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Ethiopia's volcanoes cover almost all PEI values. As such, despite the fact that none are Hazard Level 3, five are identified as Risk Level 3.

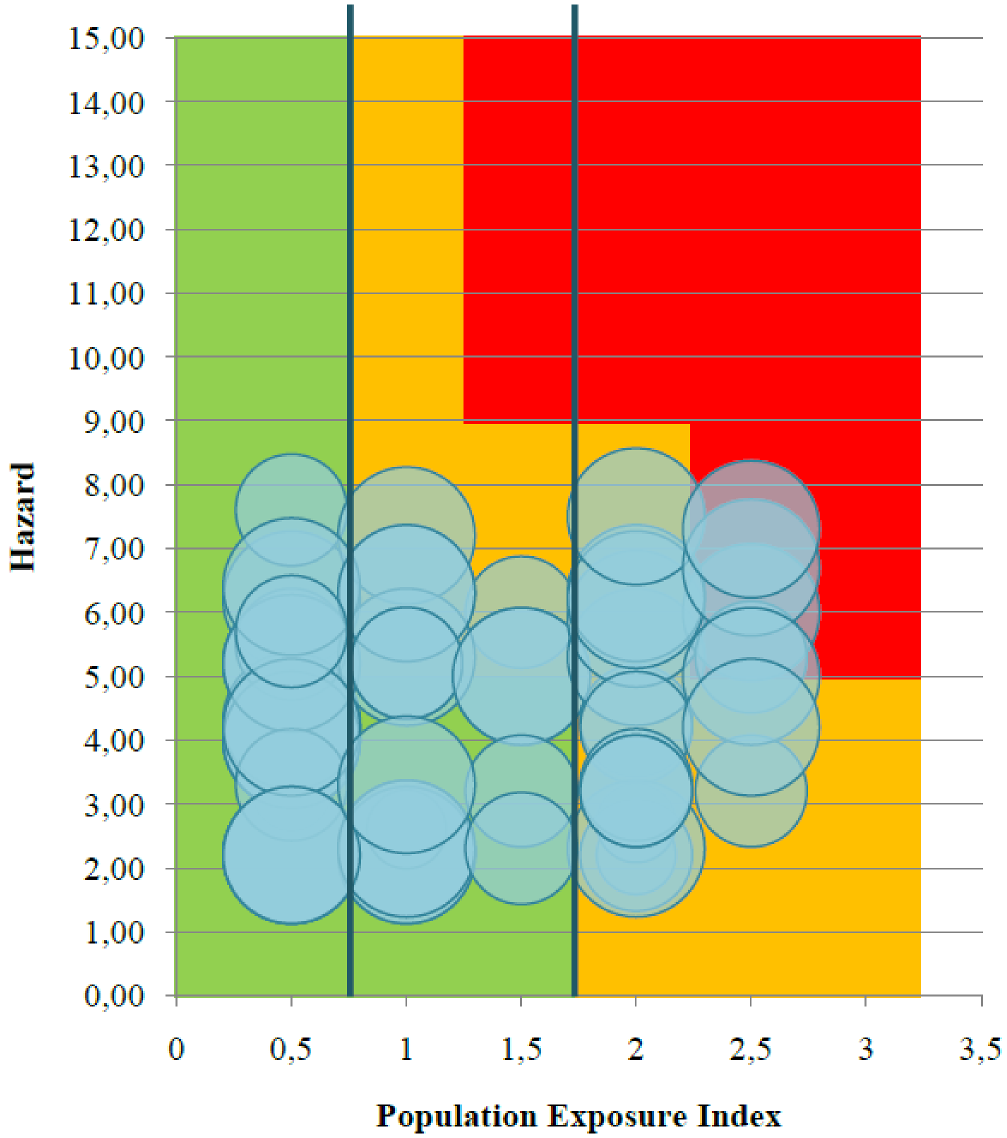


Figure 6.23: Distribution of Ethiopia's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 6.16: Identities of Ethiopia's volcanoes in each Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2	Alid Asavyo Dabbahu Dalaffilla Dubbi Gabillema Mallahle Mega Basalt Field Mousa Alli Nabro	Adwa Afderà Ayelu Borawli (0201-121) Dallol Dofen Gada Ale Liado Hayk Ma Alalta	Alutu Bilate River Field Bishoftu Volcanic Field Boset-Bericha Butajiri-Silti Field Corbetti Caldera Gedamsa Hobicha Caldera Kone O'a Caldera
Hazard Level 1	Ale Bagu Alu Assab Volcanic Field Borale Ale Borawli (0201-107) Erta Ale Groppo Gufa Hertali Jalua Kurub Mat Ala Sork Ale Tat Ali Yangudi	Beru Dabbayra Dama Ali Hayli Gubbi Korath Range Manda Gargori Manda Hararo Tepi	Alayta Bora-Bericcio Chiracha East Zway Fentale Manda-Inakir Sodore Tosa Sucha Tullu Moje Unnamed (0201-201) Unnamed (0201-221) Unnamed (0201-251) Unnamed (0201-311)
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Ethiopia's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 6.1 and Figure 6.2.

Risk Level 3:

• Bilate River Field	Uncertainty Level 3
• Bishoftu Volcanic Field	Uncertainty Level 3
• Butajiri-Silti Field	Uncertainty Level 2
• Corbetti Caldera	Uncertainty Level 3
• Hobicha Caldera	Uncertainty Level 3

Risk Level 2:

Adwa	Uncertainty Level 2
Afderà	Uncertainty Level 3
Alayta	Uncertainty Level 1
Alutu	Uncertainty Level 3
Ayelu	Uncertainty Level 2
Bora-Bericcio	Uncertainty Level 3
Borawli (0201-121)	Uncertainty Level 3
Boset-Bericha	Uncertainty Level 3
Chiracha	Uncertainty Level 3
Dallol	Uncertainty Level 2
Dofen	Uncertainty Level 3
East Zway	Uncertainty Level 2
Fentale	Uncertainty Level 2
Gada Ale	Uncertainty Level 3
Gedamsa	Uncertainty Level 3
Kone	Uncertainty Level 3
Liado Hayk	Uncertainty Level 3
Ma Alalta	Uncertainty Level 3
Manda-Inakir	Uncertainty Level 1
O’a Caldera	Uncertainty Level 3
Sodore	Uncertainty Level 2
Tosa Sucha	Uncertainty Level 2
Tullu Moje	Uncertainty Level 2
Unnamed (0201-201)	Uncertainty Level 2
Unnamed (0201-221)	Uncertainty Level 2
Unnamed (0201-251)	Uncertainty Level 2
Unnamed (0201-311)	Uncertainty Level 2

Risk Level 1:

Ale Bagu	Uncertainty Level 3
Alid	Uncertainty Level 3
Alu	Uncertainty Level 3
Asavyo	Uncertainty Level 3
Assab Volcanic Field	Uncertainty Level 2
Beru	Uncertainty Level 2
Borale Ale	Uncertainty Level 3
Borawli (0201-107)	Uncertainty Level 3
Dabbahu	Uncertainty Level 2

Dabbayra	Uncertainty Level 3
Dalaffilla	Uncertainty Level 1
Dama Ali	Uncertainty Level 3
Dubbi	Uncertainty Level 2
Erta Ale	Uncertainty Level 1
Gabillema	Uncertainty Level 3
Groppo	Uncertainty Level 3
Gufa	Uncertainty Level 2
Hayli Gubbi	Uncertainty Level 3
Hertali	Uncertainty Level 3
Jalua	Uncertainty Level 3
Korath Range	Uncertainty Level 3
Kurub	Uncertainty Level 3
Mallahle	Uncertainty Level 3
Manda Gargori	Uncertainty Level 3
Manda Hararo	Uncertainty Level 1
Mat Ala	Uncertainty Level 3
Mega Basalt Field	Uncertainty Level 2
Mousa Alli	Uncertainty Level 3
Nabro	Uncertainty Level 3
Sork Ale	Uncertainty Level 3
Tat Ali	Uncertainty Level 3
Tepi	Uncertainty Level 2
Yangudi	Uncertainty Level 3

Of Ethiopia’s sixty-five volcanoes, five are Risk Level 3, twenty-seven are Risk Level 2, and thirty-three are Risk Level 1.

Hazard-specific exposure assessments

Table 6.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both kinds of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 6.17 Extent of infrastructure exposure to lahars and pyroclastic flows in Ethiopia.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	9 14%	Number of cities: Percentage of total number of cities:	7 11%
Population	Number of people: Percentage of total number of people:	9,900,000 12%	Number of people: Percentage of total number of people:	3,700,000 4%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	2,000 4%	Length (km): Percentage of total length:	2,100 5%
Main Roads	Length (km): Percentage of total length:	1,100 12%	Length (km): Percentage of total length:	500 5%
All Railways	Length (km): Percentage of total length:	73 11%	Length (km): Percentage of total length:	150 23%
Airports	Number of airports: Percentage of all airports:	3 33%	Number of airports: Percentage of all airports:	0 0%

Figure 6.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Ethiopia.

In the north of the country, easterly (approximately 36%) and westerly (approximately 26%) winds dominate, and Mek'ele is the most proximal and vulnerable city (120 km west southwest of Dalaffilla volcano). The dominant winds in the south and central regions are easterly (about 40-47%) making the city of Nazret (and potentially Debre Zeyit and Addis Ababa), and the agricultural lands to the west of the Main Ethiopian Rift particularly vulnerable to ash impacts. Nazret is approximately 20km west of Boset-Bericha volcano. Ethiopia’s primary international airport is located in Addis Ababa, approximately 90 km northwest of Boset-Bericha and Gedamsa volcanoes (with winds in this direction about 10 % of the time) and 160 km west southwest of Dofen in roughly the dominant downwind direction. Dire Dawa Airport could be affected by ashfall from Dofen, approximately 190 km to the west (winds in this direction about 16% of the time).

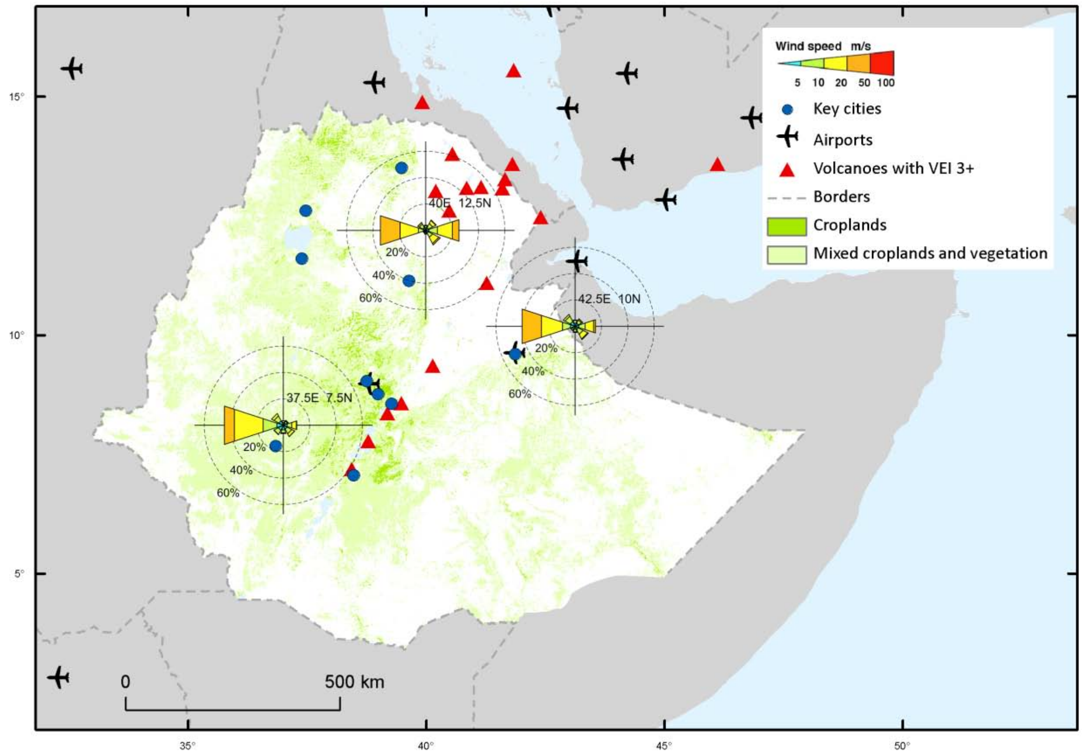


Figure 6.24: Map showing elements exposed to ash hazards in Ethiopia, with wind roses indicating dominant wind directions and speeds.

<u>Frequency of Explosive Volcanism</u>

Table 6.4 gives estimated return periods for different magnitude eruptions in the African region, which comprises Ethiopia and Yemen in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 6.18 Return periods for different magnitude eruptions in Ethiopia.

Magnitude	Return Period (years)
3	7.3
3.5	14
4	29
4.5	55
5	100
5.5	250
6	530
6.5	1,400
7	6,200
8	380,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Ethiopia's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

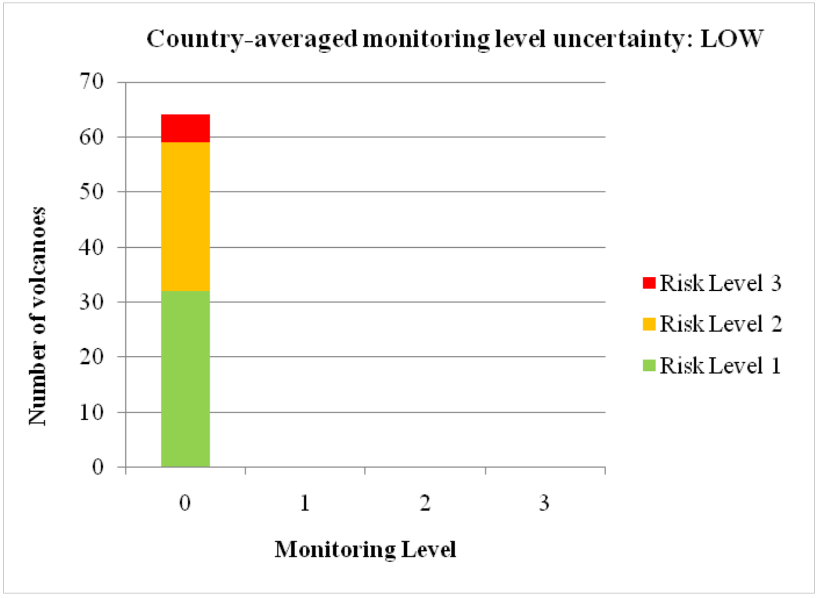


Figure 6.25: Distribution of Ethiopia's volcanoes across Monitoring and Risk Levels.

None of the sixty-five Holocene volcanoes in Ethiopia are currently monitored due to a lack of resources, and there are no known seismic networks within 15 km of any volcano. There are, however, six permanent (tectonic) seismic centres elsewhere in Ethiopia and approximately four of the sixty-three volcanoes are within about 40 km of one of these stations.

Summary

A large number of people live around some of Ethiopia's volcanoes. Although none of the sixty-five volcanoes are classified as Hazard Level 3, there is large uncertainty surrounding many of them, reflecting poor baseline geological and historic knowledge. It seems likely that several volcanoes have potential to move to Hazard Level 3 when more is known about them. Lack of a dedicated volcanic monitoring system means all of Ethiopia's volcanoes are at the lowest Monitoring Level. The volcanic risk in Ethiopia is very likely high and raising the baseline knowledge of volcanism and volcanic hazard is imperative.

C7 Guatemala

Description

The GVP database presently contains twenty-two Holocene volcanoes for Guatemala. Most are located parallel to the county's Pacific coastline, forming part of the eastern boundary of the Pacific "Ring of Fire". Guatemala's volcanoes lie in a southeast to northwest trending line, caused by the subduction of the Cocos Plate beneath the Caribbean Plate.

Fifteen of the twenty-two volcanoes in Guatemala, all located along the main volcanic belt, are classified as stratovolcanoes; five less-hazardous volcanic fields and cinder cones are situated nearer the Guatemala-El Salvador border. Three large stratovolcanoes, Acatenango, Agua, and Fuego, overlook Guatemala's former capital, Antigua Guatemala, whilst Pacaya is situated 30 km south of the present capital, Guatemala City. Further, Guatemala's second city and sixth largest population centre, Quetzaltenango, is situated approximately 10 km north-northeast of Santa María. Guatemala's volcanoes also threaten rural communities, as all have over 100,000 residents within 30 km of their summits.

Guatemala's largest volcanic disaster followed the 1902 eruption of Santa María, when a Plinian VEI 6 eruption caused approximately 10,000 deaths as a result of ash fall and secondary disease. Fuego and Pacaya are also responsible for fatalities and other socio-economic and environmental impacts. The most dramatic eruption of Fuego occurred in October 1974, generating pyroclastic flows that devastated land surrounding valleys on the east, southeast, southwest and west flanks of the volcano, and creating an ash plume that reached the stratosphere. Eruptions from Pacaya have caused lava flows in most directions that have destroyed farmland, as well as more recent Strombolian eruptions responsible for the closure of the country's main international airport, as well as building damage in villages proximal to the volcano due to bombs and ejecta. Activity at Pacaya in May 2010 is an example of such a Strombolian eruption; roughly 1,600 people were evacuated and those that remained were advised to clean off ash from their roofs. Aurora International Airport was closed.

Location of Guatemala's Volcanoes and Key Cities

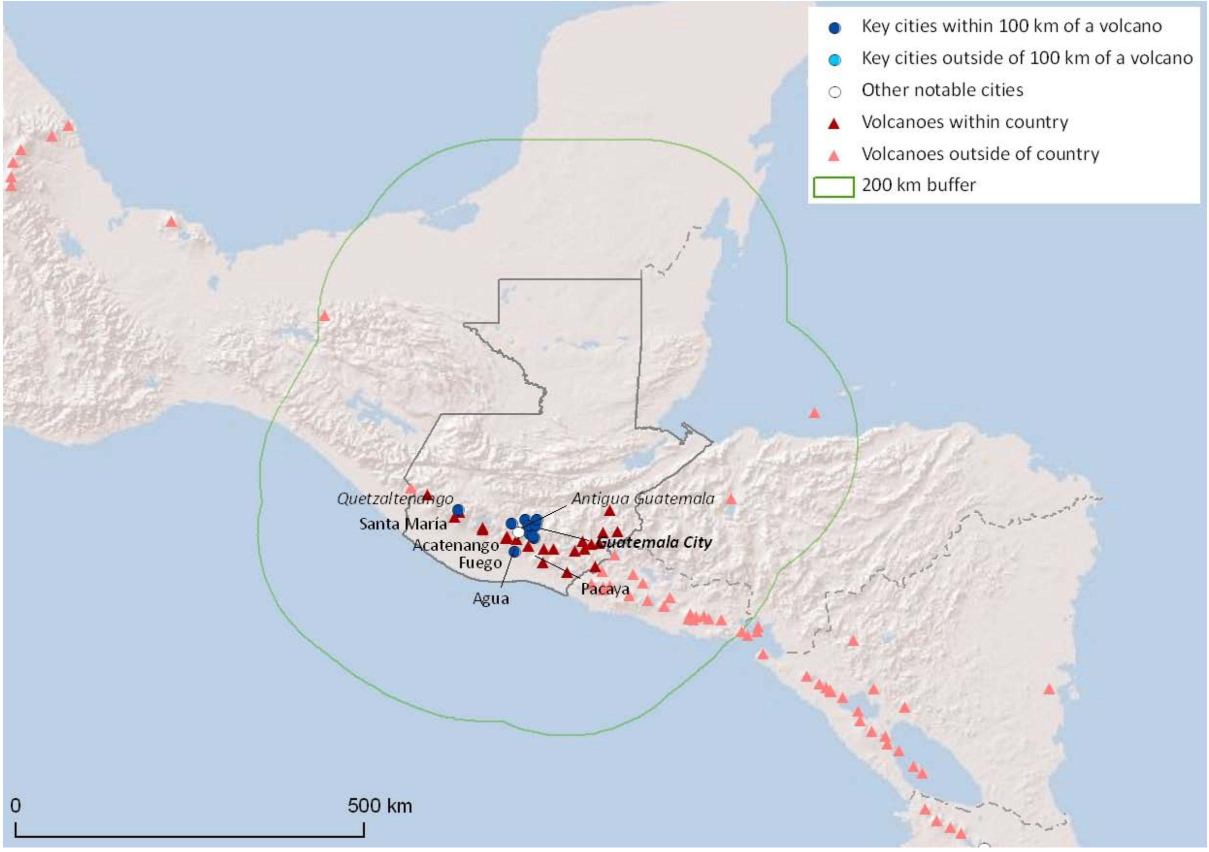


Figure 7.26: Locations of Guatemala's volcanoes, ten largest cities, and other notable cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Guatemala.

Volcanic Facts

Number of Holocene volcanoes:	22
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	17 and 5 respectively
Number of volcanoes generating pyroclastic flows:	5
Number of volcanoes generating lahars:	4
Number of volcanoes generating lava flows:	17
Number of fatalities caused by volcanic eruptions:	10,252

Socio-Economic Facts

Total population:	14,376,900
GDP per capita, 2008 PPP US$:	4,761
HDI:	0.560 – Medium

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Guatemala City (capital city)	Population:	994,938
- Mixco	Population:	473,080
- Villa Nueva	Population:	406,830
- Petapa	Population:	141,455
- San Juan Sacatepéquez	Population:	136,886
- Quetzaltenango	Population:	132,230
- Villa Canales	Population:	122,194
- Escuintla	Population :	103,165
- Chinautla	Population :	97,172
- Chimaltenango	Population :	82,370

Distance from capital city to nearest volcano:	30 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	51 (93%)
Number (percentage) of people living within 10 km of a volcano:	1,300,000 (10%)
Number (percentage) of people living within 30 km of a volcano:	7,300,000 (55%)
Number (percentage) of people living within 100 km of a volcano:	12,000,000 (90%)

Hazard and Uncertainty Assessments

The plot in Figure 7.2 shows the classifications of Guatemala’s twenty-two volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 7.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Guatemala’s volcanoes are predominantly of Hazard Levels 1 and 2, and Uncertainty Levels 2 and 3.

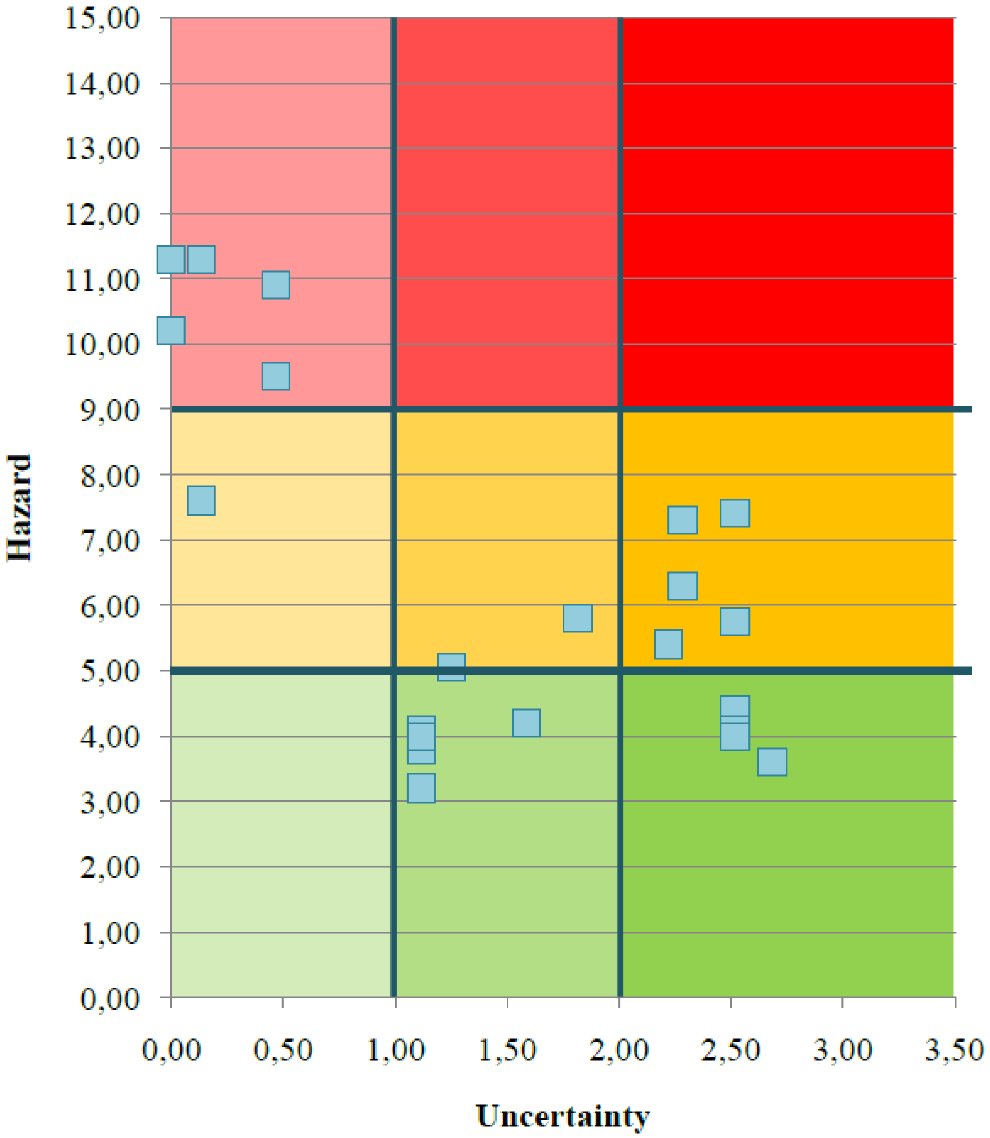


Figure 7.27: Distribution of Guatemala'a volcanoes across Hazard and Uncertainty Levels.

Table 7.19 Identities of Guatemala's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Almolonga Atitlán Fuego Pacaya Santa María		
Hazard Level 2	Acatenango	Cuilapa-Barbarena Tecuamburro	Chingo Ipala Ixtepeque Suchitàn Tahual
Hazard Level 1		Chiquimula Volcanic Field Moyuta Quezaltepeque Santiago, Cerro Tajumulco	Agua Flores Jumaytepeque Tolimán
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 7.3 shows the classifications of Guatemala's twenty-two volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 7.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

All of Guatemala's volcanoes are PEI Level 3, and are subsequently, in spite of the Level 1 Hazard of nine of the volcanoes, of Risk Level 2 or above. Six of the eight Risk Level 3 volcanoes have Uncertainty Level 1.

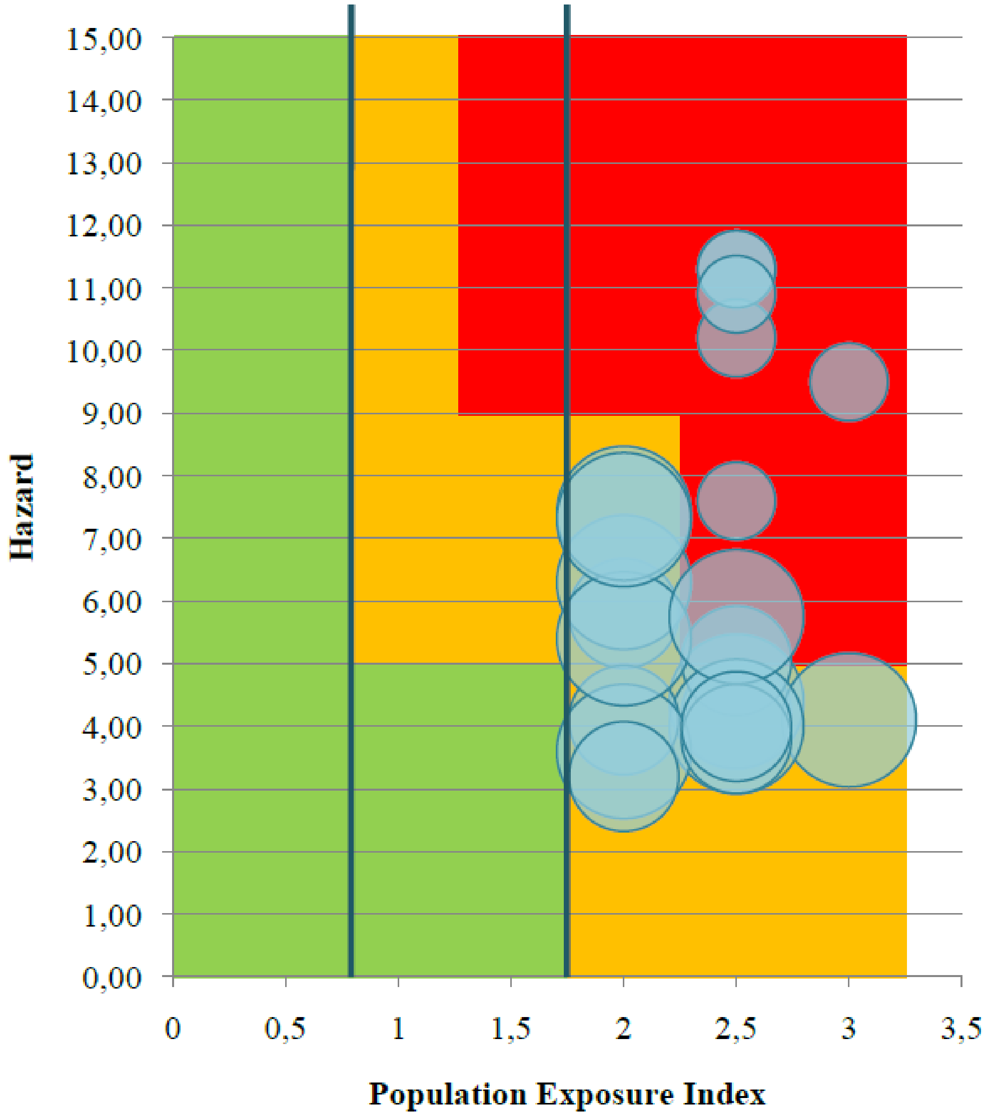


Figure 7.28: Distribution of Guatemala's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 7.20 Identities of Guatemala's volcanoes in each Hazard-PEI cohort.

Hazard Level 3			Almolonga Atitlán Fuego Pacaya Santa María
Hazard Level 2			Acatenango Chingo Cuilapa-Barbarena Ipala Ixtepeque Suchitàn Tahual Tecuamburro
Hazard Level 1			Agua Chiquimula Volcanic Field Flores Jumaytepeque Moyuta Quezaltepeque Santiago, Cerro Tajumulco Tolimán
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Guatemala’s volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 7.1 and Figure 7.2.

Risk Level 3:

• Acatenango	Uncertainty Level 1
• Almolonga	Uncertainty Level 1
• Atitlán	Uncertainty Level 1
• Chingo	Uncertainty Level 3
• Cuilapa-Barbarena	Uncertainty Level 2
• Fuego	Uncertainty Level 1
• Pacaya	Uncertainty Level 1
• Santa María	Uncertainty Level 1

Risk Level 2:

Agua	Uncertainty Level 3
Chiquimula Volcanic Field	Uncertainty Level 2
Flores	Uncertainty Level 3
Ipala	Uncertainty Level 3
Ixtepeque	Uncertainty Level 3
Jumaytepeque	Uncertainty Level 3
Moyuta	Uncertainty Level 2
Quezaltepeque	Uncertainty Level 2
Santiago, Cerro	Uncertainty Level 2
Suchitán	Uncertainty Level 3
Tahual	Uncertainty Level 3
Tajumulco	Uncertainty Level 2
Tecuamburro	Uncertainty Level 2
Tolimán	Uncertainty Level 3

Of Guatemala’s twenty-two volcanoes, eight are Risk Level 3, and fourteen are Risk Level 2.

Hazard-specific exposure assessments

Table 7.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 7.21 Extent of infrastructure exposure to lahars and pyroclastic flows in Guatemala.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	41 75%	Number of cities: Percentage of total number of cities:	25 45%
Population	Number of people: Percentage of total number of people:	8,600,000 64%	Number of people: Percentage of total number of people:	3,600,000 27%
Ports	Number of ports: Percentage of total number of ports:	1 33%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	4,900 50%	Length (km): Percentage of total length:	2,300 23%
Main Roads	Length (km): Percentage of total length:	2,600 52%	Length (km): Percentage of total length:	1,500 30%
All Railways	Length (km): Percentage of total length:	640 75%	Length (km): Percentage of total length:	250 29%
Airports	Number of airports: Percentage of all airports:	2 22%	Number of airports: Percentage of all airports:	0 0%

Figure 7.4 shows agriculture and infrastructure elements exposed to ash hazards, and a wind rose indicating prevalent conditions for Guatemala.

Winds are dominantly westerly (about 26%) and south-westerly (about 23%) and therefore most likely to transport ash inland across the country. Wind speeds in the 250 – 100 mbar altitudes are generally quite low and only exceed 20 m/s approximately 10% of the time. Most of the major cities, including Guatemala City and La Aurora International Airport, are clustered to the east of the volcanic arc (within about 50 km), therefore ash fall is likely to have an impact. The closest volcanoes to Guatemala city are Fuego and Acatenango volcanoes (40 km southwest), and Pacaya (30 km south southwest). Within approximately 100km of the historically active VEI 3+ volcanoes, agriculture is limited. Easterly or north-easterly winds occur just over 10% of the time (10% per sector) and could transport ash towards the agricultural regions along the south-west coast (a distance of approximately 50km from the volcanic arc), although transport inland is more likely.

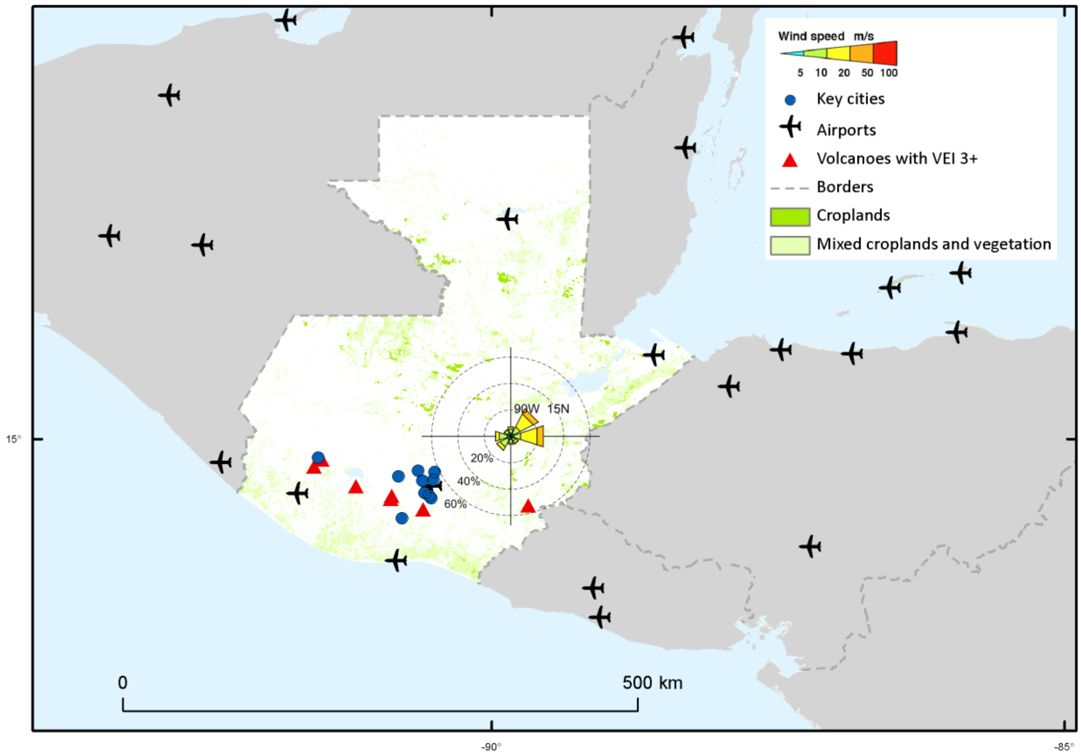


Figure 7.29: Map showing elements exposed to ash hazards in Guatemala, with wind rose indicating dominant wind directions and speeds.

Frequency of Explosive Volcanism

Table 7.4 gives estimated return periods for different magnitude eruptions in the Central American region, which comprises Guatemala, Panama, and Costa Rica in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 7.22 Return periods for different magnitude eruptions in Guatemala.

Magnitude	**Return Period (years)**
3	8.8
3.5	17
4	35
4.5	67
5	120
5.5	300
6	640
6.5	1,700
7	7,400
8	460,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Guatemala’s volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

Two established institutions monitor three of the volcanoes in Guatemala continuously; these three are Risk Level 3 volcanoes. The presence of seismic networks and regional seismometers at six other volcanoes result in a range in Monitoring Levels between zero and two. Two of the Risk Level 3 volcanoes are not monitored by CONRED or INSIVUMEH.

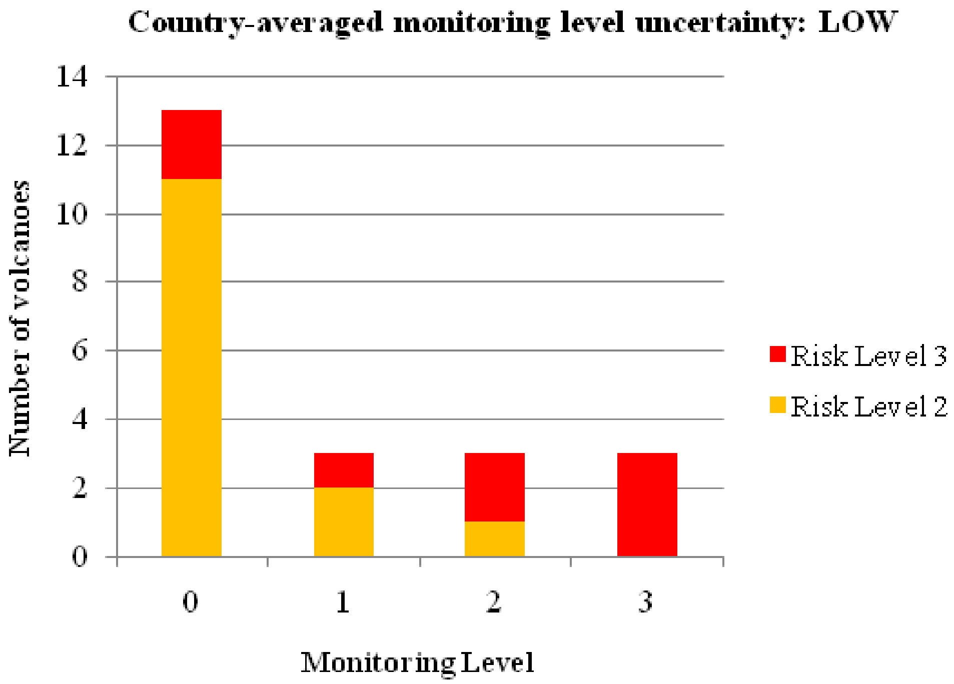


Figure 7.30: Distribution of Guatemala's volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk in Guatemala is significant, due to both the physical threat posed by the volcanoes, and the large populations living in their vicinities. Though the volcanoes that currently show unrest are well monitored, there is little monitoring of a considerable fraction of Guatemala's volcanoes with Risk Levels 2 and 3. There are many volcanoes with high uncertainty, which could well move from Hazard Levels 1 and 2 to 3 if more were known. Taken together, there remains much to be done to improve the knowledge and monitoring of Guatemala's volcanoes.

C8 Indonesia

Description

The GVP database lists 142 Holocene volcanoes in Indonesia; seventy-six of these have been active in historical time, the highest number for any country in the World. The Indonesian authority responsible for volcano monitoring, the Centre of Volcanology and Geological Hazard Mitigation (CVGHM), classifies the volcanoes into those that erupted after 1600 AD (seventy-eight), those that erupted historically before 1600 AD (twenty-nine), and Holocene volcanoes with geothermal activity but no historic activity (twenty-one). The CVGHM database was not accessible during this study, and investigations into why these totals do not agree with the numbers in the GVP database were thus not possible. There are a large number of Quaternary volcanoes, which are not included in either the CVGHM or GVP database and remain uncatalogued.

Indonesia as a country and volcanic region covers a vast area, formed of over 13,000 islands stretching 5,271 km east-west and 2,210 km north-south. Volcanoes are spread across Java, Sumatra, and 3 other islands, as well as in the Banda and Celebes seas. The majority of these volcanoes lie along the Sunda Arc, caused by subduction of the Indo-Australia Plate below the Eurasian Plate. The Arc stretches over 3,000 km from northwest Sumatra in the east to the Banda Sea in the west, and accounts for 108 (76%) of the country's volcanoes. The tectonic setting north of the Sunda Arc is more complex, with converging plate fragments creating multiple subduction zones that give rise to the volcanoes of Halmahera and Sulawesi-Sangihe.

Though the hazards posed by Indonesia's volcanoes vary widely, 130 of the 140 for which sufficient information is available are generally-explosive types. Indonesia and Japan together have in fact produced a third of all known global explosive eruptions. Thirty-six volcanoes in Indonesia have produced pyroclastic flows across ninety-six historic eruptions, and thirty-four have produced lahars during a total of eighty-four eruptions. Further, thirteen eruptions have triggered tsunamis. Given the number and coverage of volcanoes in Indonesia, almost all of the country's major population centres are located fairly near volcanoes, many within 50 km. Two dormant volcanoes, Gede and Salak, are close to Indonesia's capital, Jakarta, and the city is built on alluvial and fan deposits that may be partly related to poorly known eruptions in 1699. Densely populated rural communities, particularly on Java, further increase population exposure; ninety-three of Indonesia's volcanoes have over 100,000 people living within 30 km of their summits. Only Makassar, home to 1,321,717 and Indonesia's eighth most populous city, is not within 200 km of a volcano.

The volcanoes of Indonesia have caused many high-impact disasters; of 1,171 dated eruptions, 104 produced a total 144,000 fatalities, and 186 caused damage to arable land. Three events, at Tambora in 1815, Krakatau in 1883, and Kelut in 1919, stand out in terms of devastating loss of life and these three events alone account for roughly a fifth of historic fatalities from worldwide volcanism.

The VEI 7 eruption of the massive Tambora stratovolcano in 1815 on Sumbawa Island caused approximately 60,000 deaths. Direct deaths resulted from tsunamis, bomb impacts, tephra falls, and pyroclastic flows that reached all but the west coast, with roughly 50,000 indirect deaths on Sumbawa and Lombok islands owing to starvation following the destruction of farmland. The caldera collapse eruption of Krakatau, situated in the Sunda Strait between Java and Sumatra, in 1883 was the second largest during historical time in Indonesia (after that of Tambora). The VEI 6 eruption destroyed Krakatau island, triggering tsunamis that swept the coastlines of Sumatra and Java and killed approximately 34,000; further deaths resulted from pyroclastic surges that travelled 40 km across the Sunda Strait to the coast of Sumatra. Kelut, a stratovolcano on west Java, highlights the potential hazard posed by crater lakes. Kelut's often short but violent eruptions have frequently released volumes of water from the crater lake that generate devastating lahars; lahars following the VEI 4 event in 1919 claimed 5,110 lives, and destroyed 9,000 homes and 104 villages.

Tambora, Krakatau, and Kelut are by no means the only volcanoes that threaten Indonesia. Other frequently active and destructive volcanoes include Semeru, Awu, Karangetang (Api Siau), Lokon-Empung, Soputan and Merapi.

An eruption of Merapi, beginning in October and November 2010, is Indonesia's most recent volcanic crisis. The CVGHM raised the alert level to its highest possible on 25th October 2010, and recommended immediate evacuation for communities within a 10 km radius of the volcano (between 11,000 and 19,000 people). A day later, an explosive eruption generating pyroclastic flows began; on 27th October, reports noted roughly twenty-five deaths and several more injured. The eruption continued throughout November, with further pyroclastic flows and avalanches, and a particularly violent explosion on 5th November; ash caused diversions and cancellations at Solo and Yogyakarta airports. Activity began to decline in early December, with the CVGHM reducing the alert level to 3 (on a scale of 1 to 4) on 4th December, and to 2 on 9th January. The overall death toll exceeded 380, over 400,000 people were temporarily evacuated, and financial losses were estimated at Rp 7.1 trillion (approximately US$781 million). Lahars are an ongoing hazard.

Location of Indonesia’s Volcanoes and Key Cities

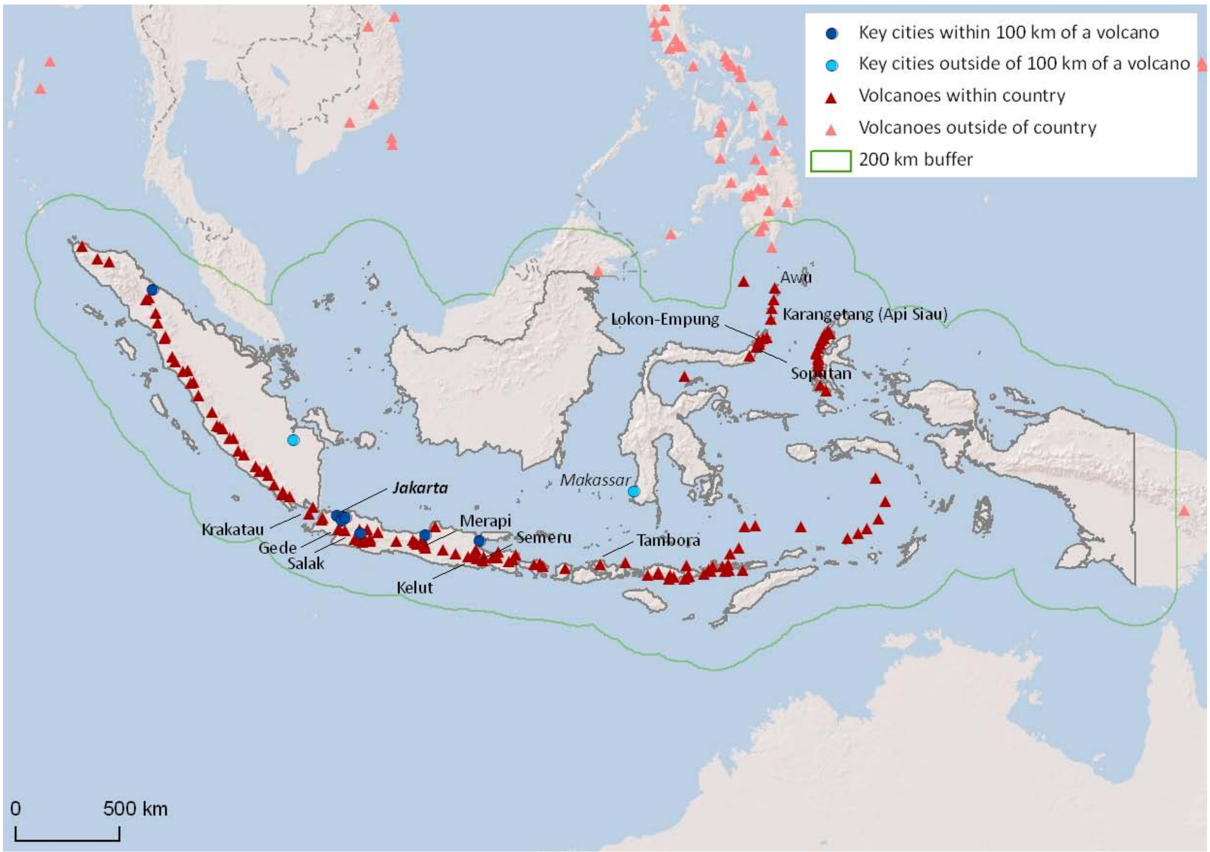


Figure 8.31: Locations of Indonesia's volcanoes and ten largest cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Indonesia.

Volcanic Facts

Number of Holocene volcanoes:	142
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	130 and 10 respectively
Number of volcanoes generating pyroclastic flows:	36
Number of volcanoes generating lahars:	34
Number of volcanoes generating lava flows:	56
Number of fatalities caused by volcanic eruptions:	144,113

Note: For two of Indonesia’s volcanoes, there is insufficient information upon which a judgement of volcano type can be made. Occurrence of pyroclastic flows, lahars, and lava flows at these volcanoes is also unknown.

Socio-Economic Facts

Total population:	232,516,800
GDP per capita, 2008 PPP US$:	4,394

HDI:	0.600 – Medium

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Jakarta (capital city)	Population:	8,540,121
- Surabaya	Population:	2,374,658
- Medan	Population:	1,750,971
- Bandung	Population:	1,699,719
- Bekasi	Population:	1,520,119
- Palembang	Population:	1,441,500
- Tangerang	Population:	1,372,124
- Makassar	Population :	1,321,717
- Semarang	Population :	1,288,084
- Depok	Population :	1,198,129

Distance from capital city to nearest volcano:	58 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	290 (82%)
Number (percentage) of people living within 10 km of a volcano:	8,500,000 (4%)
Number (percentage) of people living within 30 km of a volcano:	68,000,000 (28%)
Number (percentage) of people living within 100 km of a volcano:	190,000,000 (77%)

Hazard and Uncertainty Assessments

The plot in Figure 8.2 shows the classifications of Indonesia’s one hundred and forty-two volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 8.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

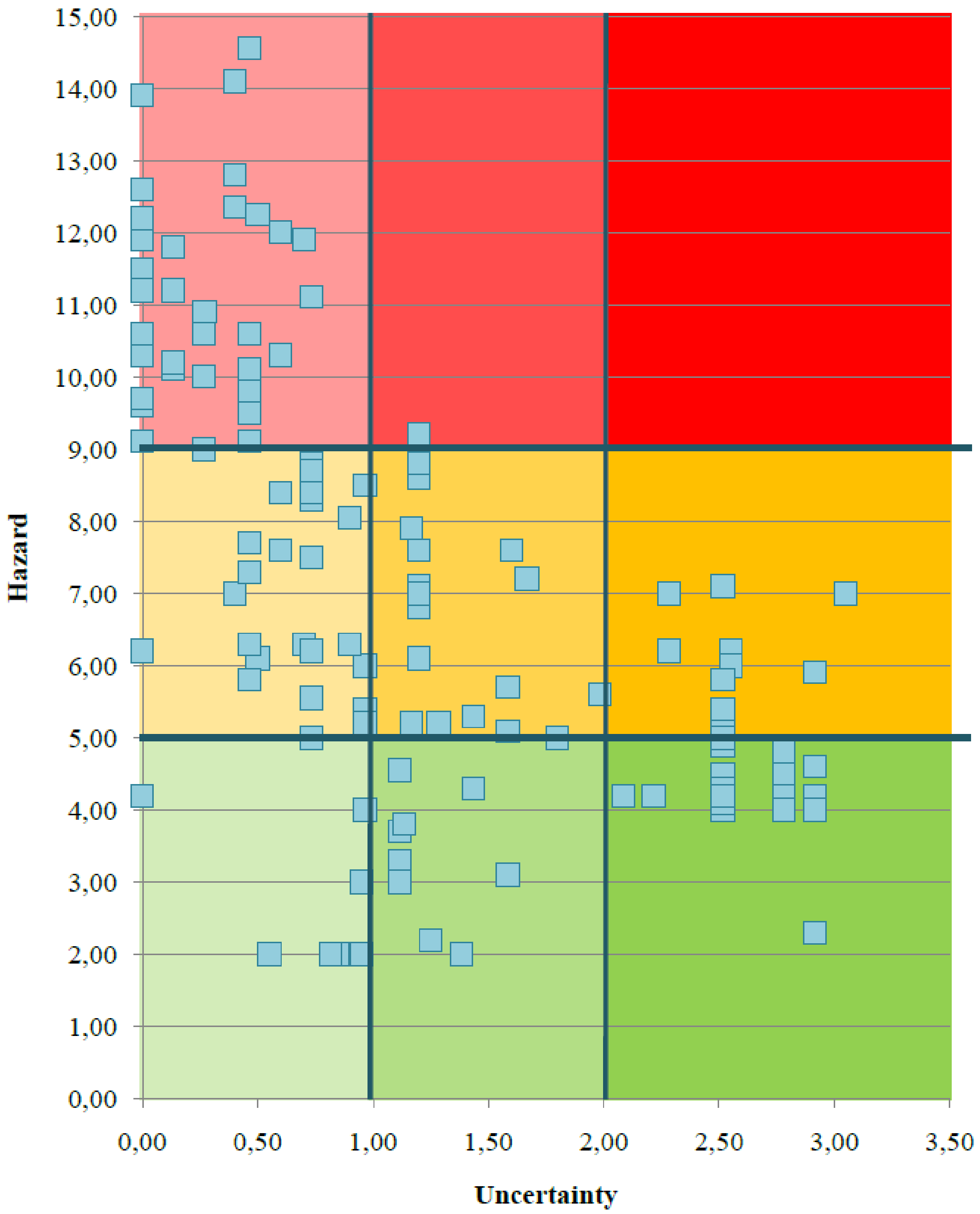


Figure 8.32: Distribution of Indonesia's volcanoes across Hazard and Uncertainty Levels.

Indonesia's volcanoes are split across all three Hazard and Uncertainty Levels, thought the largest single Hazard-Uncertainty cohort is that of Hazard Level 3, Uncertainty Level 1, with 36 volcanoes. Of note is the almost total absence of volcanoes of Hazard Level 3 with Uncertainty Levels 2 and 3.

Table 8.23 Identities of Indonesia's volcanoes in each Hazard-Uncertainty cohort.

	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**
Hazard Level 3	Agung Awu Banda Api Batur Colo (Una Una) Dempo Dieng Volcanic Complex Dukono Galunggung Gamalama Gede Guntur Ijen Iliwerung Iya Kaba Karangetang (Api Siau) Kelut Krakatau Lamongan Lewotobi Lokon-Empung Makian Marapi Merapi Paluweh Raung Rinjani Ruang Sangeang Api Semeru Soputan Sundoro Tambora Tangkubanparahu Tengger Caldera	Kerinci	
Hazard Level 2	Arjuno-Welirang Cereme Ebulobo Gamkanora Gunungapi Wetar Ibu Iliboleng Lawu	Besar Egon Inielika Kelimutu Klabat Penanggungan Perbakti-Gagak Sempu	Bratan Daun, Bukit Iyang-Argapura Kunyit Malang Plain Malintang Patah Patuha

	Leroboleng Lewotolo Mahawu Merbabu Muria Nila Papandayan Peuet Sague Ranakah Salak Serua Sorikmarapi Sumbing (0603-22=) Suoh Teon Tongkoko	Sibayak Sirung Slamet Sumbing (0601-18=) Talagabodas Talang Tandikat Tara, Batu Telong, Bur ni	Pendan Sano, Wai Sinabung Toba Tobaru Todoko-Ranu
Hazard Level 1	Banua Wuhu Emperor of China Karaha, Kawah Ndete Napu Nieuwerkerk Unnamed (0607-05=) Wurlali	Ambang Ililabalekan Ilimuda Inierie Manuk Poco Leok Seulawah Agam Sukaria Caldera Tarakan Tondano Caldera Yersey	Amasing Baluran Belirang-Beriti Bibinoi Hiri Hulubelu Hutapanjang Imun Jailolo Karang Kawi-Butak Kendang Lubukraya Lumut Balai, Bukit Lurus Malabar Mare Moti Pulosari Rajabasa Ranau Sarik-Gajah Sekincau Belirang Sibualbuali Talakmau Tampomas Telomoyo Tidore Tigalalu Ungaran Wayang-Windu Wilis
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 8.3 shows the classifications of Indonesia's one hundred and forty-two volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 8.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

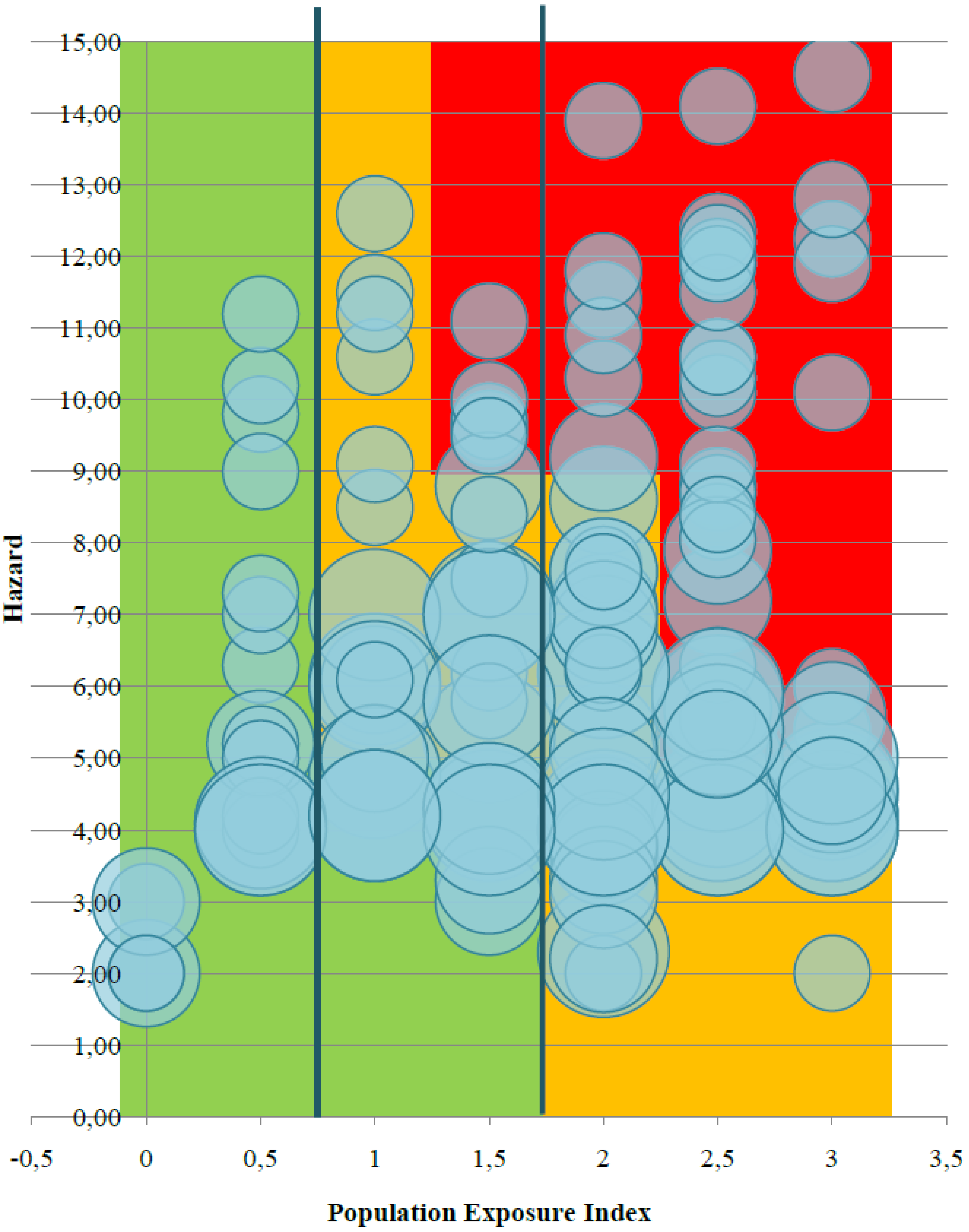


Figure 8.33: Distribution of Indonesia's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Indonesia's volcanoes cover the whole spectrum of PEI values, though the majority have PEI Levels of 2 or 3. There appears to be very little correlation between Hazard Levels and PEI Levels, and volcanoes with high Hazard Levels thus have low Risk Levels, and vice versa. Most Risk Level 3 volcanoes are of Uncertainty Level 1.

Table 8.24 Identities of Indonesia's volcanoes in each Hazard-PEI cohort.

	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**
Hazard Level 3	Colo (Una Una) Makian Paluweh Ruang	Awu Banda Api Dempo Dukono Iliwerung Karangetang (Api Siau) Krakatau Lewotobi Sangeang Api Tambora	Agung Batur Dieng Volcanic Complex Galunggung Gamalama Gede Guntur Ijen Iya Kaba Kelut Kerinci Lamongan Lokon-Empung Marapi Merapi Raung Rinjani Semeru Soputan Sundoro Tangkubanparahu Tengger Caldera
Hazard Level 2	Gunungapi Wetar Nila Peuet Sague Serua Tara, Batu Teon	Besar Gamkanora Ibu Kunyit Leroboleng Lewotolo Malintang Patah Pendan Sinabung Sirung Sorikmarapi Sumbing (0601-18=) Suoh	Arjuno-Welirang Bratan Cereme Daun, Bukit Ebulobo Egon Iliboleng Inielika Iyang-Argapura Kelimutu Klabat Lawu Mahawu Malang Plain

		Toba Tobaru Todoko-Ranu	Merbabu Muria Papandayan Patuha Penanggungan Perbakti-Gagak Ranakah Salak Sano, Wai Sempu Sibayak Slamet Sumbing (0603-22=) Talagabodas Talang Tandikat Telong, Bur ni Tongkoko
Hazard Level 1	Banua Wuhu Belirang-Beriti Emperor of China Hutapanjang Manuk Moti Nieuwerkerk Tigalalu Unnamed (0607-05=) Wurlali Yersey	Amasing Bibinoi Hulubelu Ililabalekan Lumut Balai, Bukit Mare Ranau Sekincau Belirang Sukaria Caldera Talakmau Tidore	Ambang Baluran Hiri Ilimuda Imun Inierie Jailolo Karaha, Kawah Karang Kawi-Butak Kendang Lubukraya Lurus Malabar Ndete Napu Poco Leok Pulosari Rajabasa Sarik-Gajah Seulawah Agam Sibualbuali Tampomas Tarakan Telomoyo Tondano Caldera Ungaran Wayang-Windu Wilis
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Indonesia's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 8.1 and Figure 8.2.

Risk Level 3:

Agung	Uncertainty Level 1
Arjuno-Welirang	Uncertainty Level 1
Awu	Uncertainty Level 1
Batur	Uncertainty Level 1
Bratan	Uncertainty Level 3
Cereme	Uncertainty Level 1
Dempo	Uncertainty Level 1
Dieng Volcanic Complex	Uncertainty Level 1
Dukono	Uncertainty Level 1
Galunggung	Uncertainty Level 1
Gamalama	Uncertainty Level 1
Gede	Uncertainty Level 1
Guntur	Uncertainty Level 1
Ijen	Uncertainty Level 1
Iya	Uncertainty Level 1
Iyang-Argapura	Uncertainty Level 3
Kaba	Uncertainty Level 1
Kelut	Uncertainty Level 1
Kerinci	Uncertainty Level 2
Lamongan	Uncertainty Level 1
Lawu	Uncertainty Level 1
Lewotobi	Uncertainty Level 1
Lokon-Empung	Uncertainty Level 1
Mahawu	Uncertainty Level 1
Malang Plain	Uncertainty Level 3
Marapi	Uncertainty Level 1
Merapi	Uncertainty Level 1
Merabu	Uncertainty Level 1
Muria	Uncertainty Level 1
Papandayan	Uncertainty Level 1
Patuha	Uncertainty Level 3
Penanggungan	Uncertainty Level 2
Perbakti-Gagak	Uncertainty Level 2

Raung	Uncertainty Level 1
Rinjani	Uncertainty Level 1
Salak	Uncertainty Level 1
Semeru	Uncertainty Level 1
Sempu	Uncertainty Level 2
Slamet	Uncertainty Level 2
Soputan	Uncertainty Level 1
Sumbing (0603-22=)	Uncertainty Level 1
Sundoro	Uncertainty Level 1
Talagabodas	Uncertainty Level 2
Tambora	Uncertainty Level 1
Tangkubanparahu	Uncertainty Level 1
Tengger Caldera	Uncertainty Level 1

Risk Level 2:

Ambang	Uncertainty Level 2
Baluran	Uncertainty Level 3
Banda Api	Uncertainty Level 1
Besar	Uncertainty Level 2
Daun, Buki	Uncertainty Level 3
Ebulobo	Uncertainty Level 1
Egon	Uncertainty Level 2
Gamkanora	Uncertainty Level 1
Hiri	Uncertainty Level 3
Ibu	Uncertainty Level 1
Iliboleng	Uncertainty Level 1
Ilimuda	Uncertainty Level 2
Iliwerung	Uncertainty Level 1
Imun	Uncertainty Level 3
Inielika	Uncertainty Level 2
Inierie	Uncertainty Level 2
Jailolo	Uncertainty Level 3
Karaha, Kawah	Uncertainty Level 1
Karang	Uncertainty Level 3
Karangetang (Api Siau)	Uncertainty Level 1
Kawi-Butak	Uncertainty Level 3
Kelimutu	Uncertainty Level 2
Kendang	Uncertainty Level 3
Klabat	Uncertainty Level 2

Krakatau	Uncertainty Level 1
Kunyit	Uncertainty Level 3
Leroboleng	Uncertainty Level 1
Lewotolo	Uncertainty Level 1
Lubukraya	Uncertainty Level 3
Lurus	Uncertainty Level 3
Malabar	Uncertainty Level 3
Malintang	Uncertainty Level 3
Ndete Napu	Uncertainty Level 1
Patah	Uncertainty Level 3
Pendan	Uncertainty Level 3
Poco Leok	Uncertainty Level 2
Pulosari	Uncertainty Level 3
Rajabasa	Uncertainty Level 3
Ranakah	Uncertainty Level 1
Sangeang Api	Uncertainty Level 1
Sano, Wai	Uncertainty Level 3
Sarik-Gajah	Uncertainty Level 3
Seulawah Agam	Uncertainty Level 2
Sibayak	Uncertainty Level 2
Sibualbuali	Uncertainty Level 3
Sinabung	Uncertainty Level 3
Sirung	Uncertainty Level 2
Sorikmarapi	Uncertainty Level 1
Sumbing (0601-18=)	Uncertainty Level 2
Suoh	Uncertainty Level 1
Talang	Uncertainty Level 2
Tampomas	Uncertainty Level 3
Tandikat	Uncertainty Level 2
Tarakan	Uncertainty Level 2
Telomoyo	Uncertainty Level 3
Telong, Bur ni	Uncertainty Level 2
Toba	Uncertainty Level 3
Tobaru	Uncertainty Level 3
Todoko-Ranu	Uncertainty Level 3
Tondano Caldera	Uncertainty Level 2
Tongkoko	Uncertainty Level 1
Ungaran	Uncertainty Level 3

Wayang-Windu	Uncertainty Level 3
Wilis	Uncertainty Level 3

Risk Level 1:

Amasing	Uncertainty Level 3
Banua Wuhu	Uncertainty Level 1
Belirang-Beriti	Uncertainty Level 3
Bibinoi	Uncertainty Level 3
Colo (Una Una)	Uncertainty Level 1
Emperor of China	Uncertainty Level 1
Gunungapi Wetar	Uncertainty Level 1
Hulubelu	Uncertainty Level 3
Hutapanjang	Uncertainty Level 3
Ililabalekan	Uncertainty Level 2
Lumut Balai, Bukit	Uncertainty Level 3
Makian	Uncertainty Level 1
Manuk	Uncertainty Level 2
Mare	Uncertainty Level 3
Moti	Uncertainty Level 3
Nieuwerkerk	Uncertainty Level 1
Nila	Uncertainty Level 1
Paluweh	Uncertainty Level 1
Peuet Sague	Uncertainty Level 1
Ranau	Uncertainty Level 3
Ruang	Uncertainty Level 1
Sekincau Belirang	Uncertainty Level 3
Serua	Uncertainty Level 1
Sukaria Caldera	Uncertainty Level 2
Talakamau	Uncertainty Level 3
Tara, Batu	Uncertainty Level 2
Teon	Uncertainty Level 1
Tidore	Uncertainty Level 3
Tigalau	Uncertainty Level 3
Unnamed (0607-05=)	Uncertainty Level 1
Wurlali	Uncertainty Level 1
Yersey	Uncertainty Level 2

Of Indonesia’s one hundred and forty-two volcanoes, forty-six are Risk Level 3, sixty-four are Risk Level 2, and thirty-two are Risk Level 1.

Hazard-specific exposure assessments

Table 8.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 8.25 Extent of infrastructure exposure to lahars and pyroclastic flows in Indonesia.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	160 44%	Number of cities: Percentage of total number of cities:	120 32%
Population	Number of people: Percentage of total number of people:	72,000,000 30%	Number of people: Percentage of total number of people:	40,000,000 17%
Ports	Number of ports: Percentage of total number of ports:	9 8%	Number of ports: Percentage of total number of ports:	8 7%
All Roads	Length (km): Percentage of total length:	8,900 19%	Length (km): Percentage of total length:	5,500 11%
Main Roads	Length (km): Percentage of total length:	5,800 24%	Length (km): Percentage of total length:	3,500 14%
All Railways	Length (km): Percentage of total length:	2,900 39%	Length (km): Percentage of total length:	1,400 19%
Airports	Number of airports: Percentage of all airports:	11 12%	Number of airports: Percentage of all airports:	7 7%

Figure 8.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Indonesia.

Easterly winds dominate across the region, and in particular on the equator and up to five degrees north where the data show easterly winds occurring 72 - 74 % of the time. According to the reanalysis data, the probability of wind towards the north, northeast, east, southeast or south is typically 1 - 1.5 % per sector. Around ten degrees south, the northerly wind direction becomes more variable.

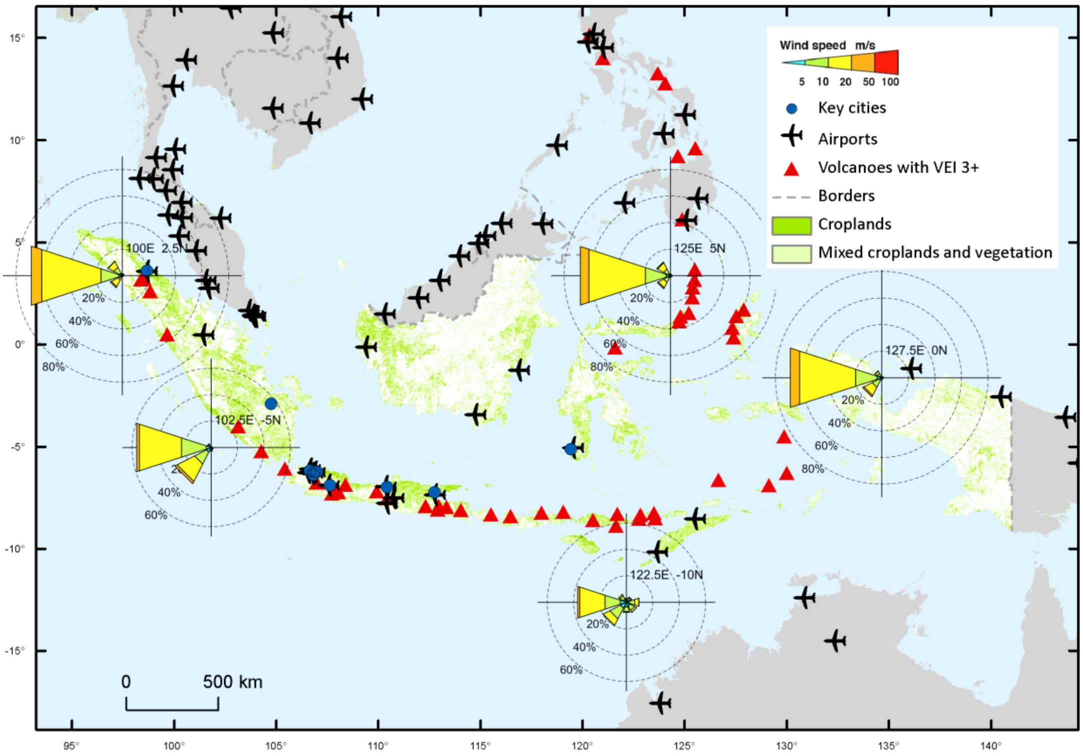


Figure 8.34: Map showing elements exposed to ash hazards in Indonesia, with wind roses indicating dominant wind directions and speeds.

Indonesia is a highly volcanically active region with large number of VEI 3+ volcanoes, and as a result many major cities and airports are vulnerable to ash fall. For example, the capital Jakarta lies 65 km north of Gede and approximately 100 km northwest of Tangkubanparahu. Java's primary airport (Soekarno-Hatta International Airport) lies approximately 80 km north northwest of Gede. A major eruption of one of the other relatively proximal volcanos along the Sunda arc to the east is likely to result in ash fall affecting air traffic (notably airports at Bandung, Semarang and Surabaya) and agriculture in Java. In Sumatra, Medan city and Polonia International Airport are approximately 40 km northeast of Sibayak and Sinabung volcanoes. Due to the dominant wind direction, and eruption along the Sundan arc from Java to the east is likely to result in the most widespread ash impacts on agriculture and transport.

Frequency of Explosive Volcanism

Table 8.4 gives estimated return periods for different magnitude eruptions in Indonesia. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 8.26: Return periods for different magnitude eruptions in Indonesia.

Magnitude	Return Period (years)
3	2
3.5	3.7
4	7.8
4.5	15
5	27
5.5	68
6	140
6.5	370
7	1,700
8	100,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Indonesia's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

The Centre for Volcanology and Geological Hazard Mitigation (CVGHM) in Indonesia monitor sixty-seven volcanoes that have been active since 1600AD, out of a total of one hundred and forty-two volcanoes active in the Holocene. They are a well-established institution, though facilities are not wide-ranging and only ten of the monitored volcanoes have more than one seismometer; the remaining majority have only one seismometer. Five of the ten volcanoes with Monitoring Level 3 are Risk Level 3.

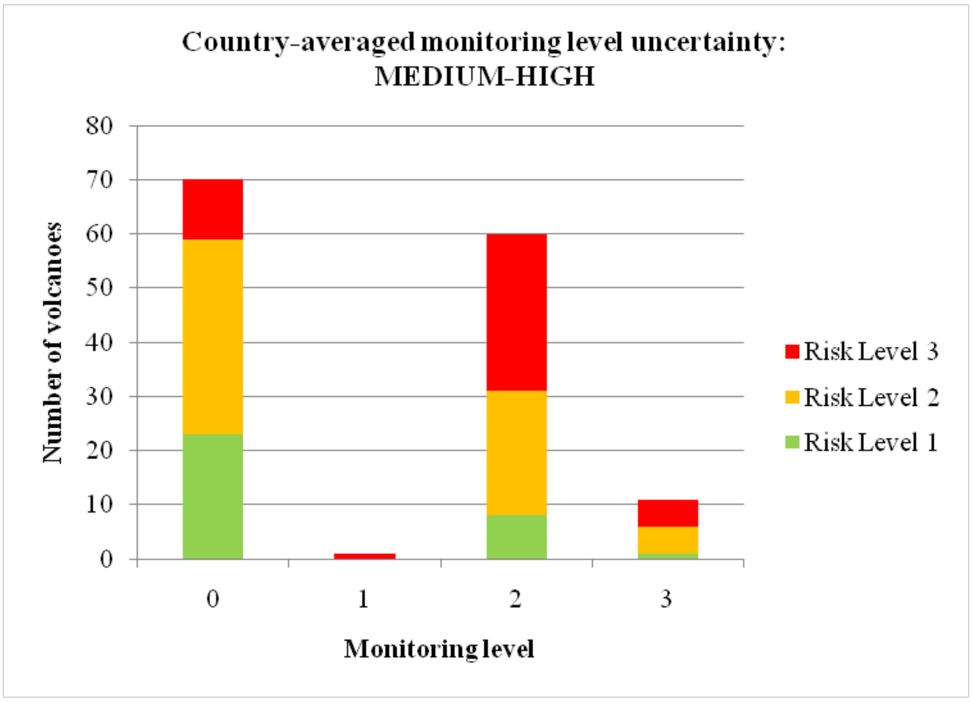


Figure 8.35: Distribution of Indonesia's volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk in Indonesia is very significant, with many high hazard volcanoes, some of which are located very close to large settlements and threaten much infrastructure. Whilst uncertainty surrounding many Hazard Level 3 volcanoes is low, little is known about many less recently active, lower risk volcanoes. Where it exists, monitoring is good; over half of Indonesia's volcanoes are however totally unmonitored, and some of these are Risk Level 3.

C9 Madagascar

Description

The GVP database identifies five Holocene volcanoes for Madagascar, which arise as a result of the country's position above an intra-plate volcanic hotspot off the southeast coast of Africa. One volcanic field and two groups of cinder cones are located in the north of the island. The remaining two volcanoes are a group of scoria cones and a group of cinder cones, located towards the island's centre.

There are few dated eruption records for Madagascar's volcanoes; only two eruptions, both in the Itasy Volcanic Field, are dated, and the most recent of these was 6050 BC or before. However, there are historic or geologic descriptions of eruptive periods at all five volcanoes. Early activity at two volcanoes produced minor pyroclastic flows, with trachytic lava domes produced at two others; more recent eruptions have been dominated mostly by basaltic lava flows. Though the cities of Antananarivo, Madagascar's capital, and Antanifotsy are only 65 km and 30 km from their nearest volcanoes respectively, known styles of volcanic activity pose little hazard at these distances. However, Itasy Volcanic Field and Ankaratra Field both have over 100,000 people living within a 30 km radius. There is, however, a lack of basic scientific data on the volcanoes of Madagascar, so all hazards evaluations have significant uncertainties.

Location of Madagascar's Volcanoes and Key Cities

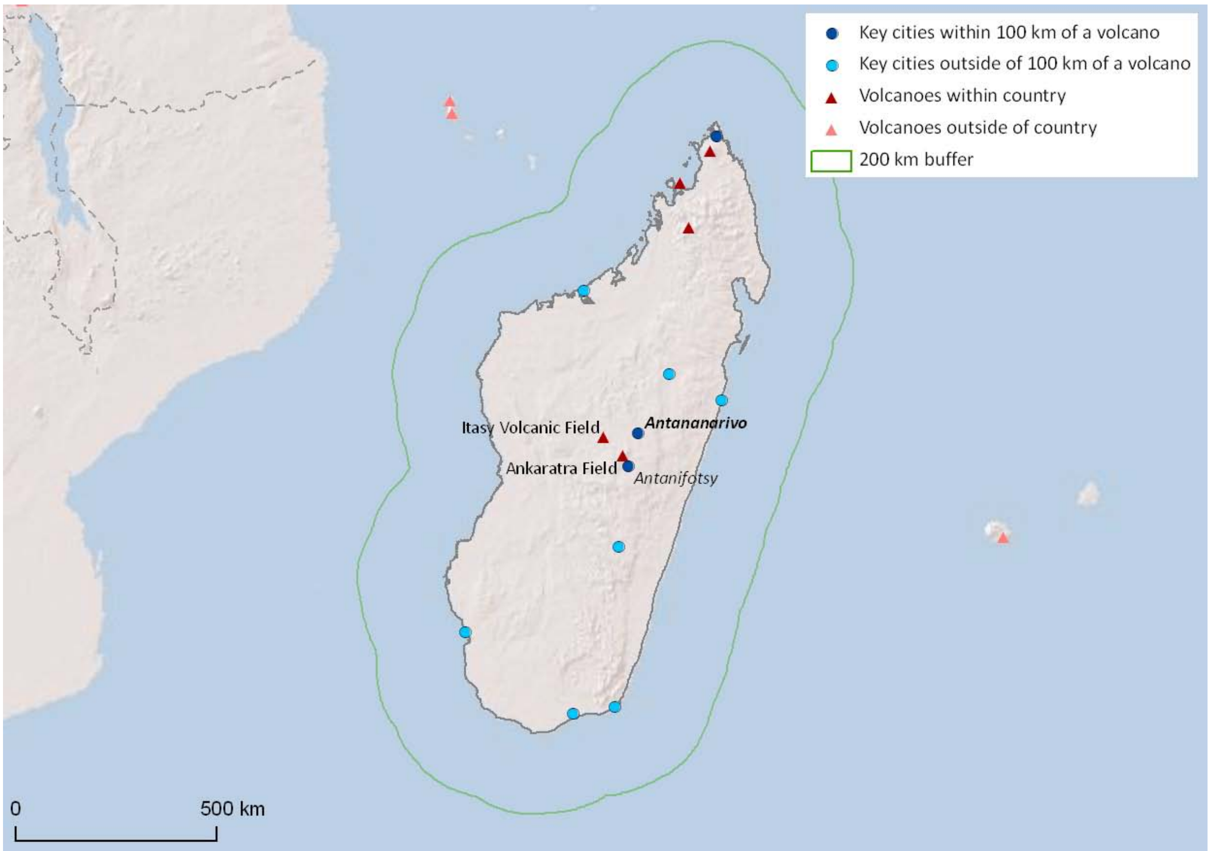


Figure 9.36: Locations of Madagascar's volcanoes and ten largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Madagascar.

Volcanic Facts

Number of Holocene volcanoes:	5
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	0 and 5 respectively
Number of volcanoes generating pyroclastic flows:	1
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	4
Number of fatalities caused by volcanic eruptions:	0

Socio-Economic Facts

Total population:	20,146,400
GDP per capita, 2008 PPP US$:	958
HDI:	0.435 – Low

Ten largest cities, as measured by population ("Key Cities"), and populations:

- Antananarivo (capital city)	Population:	1,391,433
- Toamasina	Population:	206,373
- Fianarantsoa	Population:	167,227
- Mahajanga	Population:	154,657
- Toliara	Population:	115,319
- Antsiranana	Population:	82,937
- Antanifotsy	Population:	70,626
- Ambovombe	Population :	66,818
- Amparafaravola	Population :	51,519
- Fort Dauphin	Population :	45,141

Distance from capital city to nearest volcano: 64 km

Number (percentage) of cities (population over 20,000) within 100 km of a volcano: 14 (25%)

Number (percentage) of people living within 10 km of a volcano: 64,000 (~ 0%)

Number (percentage) of people living within 30 km of a volcano: 880,000 (4%)

Number (percentage) of people living within 100 km of a volcano: 7,000,000 (34%)

Hazard and Uncertainty Assessments

The plot in Figure 9.2 shows the classifications of Madagascar's five volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 9.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

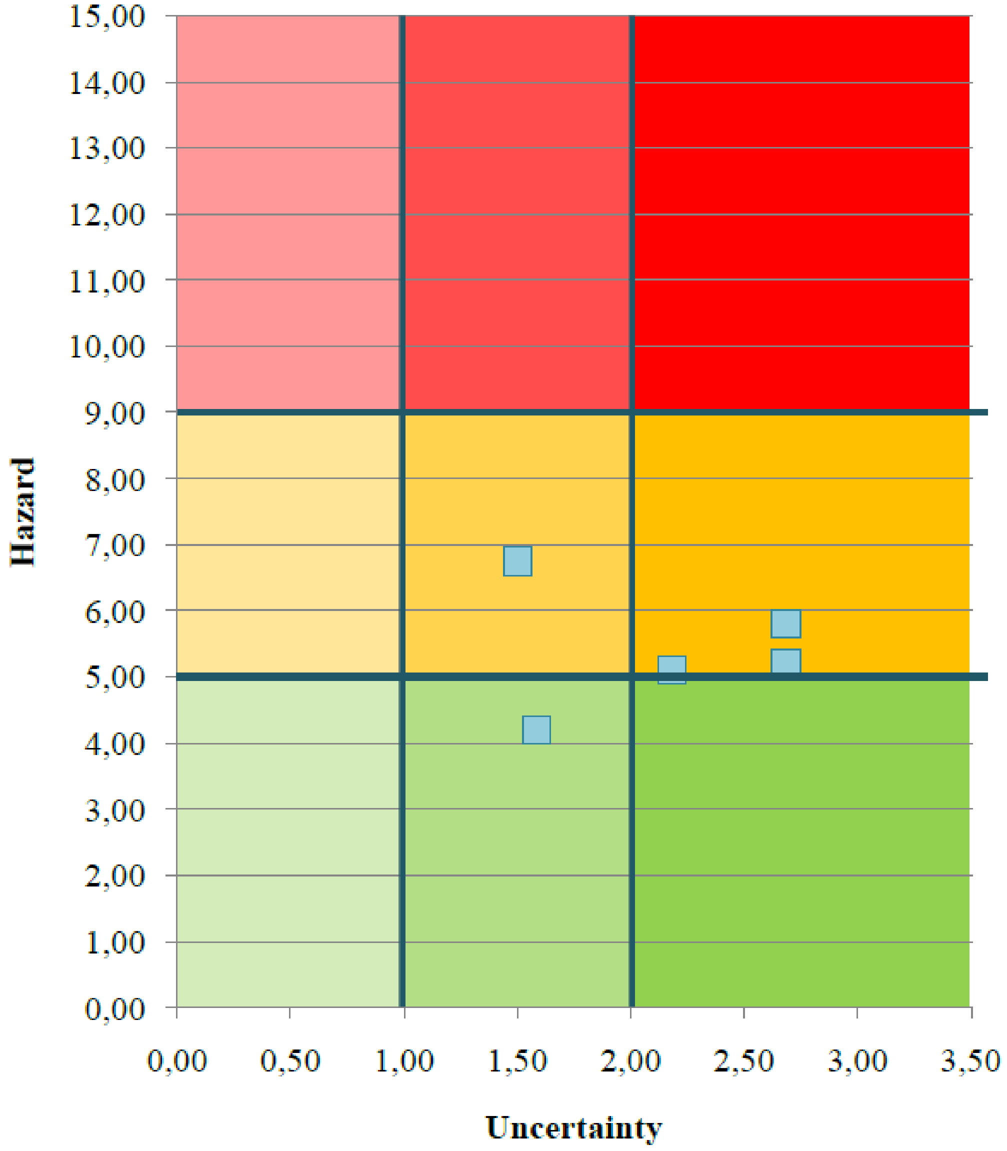


Figure 9.37: Distribution of Madagascar's volcanoes across Hazard and Uncertainty Levels.

Madagascar’s volcanoes are all of Hazard Levels 1 and 2, and Uncertainty Levels 2 and 3. Uncertainty is lowest for the highest hazard volcano.

Table 9.27 Identities of Madagascar's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2		Itasy Volcanic Field	Ambre-Bobaomby Ankaiznina Field Ankaratra Field
Hazard Level 1		Nosy-Be	
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Basic results – Population Exposure Index (PEI)
The plot in Figure 9.3 shows the classifications of Madagascar’s five volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 9.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

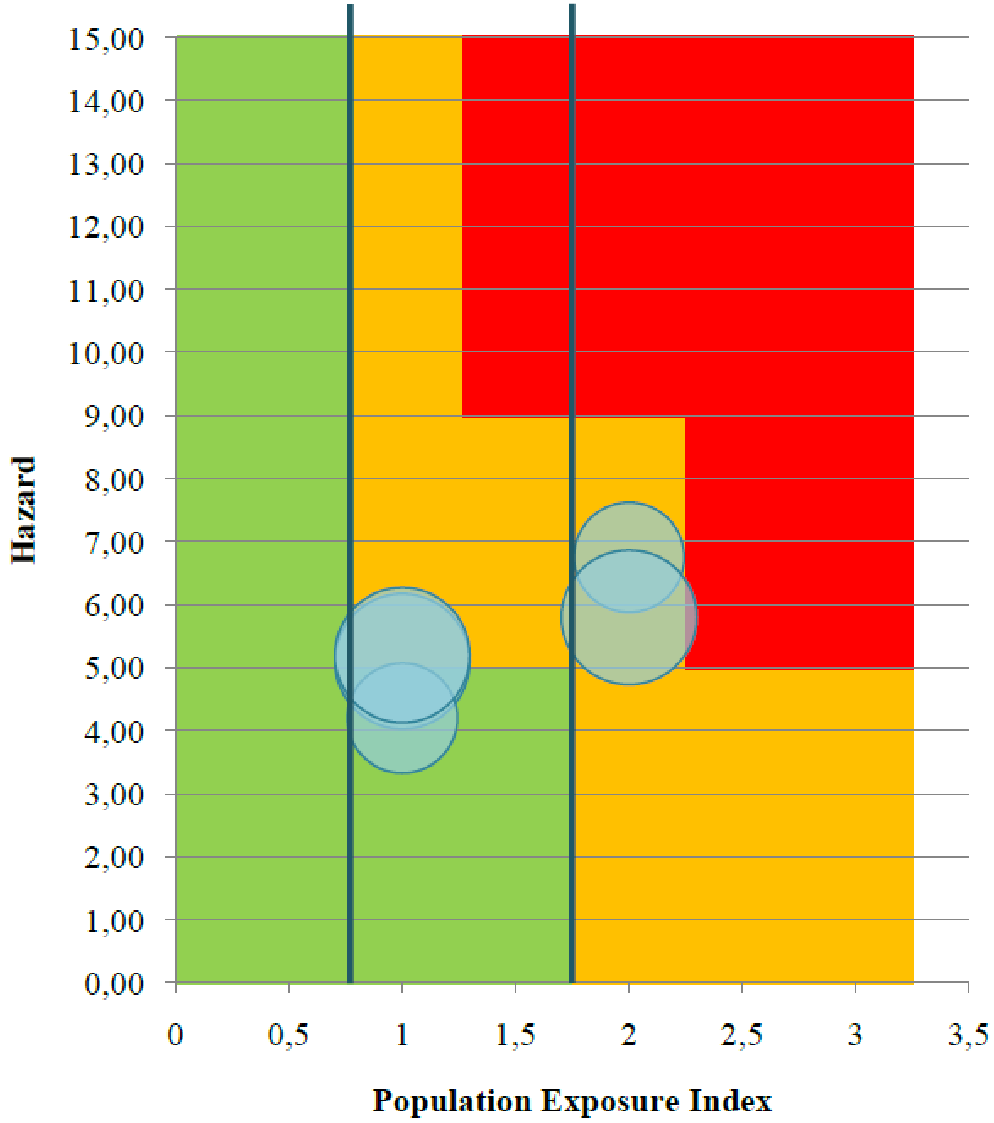


Figure 9.38: Distribution of Madagascar's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Madagascar’s volcanoes fall in PEI Levels 2 and 3; they are subsequently classed as Risk Levels 1 and 2.

Table 9.28 Identities of Madagascar's volcanoes in each Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2	Ambrae-Bobaomby Ankaizina Field	Ankaratra Field Itasy Volcanic Field	
Hazard Level 1	Nosy-Be		
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Madagascar's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 9.1 and Figure 9.2.

Risk Level 2:

• Ambrae-Bobaomby	Uncertainty Level 3
• Ankaizina Field	Uncertainty Level 3
• Ankaratra Field	Uncertainty Level 3
• Itasy Volcanic Field	Uncertainty Level 2

Risk Level 1:

• Nosy-Be	Uncertainty Level 2

Of Madagascar's five volcanoes, four are Risk Level 2, and one is Risk Level 1.

Hazard-specific exposure assessments

Table 9.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 9.29 Extent of infrastructure exposure to lahars and pyroclastic flows in Madagascar.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	7 13%	Number of cities: Percentage of total number of cities:	0 0%
Population	Number of people: Percentage of total number of people:	4,600,000 22%	Number of people: Percentage of total number of people:	17,000 0%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	2,500 10%	Length (km): Percentage of total length:	26 0%
Main Roads	Length (km): Percentage of total length:	1,300 10%	Length (km): Percentage of total length:	9 0%
All Railways	Length (km): Percentage of total length:	0 0%	Length (km): Percentage of total length:	0 0%
Airports	Number of airports: Percentage of all airports:	2 8%	Number of airports: Percentage of all airports:	0 0%

Figure 9.4 shows agriculture and infrastructure elements exposed to ash hazards, and a wind rose indicating prevalent conditions for Madagascar.

There is a strong predominant wind direction, with westerly winds occurring approximately 48% of the time, north-westerlies about 27% of the time, and approximately 10% south-westerly winds. A VEI 3+ eruption of the Itasy Volcanic Field is therefore likely to lead to ash fallout affecting the capital city and primary international airport of Antananarivo (about 90 km to the east), and also the stretch of agricultural land along the east coast. Toamasina airport (290 km east northeast of Itasy Volcanic Field) could also be affected by an eruption. Due to the dominant westerly winds, other airports on the island are less likely to be directly impacted by ash fall, though flight paths could be affected.

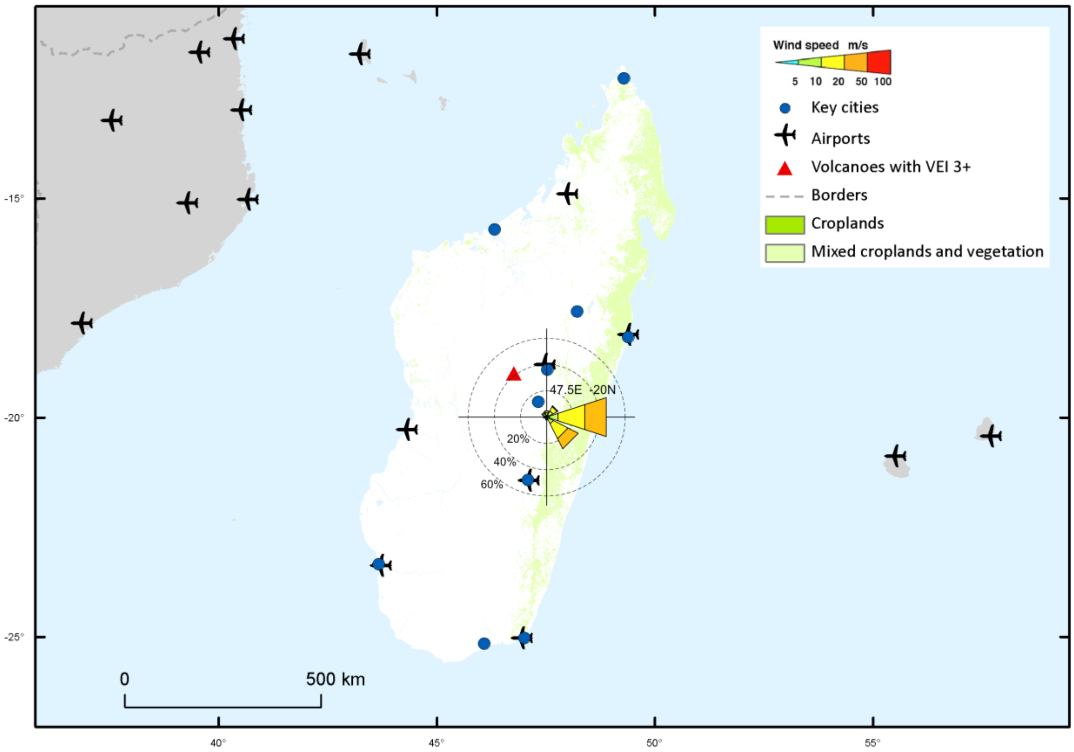


Figure 9.39: Map showing elements exposed to ash hazards in Madagascar, with wind rose indicating dominant wind directions and speeds.

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Madagascar's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

None of the five Holocene volcanoes in Madagascar are monitored regularly by a single dedicated institution. One of the volcanic fields is however within 15 km of a seismic network and has therefore been allocated a Monitoring Level of 1.

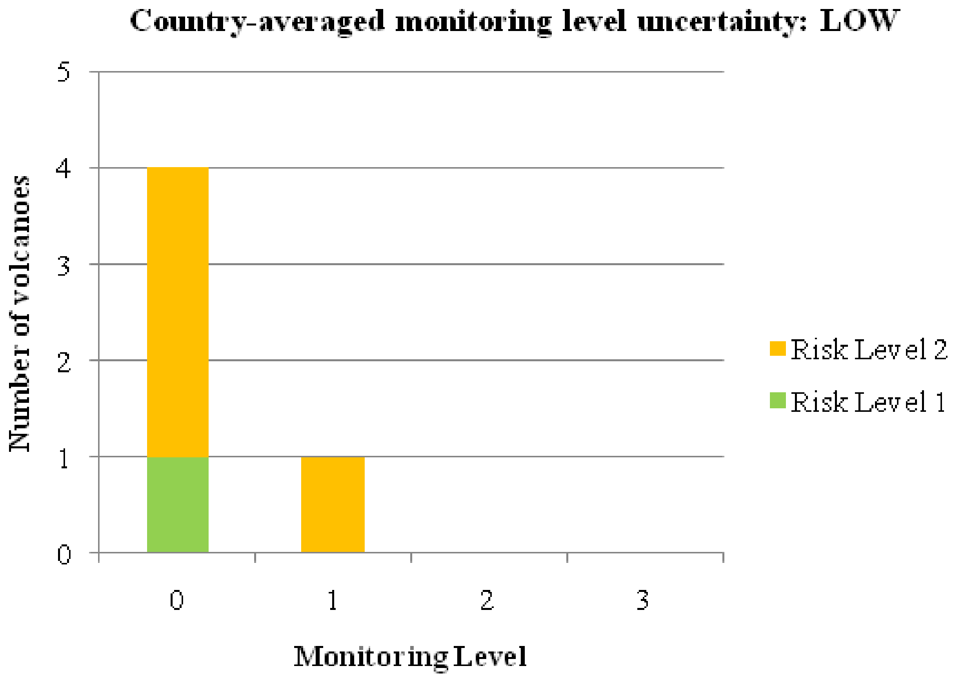


Figure 9.40: Distribution of Madagascar's volcanoes across Monitoring and Risk Levels.

Summary

Volcanism in Madagascar is dominated by basalt volcanism and lavas so the hazard is likely quite mild. However, data is limited and uncertainty about Hazard Levels is quite high. Minor pyroclastic flows are recognised, suggesting volcanic risk is potentially higher than that indicated by the risk assessments presented here. Further research is needed to reduce the uncertainty surrounding volcano risk assessments in Madagascar.

C10 Mali

Description

Only one Holocene volcanic feature, the Tin Zaouatene Volcanic Field, is listed for Mali in the GVP database; it is located in the west of the country, near the border with Algeria and Niger. Of the ten most populous cities in Mali, the nearest to the Tin Zaouatene Volcanic Field is about 500 km away. There are no recorded eruptions from Tin Zaouatene, nor descriptions of eruptive styles or products.

Location of Mali's Volcano and Key Cities

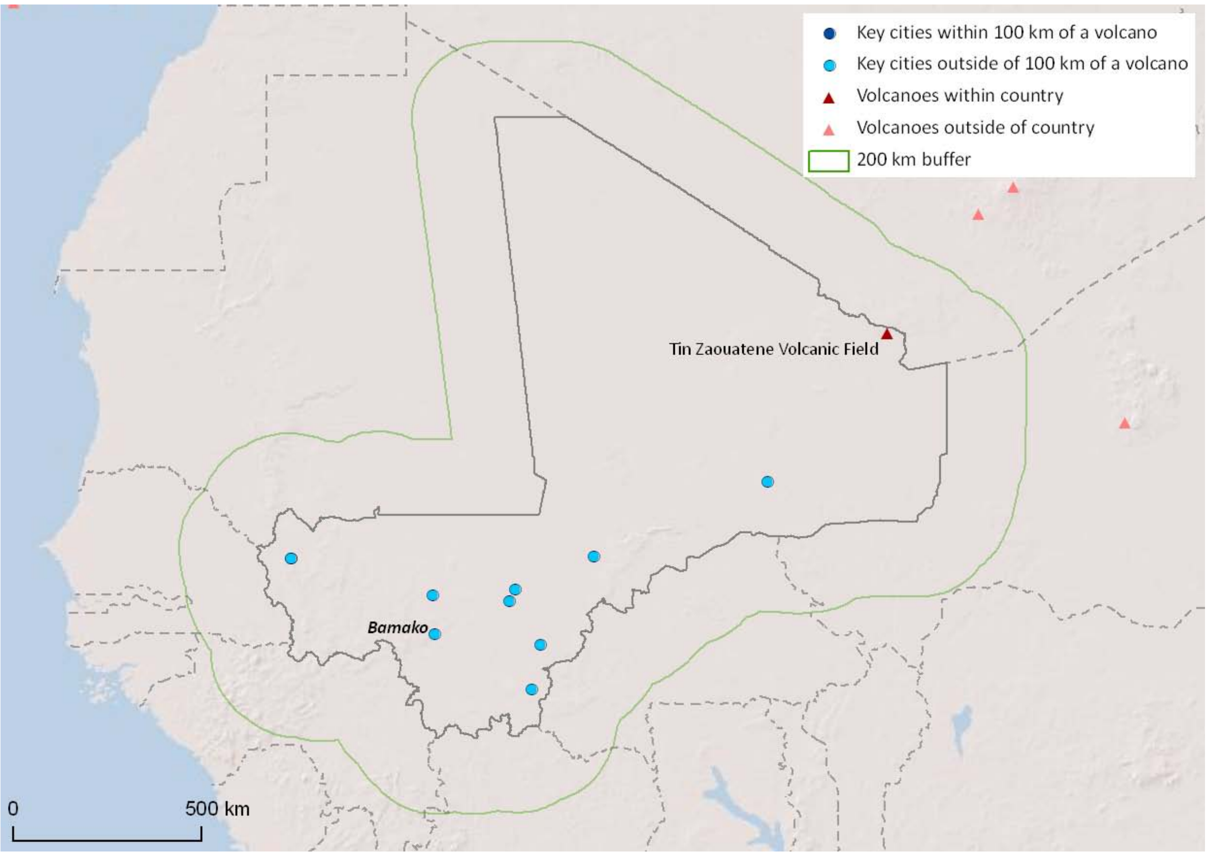


Figure 10.41: Locations of Mali's volcano, and ten largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Mali.

Volcanic Facts

Number of Holocene volcanoes:	1
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	0 and 1 respectively
Number of volcanoes generating pyroclastic flows:	0
Number of volcanoes generating lahars:	0

Number of volcanoes generating lava flows:	1
Number of fatalities caused by volcanic eruptions:	0

Socio-Economic Facts

Total population:	13,323,100
GDP per capita, 2008 PPP US$:	1,207
HDI:	0.309 – Low

Ten largest cities, as measured by population ("Key Cities"), and populations:

- Bamako (capital city)	Population:	1,297,281
- Sikasso	Population:	144,786
- Mopti	Population:	108,456
- Koutiala	Population:	99,353
- Kayes Ndi	Population:	97,464
- Ségou	Population:	92,552
- Gao	Population:	87,000
- Kayes	Population:	78,406
- Markala	Population:	53,783
- Kolokani	Population:	48,774

Distance from capital city to nearest volcano:	1400 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	0 (0%)
Number (percentage) of people living within 10 km of a volcano:	< 1,000 (~0%)
Number (percentage) of people living within 30 km of a volcano:	< 1,000 (~0%)
Number (percentage) of people living within 100 km of a volcano:	2,300 (~ 0%)

Hazard and Uncertainty Assessments

The plot in Figure 10.2 shows classification of Mali's volcano across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 10.1 lists the name of the volcano and the Hazard-Uncertainty class to which it is assigned.

Mali's volcano is classed as Hazard Level 1, Uncertainty Level 3.

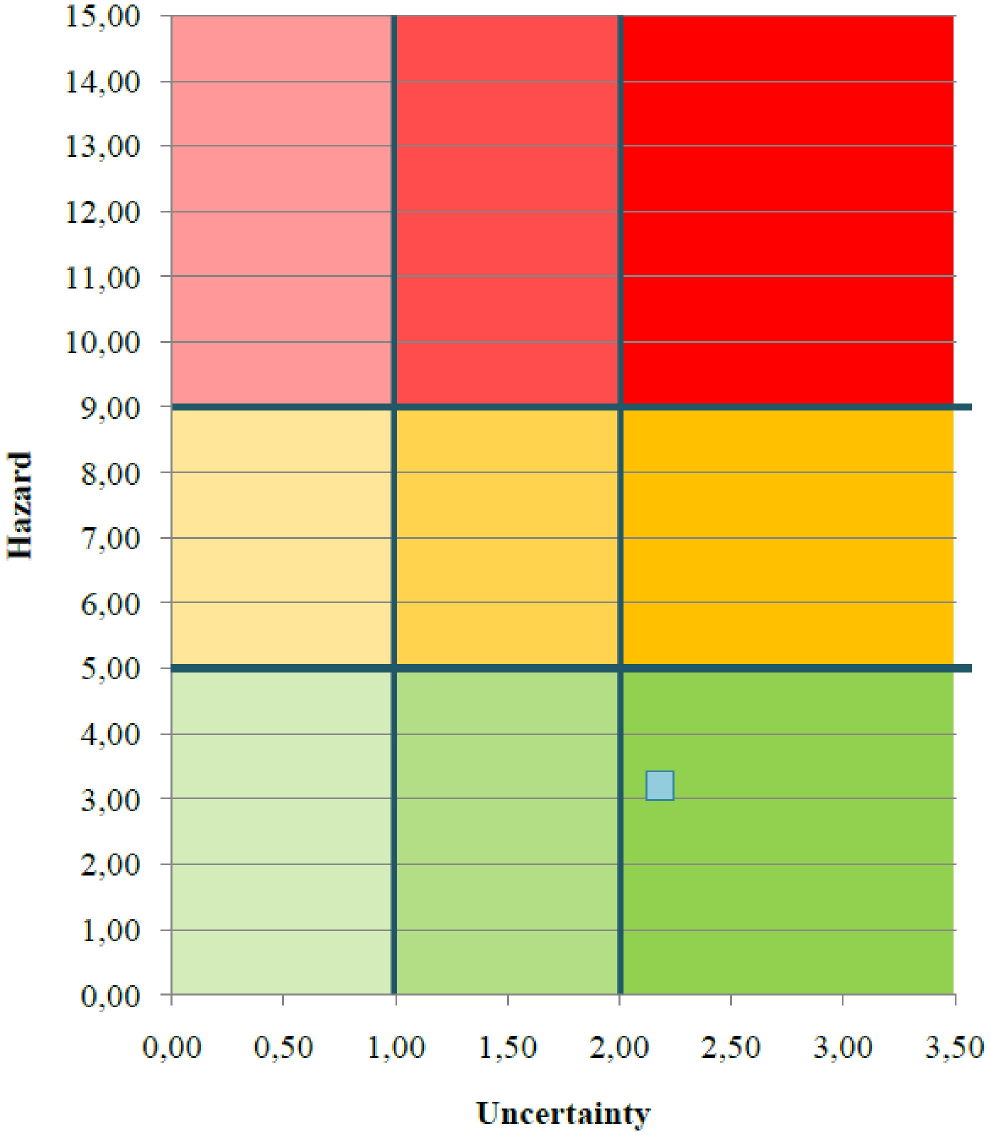


Figure 10.42: Distribution of Mali's volcano across Hazard and Uncertainty Levels.

Table 10.30 Identity of Mali's volcano in its Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1			Tin Zaouatene Volcanic Field
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 10.3 shows the classification of Mali’s volcano across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 10.2 lists the volcano name and its Hazard-PEI class.

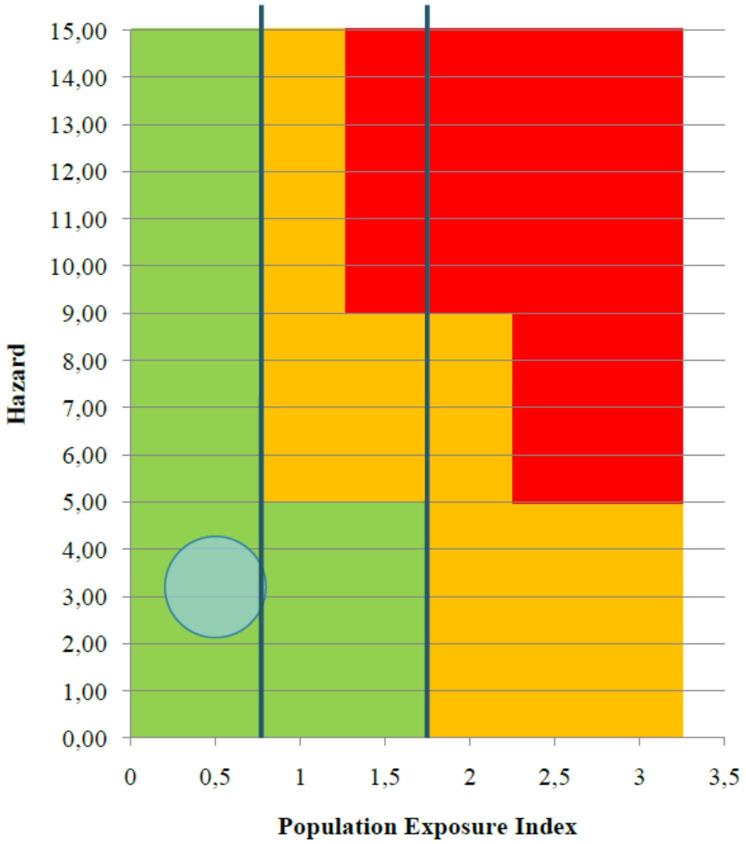


Figure 10.43: Distribution of Mali's volcano across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 10.31 Identity of Mali's volcano in its Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1	Tin Zaouatene Volcanic Field		
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Mali's volcano has a low PEI Level, and is thus classed as Risk Level 1.

Basic results – Risk assessments
The list below gives the Risk Level of Mali's volcano, a measure that combines Hazard Level and PEI. The Uncertainty Level quoted is that ascribed during the hazard assessment, as in Table 10.1 and Figure 10.2.

Risk Level 1:

- Tin Zaouatene Volcanic Field Uncertainty Level 3

Mali's volcano is Risk Level 1.

Hazard-specific exposure assessments

No pyroclastic flow, lahar, or ash hazards are known for Mali.

National Capacity for Coping with Volcanic Risk

Graphical display of Mali's capacity for coping with volcanic risk is not possible due to a lack of information.

Summary

Volcanic risk in Mali is low. Population and infrastructure exposure is minimal, though assessments regarding hazard, PEI, and monitoring capabilities are highly uncertain.

C11 Panama

Description

Only two Holocene volcanoes are listed in the GVP database for Panama. They are located adjacent to the Cocos - Caribbean Plate boundary responsible for much volcanism further north in Central America. Both are stratovolcanoes, located roughly 260 km apart; Barú in the west of the country towards the Costa Rica border, and El Valle in the centre, approximately 22 km from the Pacific coastline.

Panama's capital, Panama City, and other major cities are located sufficiently far from Barú and El Valle to be threatened only by very large eruptions, though sufficiently-sized eruption columns could deposit ash as far away as these large settlements. However, the city of David, Panama's fourth most populous city, is located roughly 40 km SSE of Barú, and has been mapped by the U.S. Geological Survey as within the lahar plain on the volcano's southern flanks.

No dated eruptions of El Valle volcano are known, and thus the volcano's Holocene status needs confirmation. Eruptions at Barú are better documented, however, with four eruptive episodes over the last 1,600 years and several other older events. No fatalities have been recorded, though the volcano has produced pyroclastic flows on numerous occasions with damage to land and property as a result.

Location of Panama’s Volcanoes and Key Cities

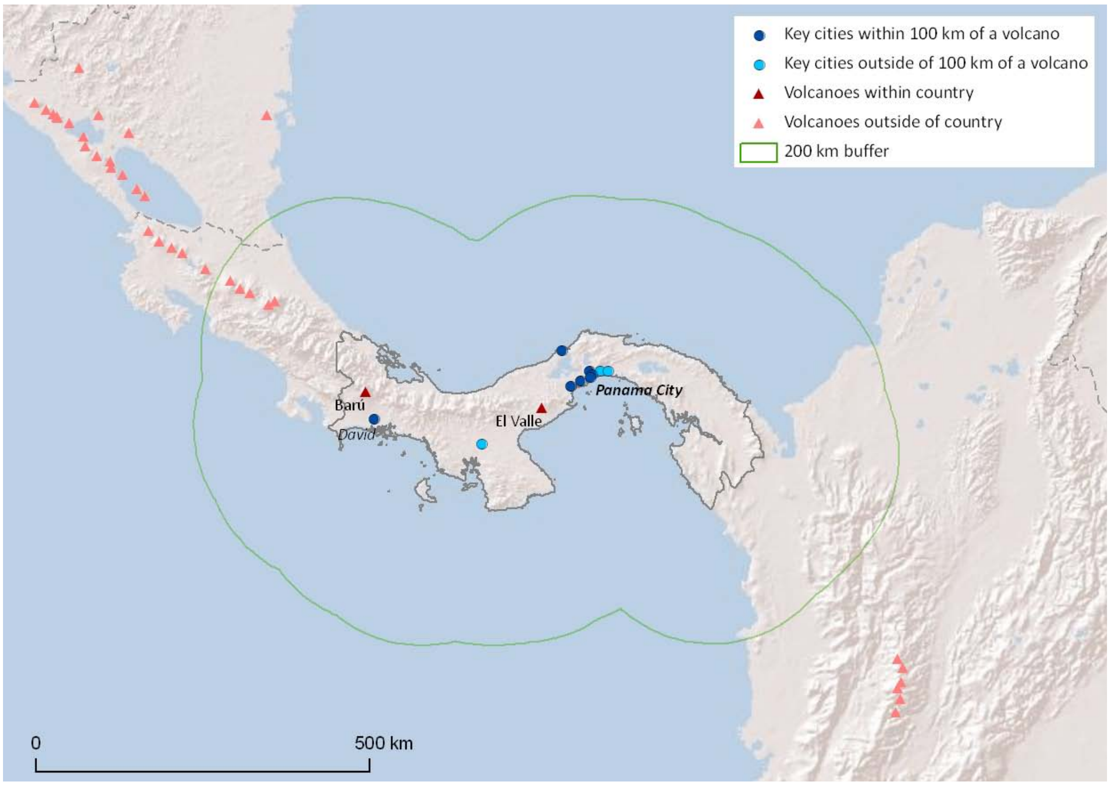


Figure 11.44: Locations of Panama's volcanoes and ten largest cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Panama.

Volcanic Facts

Number of Holocene volcanoes:	2
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	2 and 0 respectively
Number of volcanoes generating pyroclastic flows:	1
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	0
Number of fatalities caused by volcanic eruptions:	0

Socio-Economic Facts

Total population:	3,508,500
GDP per capita, 2008 PPP US$:	13,210
HDI:	0.755 – High

Ten largest cities, as measured by population ("Key Cities"), and populations:

- Panamá City (capital city)	Population:	408,168
- San Miguelito	Population:	321,501
- Tocumen	Population:	88,543
- David	Population:	82,859
- Arraiján	Population:	76,815
- Colón	Population:	76,643
- Las Cumbres	Population:	69,102
- La Chorrera	Population :	61,232
- Pacora	Population :	55,530
- Santiago de Veraguas	Population :	45,355

Distance from capital city to nearest volcano:	85 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	13 (81%)
Number (percentage) of people living within 10 km of a volcano:	15,000 (~ 0%)
Number (percentage) of people living within 30 km of a volcano:	220,000 (7%)
Number (percentage) of people living within 100 km of a volcano:	2,800,000 (83%)

Hazard and Uncertainty Assessments

The plot in Figure 11.2 shows the classifications of Panama's two volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 11.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

One of Panama's volcanoes is Hazard Level 2, and the other is Hazard Level 1. Greatest uncertainty surrounds the latter.

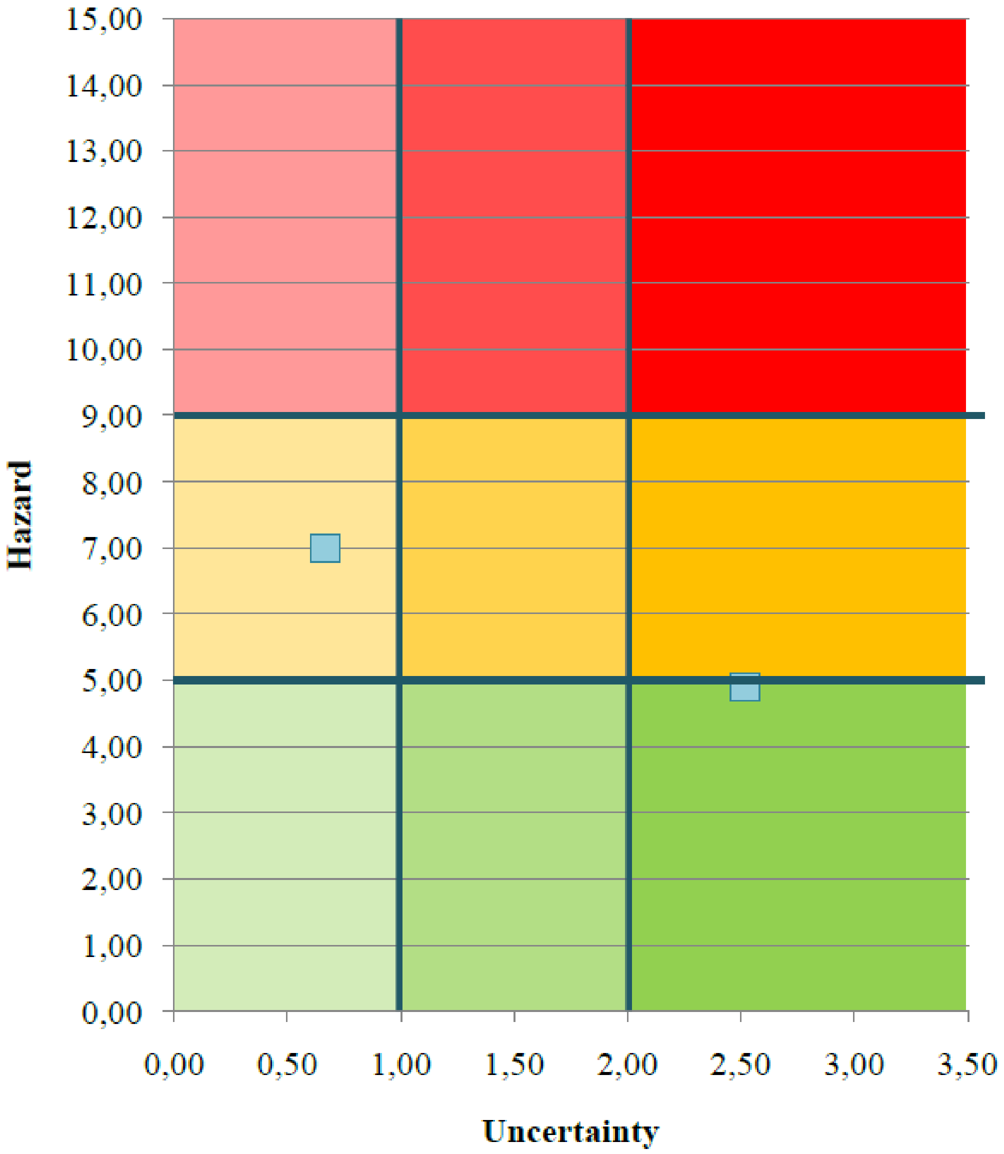


Figure 11.45: Distribution of Panama's volcanoes across Hazard and Uncertainty Levels.

Table 11.32 Identities of Panama's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2	Barú		
Hazard Level 1			Valle, El
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 11.3 shows the classifications of Panama's two volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 11.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Panama's volcanoes have identical PEI scores. Their different Hazard Levels, however, mean that one is classed as Risk Level 2, and the other as Risk Level 1. Highest uncertainty surrounds the Risk Level 1 volcano.

Figure 11.46: Distribution of Panama's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 11.2 Identities of Panama's volcanoes in each Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2		Barú	
Hazard Level 1		Valle, El	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Panama's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 11.1 and Figure 11.2.

Risk Level 2:

• Barú	Uncertainty Level 1

Risk Level 1:

• Valle, El	Uncertainty Level 3

Of Panama's two volcanoes, one is Risk Level 2, and one is Risk Level 1.

Hazard-specific exposure assessments

Table 11.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 11.33 Extent of infrastructure exposure to lahars and pyroclastic flows in Panama.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities:	0	Number of cities:	0
	Percentage of total number of cities:	0%	Percentage of total number of cities:	0%
Population	Number of people:	0	Number of people:	110,000
	Percentage of total number of people:	0%	Percentage of total number of people:	3%
Ports	Number of ports:	0	Number of ports:	0
	Percentage of total number of ports:	0%	Percentage of total number of ports:	0%
All Roads	Length (km):	0	Length (km):	200
	Percentage of total length:	0%	Percentage of total length:	5%
Main Roads	Length (km):	0	Length (km):	30
	Percentage of total length:	0%	Percentage of total length:	2%
All Railways	Length (km):	0	Length (km):	6
	Percentage of total length:	0%	Percentage of total length:	3%
Airports	Number of airports:	0	Number of airports:	2
	Percentage of all airports:	0%	Percentage of all airports:	4%

Figure 11.4 shows agriculture and infrastructure elements exposed to ash hazards, and a wind rose indicating prevalent conditions for Panama.

Wind direction is variable, although predominantly towards the northeast (approximately 20%) and west (19%). Stronger winds (20-50 m/s) are typically south-westerly and westerly The only historically active VEI 3+ volcano in Panama is Barú, which lies approximately 300 km east northeast of Panama city. As winds in this direction are relatively infrequent the city is less likely to be significantly affected by ash fall, although flights in and out of the country could be impacted. Enrique Malek International Airport (David city) is 50 km to the south of Barú. The main agricultural lands are to the east of the country, and could be affected by ash fall from a major eruption in conjunction with strong westerly winds.

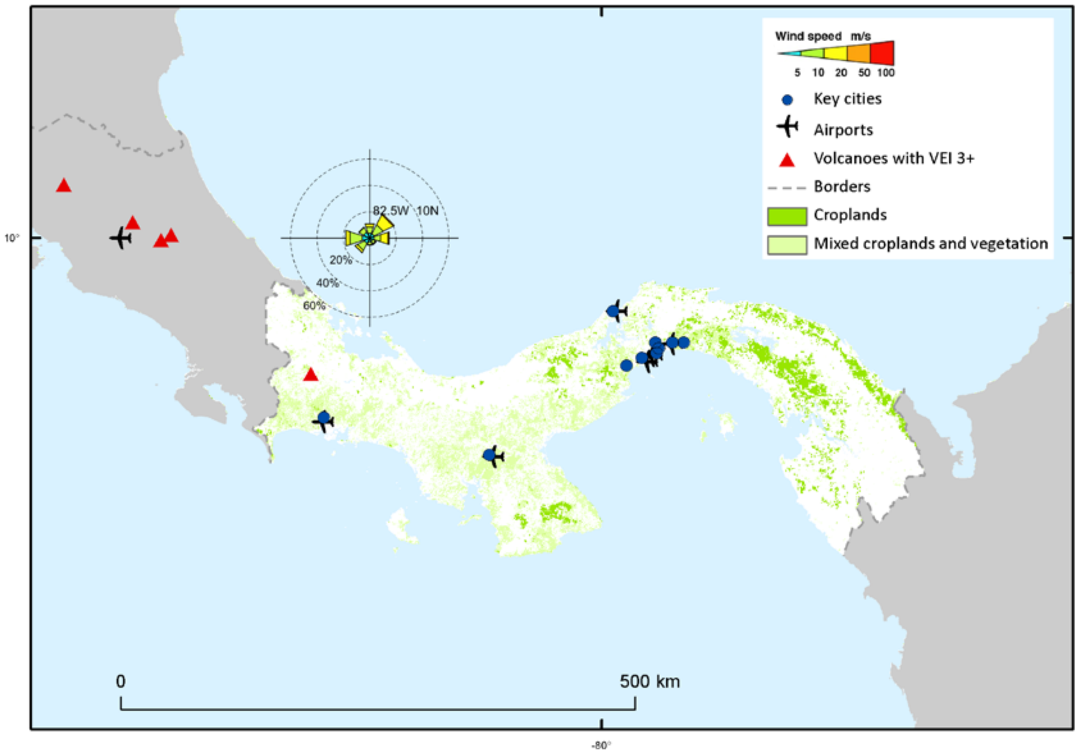


Figure 11.47: Map showing elements exposed to ash hazards in Panama, with wind rose indicating dominant wind directions and speeds.

<u>Frequency of Explosive Volcanism</u>

Table 11.4 gives estimated return periods for different magnitude eruptions in the Central American region, which comprises Panama, Guatemala, and Costa Rica in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 11.34: Return periods for different magnitude eruptions in Panama.

Magnitude	**Return Period (years)**
3	8.8
3.5	17
4	35
4.5	67
5	120
5.5	300
6	640
6.5	1,700
7	7,400
8	460,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Panama's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

The higher risk of the two Holocene volcanoes in Panama also has a slightly higher Monitoring Level, as it is monitored continuously and has a permanent seismic network.

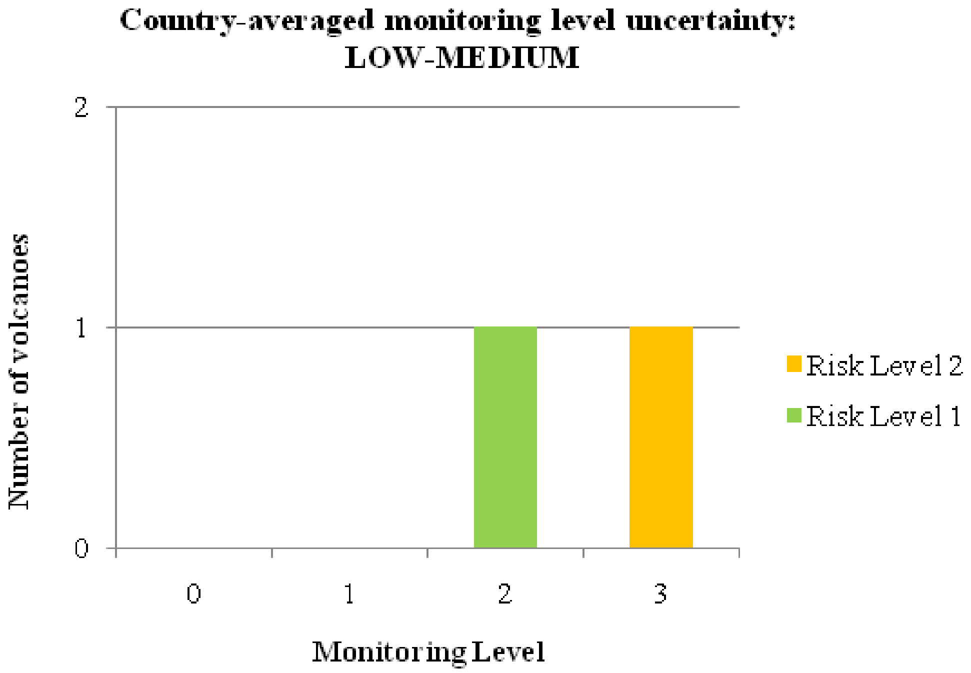


Figure 11.48: Distribution of Panama's volcanoes across Monitoring and Risk Levels.

Summary

Panama's two volcanoes pose moderate risk. Geological knowledge is somewhat limited, though both volcanoes are monitored to an adequate level.

C12 Papua New Guinea

Description

The fifty-six Holocene volcanoes located in Papua New Guinea in the GVP database are some of the most active in the southwest Pacific. The volcanoes of Papua New Guinea cover a large area, stretching from Doma Peaks near the Indonesian border in the west to Loloru on Bougainville Island in the east, and from St. Andrew Strait in the Admiralty Islands in the north to Dawson Strait Group in the D'Entrecasteaux Islands in the south. Papua New Guinea is located within one of the world's most complex tectonic settings, with seven different plates interacting within the region. The main volcanoes of Papua New Guinea are related to the subduction of the Solomon Sea Plate to the south, and of the Pacific Plate beneath the North Bismarck Plate to the north.

The volcanoes of Papua New Guinea are of dominantly-explosive types, with only thirteen volcanic fields, submarine volcanoes or similar. Seventeen of Papua New Guinea's volcanoes have produced pyroclastic flows, and nine have triggered lahars. Some of the country's most populous cities are overlooked by volcanoes responsible for powerful explosive eruptions; Popondetta, home to 28,000, is located 25 km north northeast of Lamington, and Kokopo, which has a population of roughly 26,000, is situated just over 10 km from Rabaul.

The most renowned eruption of a Papua New Guinean volcano is probably that of Lamington in 1951. The peak was not recognised as a volcano before it sprang to life in January 1951, with a VEI 4 eruption that caused pyroclastic flows and surges that swept all sides of the volcano. The eruption caused 2,492 fatalities and extensive damage. Rabaul is also notable for recent destructive activity. A VEI 4 eruption in 1937 which triggered pyroclastic flows, lahars, and tsunami caused 507 deaths, whilst powerful explosive eruptions in 1994 caused the temporary abandonment of Rabaul City.

Whilst Lamington and Rabaul are well known for fairly recent, high impact eruptions, in terms of loss of life the largest volcanic disaster in Papua New Guinea was in fact the 1888 eruption of Ritter Island. Located off the western tip of New Britain, this eruption caused massive slope failure that triggered tsunamis that devastated the coastline of mainland Papua New Guinea and claimed approximately 3,000 lives. Along with these three volcanoes, Manam is notable for its persistent activity with forty-three eruptions recorded since 1616. Though activity at Manam is typically mild to moderate, some larger eruptions have impacted populated areas through generation of pyroclastic flows and lavas that have reached low-lying coastal towns.

Location of Papua New Guinea’s Volcanoes and Key Cities

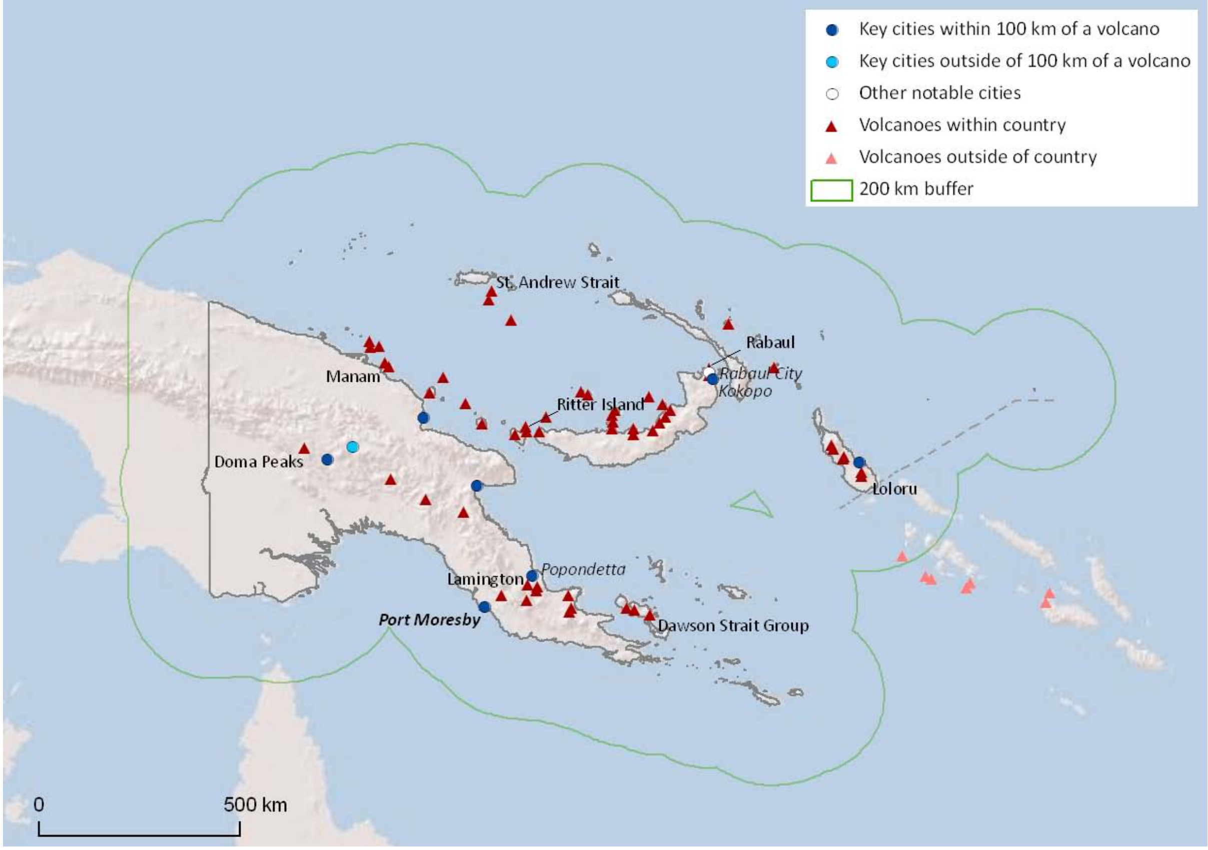


Figure 12.49: Locations of Papua New Guinea's volcanoes, eight largest cities, and other notable cities. A zone extending 200 km beyond the country’s borders shows other volcanoes whose eruptions may affect Papua New Guinea.

Volcanic Facts

Number of Holocene volcanoes:	56
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	43 and 13 respectively
Number of volcanoes generating pyroclastic flows:	18
Number of volcanoes generating lahars:	9
Number of volcanoes generating lava flows:	27
Number of fatalities caused by volcanic eruptions:	9,499

Socio-Economic Facts

Total population:	6,888,400
GDP per capita, 2008 PPP US$:	2,395
HDI:	0.431 – Low

Eight largest cities, as measured by population ("Key Cities"), and populations:

- Port Moresby (capital city)	Population:	283,733
- Lae	Population:	76,255
- Arawa	Population:	40,266
- Mount Hagen	Population:	33,623
- Popondetta	Population:	28,198
- Madang	Population:	27,419
- Kokopo	Population:	26,273
- Mendi	Population :	26,252

Distance from capital city to nearest volcano:	51 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	7 (88%)
Number (percentage) of people living within 10 km of a volcano:	170,000 (3%)
Number (percentage) of people living within 30 km of a volcano:	830,000 (14%)
Number (percentage) of people living within 100 km of a volcano:	4,200,000 (70%)

Hazard and Uncertainty Assessments

The plot in Figure 12.2 shows the classifications of Papua New Guinea's fifty-six volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 12.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Papua New Guinea's volcanoes fall in broadly three areas of the Hazard-Uncertainty distribution: Hazard Level 3, Uncertainty Level 1; Hazard Level 2, all Uncertainty Levels; and Hazard Level 1, Uncertainty Level 3. Of note are the six volcanoes of Hazard Level 2 and Uncertainty Level 3. The general pattern of increasing uncertainty with decreasing hazard is common to many of the GFDRR priority countries.

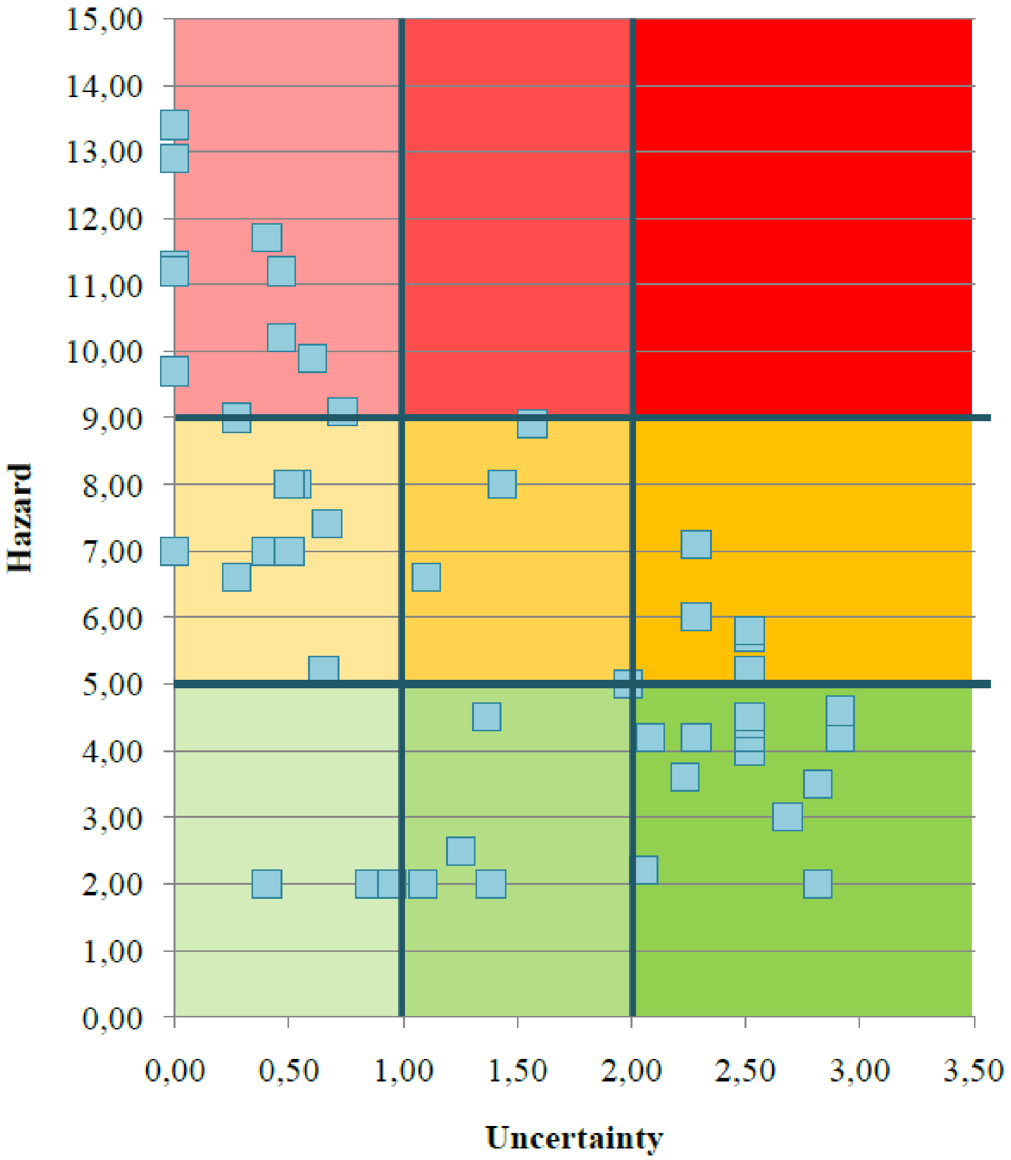


Figure 12.50: Distribution of Papua New Guinea's volcanoes across Hazard and Uncertainty Levels.

Table 12.35 Identities of Papua New Guinea's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Bagana Billy Mitchell Dakataua Karkar Lamington Langila Long Island Manam Pago Rabaul Ulawun		
Hazard Level 2	Bamus Garbuna Group Loloru Ritter Island St. Andrew Strait Tavui Victory Waiowa	Balbi Bam Hargy Lolobau	Doma Peaks Mundua Sakar Sulu Range Takuan Group Umboi
Hazard Level 1	Musa River Unnamed (0500-03-) Unnamed (0501-04=)	Ambitle Managlase Plateau Unnamed (0502-001) Unnamed (0502-131) Yomba	Baluan Blup Blup Boisa Bola Crater Mountain Dawson Strait Group Garove Garua Harbour Goodenough Hydrographers Range Iamalele Kadovar Koranga Lihir Lolo Madilogo Sessagara Tore Yelia
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot below shows the classifications of Papua New Guinea's fifty-six volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 12.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

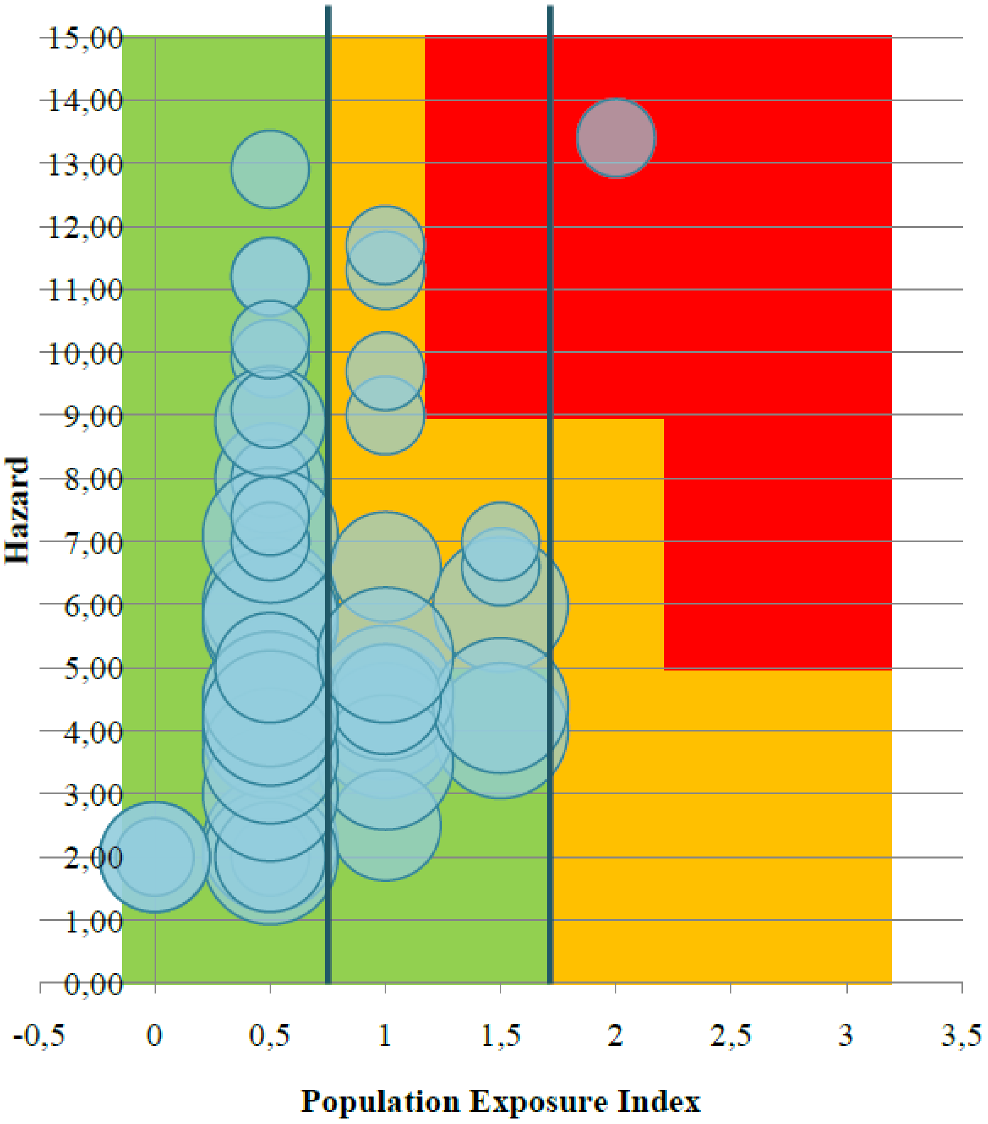


Figure 12.51: Distribution of Papua New Guinea's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Papua New Guinea's volcanoes are concentrated in PEI Levels 1 and 2; only one volcano has a PEI of Level 3. As such, the majority of the volcanoes, forty-six of fifty-six, are Risk Level 1. Uncertainty surrounding Risk Level 2 and 3 volcanoes is generally lower than that for Risk Level 1 volcanoes.

Table 12.36 Identities of Papua New Guinea's volcanoes in each Hazard-PEI cohort.

Hazard Level 3	Bagana Billy Mitchell Dakataua Langila Long Island Ulawan	Karkar Lamington Manam Pago	Rabaul
Hazard Level 2	Balbi Bam Bamus Lolobau Loloru Mundua Ritter Island Sakar St. Andrew Strait Sulu Range Umboi Victory Waiowa	Doma Peaks Garbuna Group Hargy Takuan Group Tavui	
Hazard Level 1	Baluan Blup Blup Boisa Bola Dawson Strait Group Goodenough Iamalele Kadovar Lihir Madilogo Musa River Sessagara Tore Unnamed (0500-03-) Unnamed (0501-04=) Unnamed (0502-001) Unnamed (0502-131) Yelia Yomba	Ambitle Crater Mountain Garove Garua Harbour Hydrographers Range Koranga Lolo Managlase Plateau	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Papua New Guinea’s volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 12.1 and Figure 12.2.

Risk Level 3:

• Rabaul	Uncertainty Level 1

Risk Level 2:

• Doma Peaks	Uncertainty Level 3
• Garbuna Group	Uncertainty Level 1
• Hargy	Uncertainty Level 2
• Karkar	Uncertainty Level 1
• Lamington	Uncertainty Level 1
• Manam	Uncertainty Level 1
• Pago	Uncertainty Level 1
• Takuan Group	Uncertainty Level 3
• Tavui	Uncertainty Level 1

Risk Level 1:

• Ambitle	Uncertainty Level 2
• Bagana	Uncertainty Level 1
• Balbi	Uncertainty Level 2
• Baluan	Uncertainty Level 3
• Bam	Uncertainty Level 2
• Bamus	Uncertainty Level 1
• Billy Mitchell	Uncertainty Level 1
• Blup Blup	Uncertainty Level 3
• Boisa	Uncertainty Level 3
• Bola	Uncertainty Level 3
• Crater Mountain	Uncertainty Level 3
• Dakataua	Uncertainty Level 1
• Dawson Strait Group	Uncertainty Level 3
• Garove	Uncertainty Level 3
• Garua Harbour	Uncertainty Level 3
• Goodenough	Uncertainty Level 3
• Hydrographers Range	Uncertainty Level 3
• Iamalele	Uncertainty Level 3
• Kadovar	Uncertainty Level 3
• Koranga	Uncertainty Level 3

Langila	Uncertainty Level 1
Lihir	Uncertainty Level 3
Lolo	Uncertainty Level 3
Lolobau	Uncertainty Level 2
Loloru	Uncertainty Level 1
Long Island	Uncertainty Level 1
Madilogo	Uncertainty Level 3
Managlase Plateau	Uncertainty Level 2
Mundua	Uncertainty Level 3
Musa River	Uncertainty Level 1
Ritter Island	Uncertainty Level 1
Sakar	Uncertainty Level 3
Sessagara	Uncertainty Level 3
St. Andrew Strait	Uncertainty Level 1
Sulu Range	Uncertainty Level 3
Tore	Uncertainty Level 3
Ulawun	Uncertainty Level 1
Umboi	Uncertainty Level 3
Unnamed (0500-03-)	Uncertainty Level 1
Unnamed (0501-04=)	Uncertainty Level 1
Unnamed (0502-001)	Uncertainty Level 2
Unnamed (0502-131)	Uncertainty Level 2
Victory	Uncertainty Level 1
Waiowa	Uncertainty Level 1
Yelia	Uncertainty Level 3
Yomba	Uncertainty Level 2

Of Papua New Guinea’s fifty-six volcanoes, one is Risk Level 3, nine are Risk Level 2, and forty-six are Risk Level 1.

Hazard-specific exposure assessments

Table 12.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies. Note no data, and thus results, were available for railways in Papua New Guinea.

Table 12.37 Extent of infrastructure exposure to lahars and pyroclastic flows in Papua New Guinea.

Exposed Elements	Lahars	Pyroclastic Flows
Cities (population > 20,000)	Number of cities: 3 Percentage of total number of cities: 38%	Number of cities: 1 Percentage of total number of cities: 13%
Population	Number of people: 750,000 Percentage of total number of people: 13%	Number of people: 260,000 Percentage of total number of people: 4%
Ports	Number of ports: 2 Percentage of total number of ports: 10%	Number of ports: 3 Percentage of total number of ports: 15%
All Roads	Length (km): 1,200 Percentage of total length: 12%	Length (km): 49 Percentage of total length: 5%
Main Roads	Length (km): 68 Percentage of total length: 12%	Length (km): 0 Percentage of total length: 0%
Airports	Number of airports: 1 Percentage of all airports: 6%	Number of airports: 1 Percentage of all airports: 6%

Figure 12.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Papua New Guinea.

In the north of Papua New Guinea, easterly winds dominate (occurring approximately 60% of the time) and average speeds exceed 20 m/s several times in the year. In the south (in the region of Lamington and Waiowa volcanoes) winds are much more variable. The capital city of Port Moresby and primary international airport lies approximately 100 km west southwest of Lamington. Flights to airports on the north east coast could be affected by ash fall from the island volcanoes in the northeast and on New Britain island, due to dominant easterly winds. Madang (city and airport for domestic flights) is perhaps the most likely to be impacted. Mixed croplands can be found across the country, with dedicated crop lands to the west of Lamington, and along the northeast, within approximately 100 km and largely downwind of the volcanic islands of Bam, Manam, Karkar and Long Island.

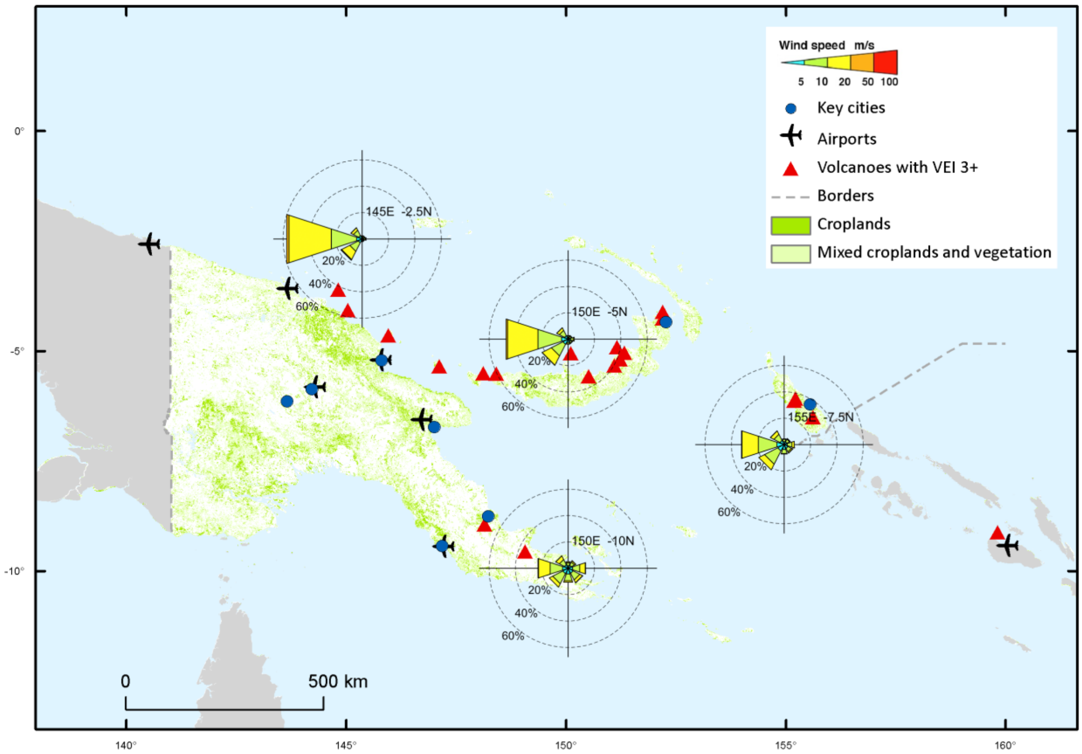


Figure 12.52: Map showing elements exposed to ash hazards in Papua New Guinea, with wind roses indicating dominant wind directions and speeds.

Frequency of Explosive Volcanism

Table 12.4 gives estimated return periods for different magnitude eruptions in the Pacific region, which comprises Papua New Guinea, The Solomon Islands, and Vanuatu in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 12.4 Return periods for different magnitude eruptions in Papua New Guinea.

Magnitude	**Return Period (years)**
3	4.3
3.5	8.2
4	17
4.5	33
5	60
5.5	150
6	310
6.5	820
7	3,700
8	220,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Papua New Guinea's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

The Rabaul Volcanological Observatory monitors six of the fifty-six Holocene volcanoes in Papua New Guinea continuously, four of which are Risk Level 2 or 3 volcanoes. There are also eleven seismic stations in Papua New Guinea which provide seismic monitoring for four more volcanoes, three of which are Risk Level 2. The Rabaul Volcanological Observatory appears a well established institution but facilities are not particularly wide-ranging and there is a high level of uncertainty surrounding the monitoring status of the remaining forty-six volcanoes.

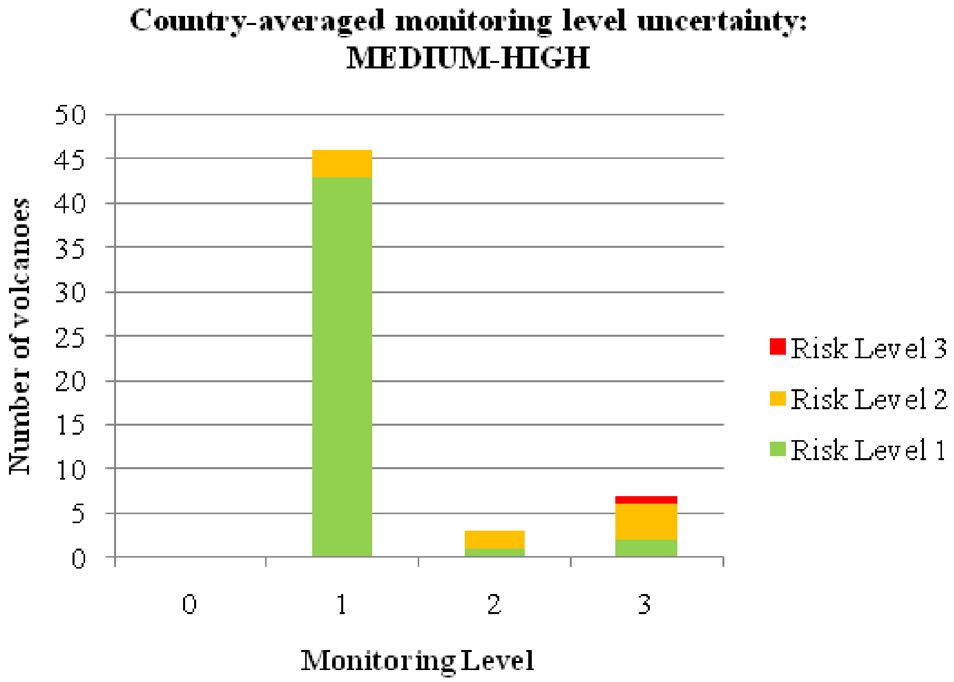


Figure 12.53: Distribution of Papua New Guinea's volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk in Papua New Guinea is moderate to significant in a few localities. Whilst only one volcano is classed as Risk Level 3, physical Hazard Levels are high at other volcanoes; the historical record indicates that many of Papua New Guinea's volcanoes can cause high-impact eruptions. Many of the highest risk volcanoes are monitored well. However, knowledge surrounding quite a large group of volcanoes, here classified mostly as Hazard Level 1, is lacking.

C13 The Philippines

Description

The GVP database holds records of forty-seven Holocene volcanoes in the Philippines. Forty-two are spread across four islands, with a further five located in the sea to the north of the country. The tectonic setting of the Philippines is quite complex. Most of the country's volcanism results from the subduction of the oceanic Philippine Plate below the Eurasian Plate, giving a line of volcanoes located along the eastern side of the archipelago.

Forty-five of forty-seven of the Philippines' volcanoes are of generally-explosive type, namely stratovolcanoes, complex volcanoes, compound volcanoes, or calderas. Eruptions of Philippine volcanoes frequently result in lahars, as heavy rainfall associated with typhoons regularly remobilises tephra; a secondary lahar in 1875 at Mayon volcano followed the 1873 eruption and claimed 1,500 lives. Ten of the volcanoes in the Philippines have also generated pyroclastic flows; in combination, these flows have lead to high human impacts, with 13% of Philippine eruptions having caused a total 7,900 fatalities, and 22% causing recorded damage.

The country's best known volcanoes are Mayon, Taal, and Pinatubo, all of which have over 100,000 living within 30 km of their summits, along with thirty-seven others. Mayon is the Philippines' most active volcano, with sixty eruptions recorded since 1616. Mayon has frequently generated pyroclastic flows and lahars that have travelled down many of the valleys that radiate from the summit, devastating populated areas at the base of the volcano. Though its location in southeast Luzon Island means the Philippines' largest population centres are not threatened by Mayon, its most violent eruption nevertheless killed 1,200 and destroyed several towns. Taal volcano is located roughly 30 km south of the country's 9th most populous city, Dasmariñas City, and 65 km south of the capital, Manila. Taal has produced some of the Philippines' most powerful eruptions, with a VEI 3 eruption in 1911 causing extensive pyroclastic flows and up to 2,000 fatalities.

The 1991 eruption of Pinatubo, one of the largest eruptions in the World in the 20th century at VEI 6, ejected enormous volumes of ash and generated pyroclastic flows which extended up to 20 km from the summit. Secondary lahars have been generated since the eruption, causing further disruption and damage. Though the damage caused by the eruption led to huge socio-economic impacts, the number of fatalities was low relative to the eruption size as a result of successful monitoring and evacuation. An estimated 800 lives were lost, though up to half of these are attributable to disease in evacuation camps. In general, the emergency response to the eruption was widely viewed as a major success with many tens of thousands of people having been evacuated in time, thus averting a disaster potentially as great as the 2004 Sumatra earthquake and tsunami.

An eruption of Mayon in December 2009 was the Philippines' most recent volcanic crisis. The VEI 2 eruption started on 14th December, with ash emissions, lava flows, and pyroclastic flows that moved roughly 2 km from the crater. The alert level peaked at 4, meaning "a hazardous explosive eruption is possible within days," on 20th December, and was lowered to level 3 on 2nd January 2010. Over 47,000 people were ordered to evacuate, requiring the abandonment of homes and farms.

Location of The Philippines' Volcanoes and Key Cities

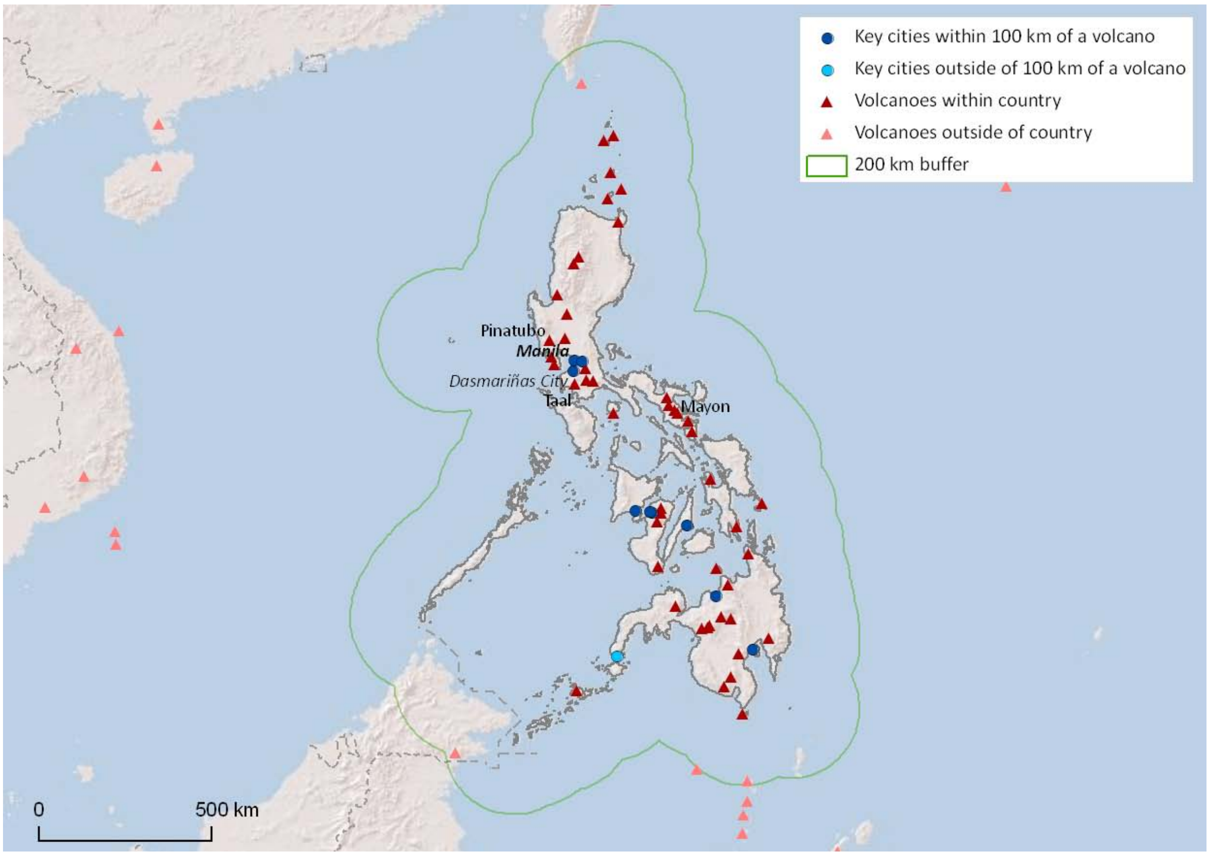


Figure 13.54: Locations of The Philippines' volcanoes and ten largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect The Philippines.

Volcanic Facts

Number of Holocene volcanoes:	47
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	45 and 2 respectively
Number of volcanoes generating pyroclastic flows:	10

Number of volcanoes generating lahars:	8
Number of volcanoes generating lava flows:	9
Number of fatalities caused by volcanic eruptions:	7,990

Socio-Economic Facts

Total population:	93,616,900
GDP per capita, 2008 PPP US$:	3,601
HDI:	0.638 – Medium

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Manila (capital city)	Population:	10,444,527
- Davao	Population:	1,212,504
- Cebu City	Population:	798,634
- Antipolo	Population:	549,543
- Zamboanga	Population:	457,623
- Bacolod City	Population:	454,898
- Mansilingan	Population:	454,150
- Cagayan de Oro	Population :	445,103
- Dasmariñas	Population :	441,876
- Iloilo	Population :	387,681

Distance from capital city to nearest volcano:	37 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	320 (96%)
Number (percentage) of people living within 10 km of a volcano:	3,100,000 (3%)
Number (percentage) of people living within 30 km of a volcano:	32,000,000 (33%)
Number (percentage) of people living within 100 km of a volcano:	90,000,000 (92%)

Hazard and Uncertainty Assessments

The plot in Figure 13.2 shows the classifications of The Philippines’ forty-seven volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 13.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

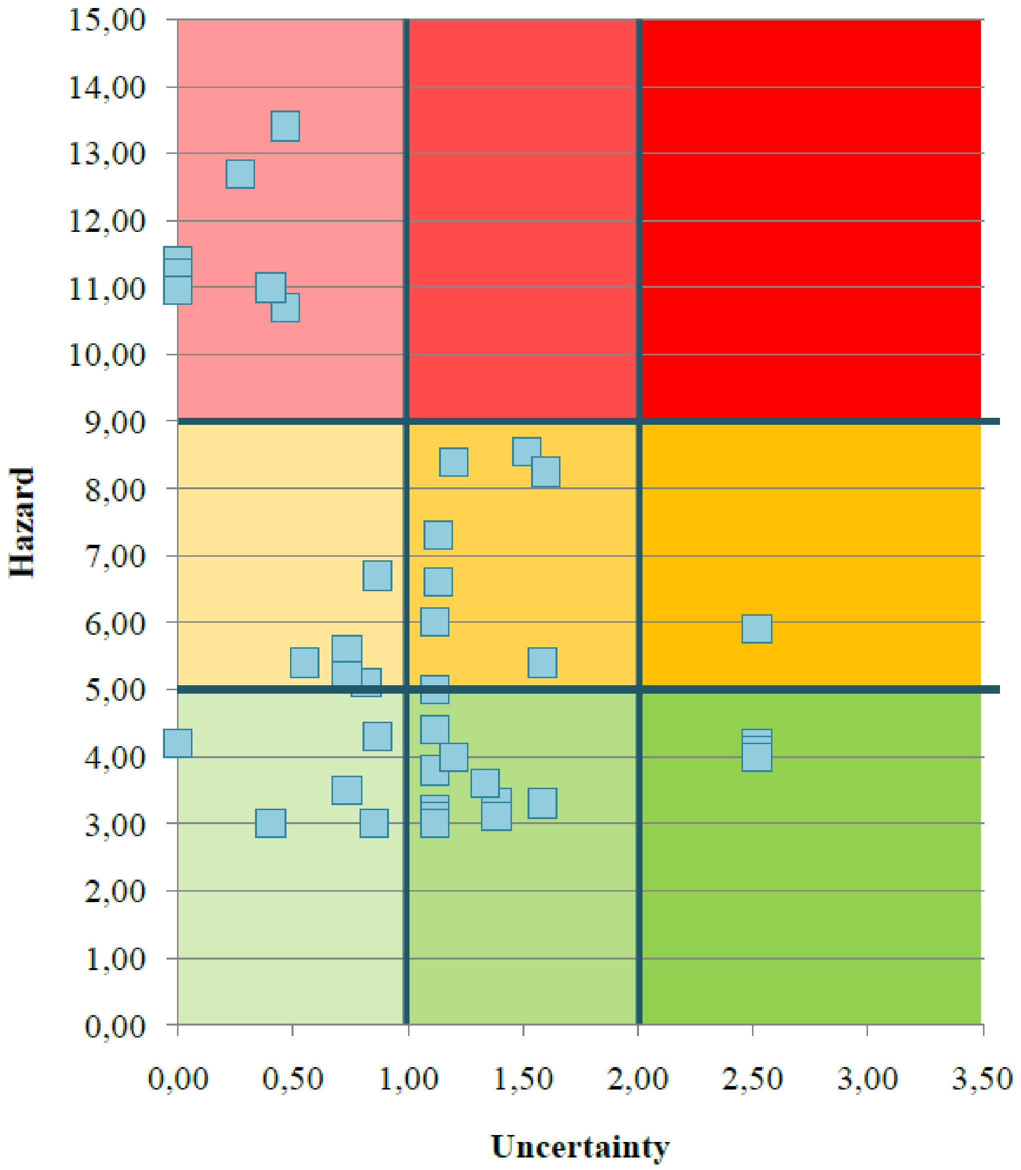


Figure 13.55: Distribution of The Philippines' volcanoes across Hazard and Uncertainty Levels.

The Philippines’ volcanoes are mostly classed as Hazard Level 1 or 2, though a not insignificant group of seven volcanoes are Hazard Level 3. With the exception of these seven Hazard Level 3 volcanoes, the overall pattern appears to be one of increasing uncertainty with increasing hazard; this is the opposite to what is seen in many other GFDRR priority countries. Of note is Paco, which has somewhat higher Uncertainty Levels than would be expected given its Hazard Level.

Table 13.38 Identities of The Philippines' volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Bulusan Camiguin Kanlaon Mayon Parker Pinatubo Taal		
Hazard Level 2	Ambalatungan Group Babuyan Claro Cagua Mahagnao Ragang	Apo Banahaw Cabalían Iraya Laguna Caldera Leonard Range Makaturing Matutum San Pablo Volcanic Field	Paco
Hazard Level 1	Biliran Camiguin de Babuyanes Didicas Malindig Unnamed (0704-05=)	Amorong Balatukan Balut Cuernos de Negros Isarog Jolo Mandalagan Mariveles Musuan Natib Patoc Pocdol Mountains Silay	Arayat Iriga Kalatungan Latukan Malindang Masaraga Santo Tomas
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 13.3 shows the classifications of The Philippines' forty-seven volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 13.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

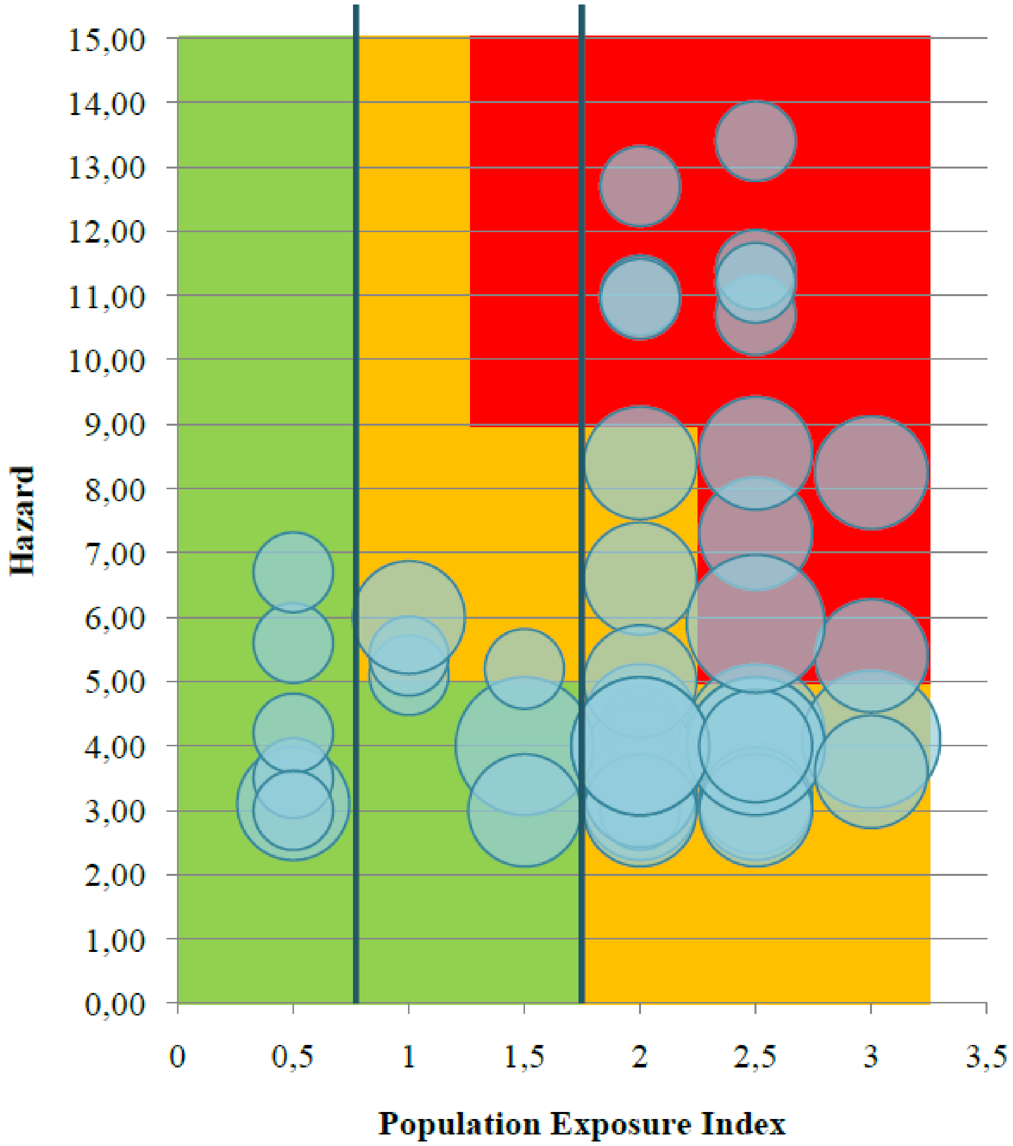


Figure 13.3: Distribution of The Philippines' volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

The Philippines' volcanoes are mostly of PEI Level 3. However, the Level 1 Hazard of many of these means more volcanoes are of Risk Level 2 than Risk Level 3. All three Risk Levels contain volcanoes of each Uncertainty Level.

Table 13.39 Identities of The Philippines' volcanoes in each Hazard-PEI cohort.

Hazard Level 3			Bulusan Camiguin Kanlaon Mayon Parker Pinatubo Taal
Hazard Level 2	Babuyan Claro Cagua	Ambalatungan Group Iraya Mahagnao Ragang	Apo Banahaw Cabalían Laguna Caldera Leonard Range Makaturing Matutum Paco San Pablo Volcanic Field
Hazard Level 1	Balut Camiguin de Babuyanes Didicas Unnamed (0704-05=)	Balatukan Latukan	Amorong Arayat Biliran Cuernos de Negros Iriga Isarog Jolo Kalatungan Malindang Malindig Mandalagan Mariveles Masaraga Musuan Natib Patoc Pocdol Mountains Santa Tomas Silay
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of The Philippines' volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 13.1 and Figure 13.2.

Risk Level 3:

Banahaw	Uncertainty Level 2
Bulusan	Uncertainty Level 1
Cabalían	Uncertainty Level 2
Camiguin	Uncertainty Level 1
Kanlaon	Uncertainty Level 1
Laguna Caldera	Uncertainty Level 2
Mayon	Uncertainty Level 1
Paco	Uncertainty Level 3
Parker	Uncertainty Level 1
Pinatubo	Uncertainty Level 1
San Pablo Volcanic Field	Uncertainty Level 2
Taal	Uncertainty Level 1

Risk Level 2:

Ambalatungan Group	Uncertainty Level 1
Amorong	Uncertainty Level 2
Apo	Uncertainty Level 2
Arayat	Uncertainty Level 3
Biliran	Uncertainty Level 1
Cuernos de Negros	Uncertainty Level 2
Iraya	Uncertainty Level 2
Iriga	Uncertainty Level 3
Isarog	Uncertainty Level 2
Jolo	Uncertainty Level 2
Kalatungan	Uncertainty Level 3
Leonard Range	Uncertainty Level 2
Mahagnao	Uncertainty Level 1
Makaturing	Uncertainty Level 2
Malindang	Uncertainty Level 3
Malindig	Uncertainty Level 1
Mandalagan	Uncertainty Level 2
Mariveles	Uncertainty Level 2
Masaraga	Uncertainty Level 3
Matutum	Uncertainty Level 2
Musuan	Uncertainty Level 2
Natib	Uncertainty Level 2
Patoc	Uncertainty Level 2
Pocdol Mountains	Uncertainty Level 2

Ragang	Uncertainty Level 1
Santo Tomas	Uncertainty Level 3
Silay	Uncertainty Level 2

Risk Level 1:

Babuyan Claro	Uncertainty Level 1
Balatukan	Uncertainty Level 2
Balut	Uncertainty Level 2
Cagua	Uncertainty Level 1
Camiguin de Babuyanes	Uncertainty Level 1
Didcas	Uncertainty Level 1
Latukan	Uncertainty Level 3
Unnamed (0704-05=)	Uncertainty Level 1

Of The Philippines’ forty-seven volcanoes, twelve are Risk Level 3, twenty-seven are Risk Level 2, and eight are Risk Level 1.

<u>Hazard-specific exposure assessments</u>

Table 13.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 13.40 Extent of infrastructure exposure to lahars and pyroclastic flows in The Philippines.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities:	110	Number of cities:	66
	Percentage of total number of cities:	33%	Percentage of total number of cities:	20%
Population	Number of people:	15,000,000	Number of people:	8,300,000
	Percentage of total number of people:	15%	Percentage of total number of people:	8%
Ports	Number of ports:	3	Number of ports:	6
	Percentage of total number of ports:	4%	Percentage of total number of ports:	9%
All Roads	Length (km):	3,100	Length (km):	1,400
	Percentage of total length:	16%	Percentage of total length:	7%
Main Roads	Length (km):	2,900	Length (km):	1,400
	Percentage of total length:	14%	Percentage of total length:	7%
All Railways	Length (km):	780	Length (km):	520
	Percentage of total length:	32%	Percentage of total length:	22%
Airports	Number of airports:	8	Number of airports:	6
	Percentage of all airports:	13%	Percentage of all airports:	9%

Figure 13.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for The Philippines.

Wind patterns vary greatly across the islands. Easterlies dominate in the south (near Parker volcano) and according to the reanalysis data occur approximately 71 % of the time. Zamboanga lies about 320 km east northeast of Parker and the airport (providing international and domestic flights) could therefore be affected by ash fall. In the central islands (around fifteen degrees north, near Taal and Pinatubo) wind direction is much more variable, although easterly winds still dominate 27% of the time. The capital Manila (and international airport) lies 65 km north of Taal, and in this region winds are expected to travel in a northerly direction about 11 % of the time. Manila is also relatively close to Pinatubo (approximately 90 km) although winds from the northwest are less frequent. The large expanses of croplands around Pinatubo would also be vulnerable to ash.

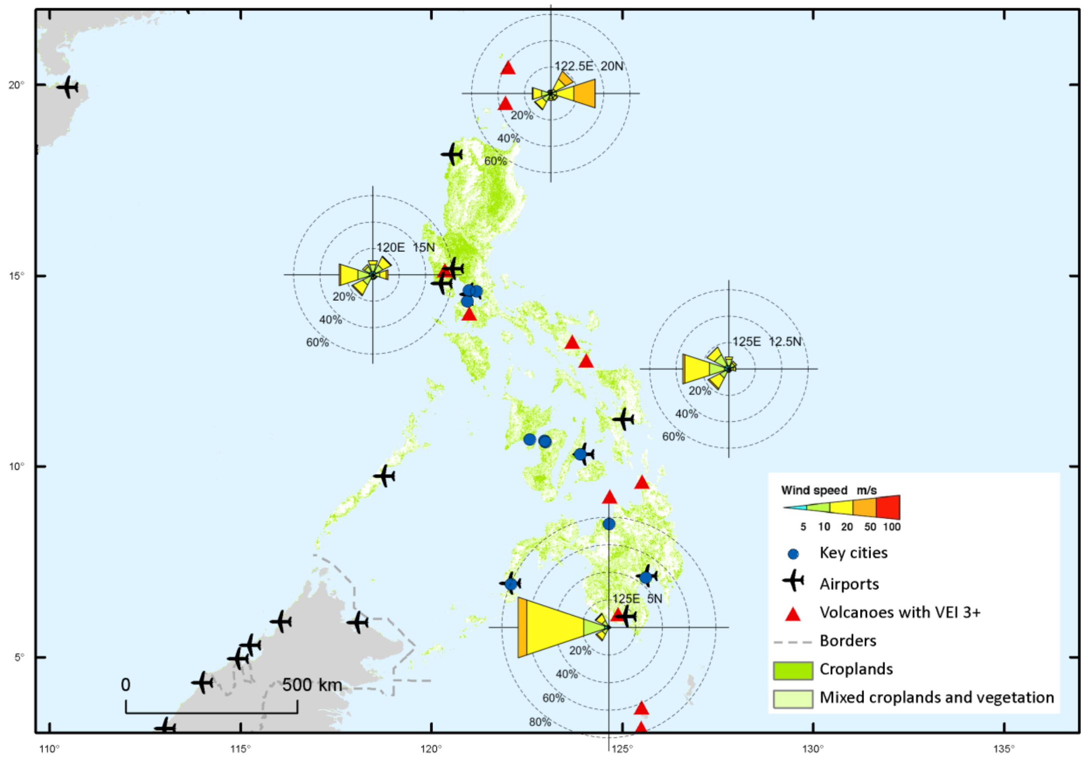


Figure 13.4: Map showing elements exposed to ash hazards in The Philippines, with wind roses indicating dominant wind directions and speeds.

Frequency of Explosive Volcanism

Table 13.4 gives estimated return periods for different magnitude eruptions in The Philippines. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 13.41: Return periods for different magnitude eruptions in The Philippines.

Magnitude	Return Period (years)
3	5.7
3.5	11
4	23
4.5	43
5	78
5.5	196
6	410
6.5	1,100
7	4,800
8	290,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of The Philippines' volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

Eight of the forty-seven Philippine volcanoes are monitored continuously by PHIVOLCS at facilitated observatories. All of these eight volcanoes are also classified as Risk Level 3. There is a high degree of uncertainty surrounding whether local observatories monitor the remaining thirty-nine volcanoes, and they were therefore assigned a Monitoring Level of 1. There are however sixty-five seismic stations across the Philippines, and twenty-six volcanoes are within approximately 15 km of at least one of these regional stations. No volcanoes have therefore been assigned Monitoring Level 0.

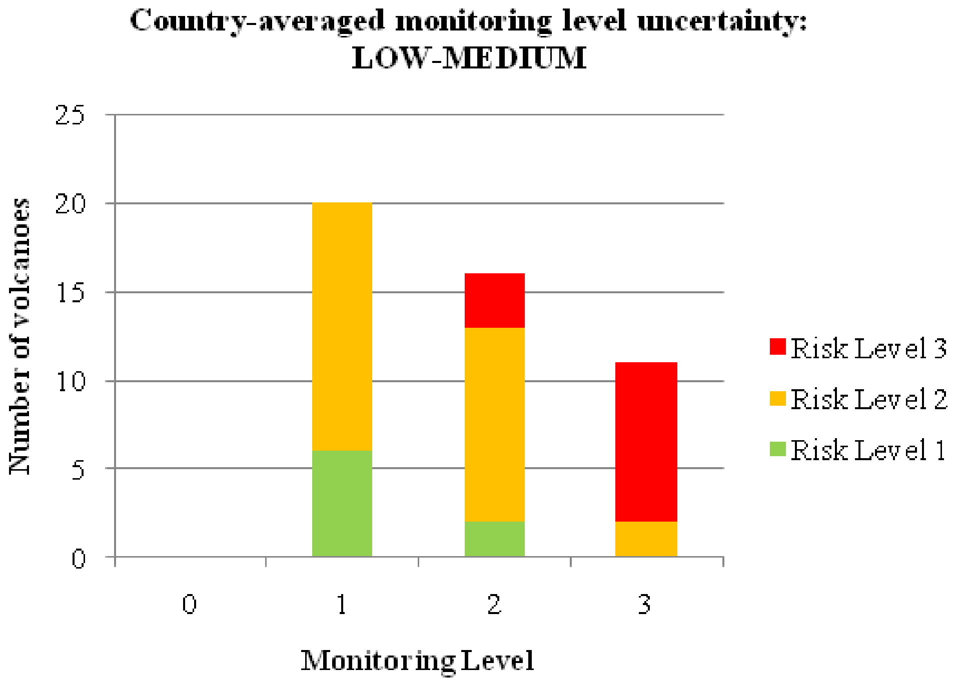


Figure 13.5: Distribution of The Philippines' volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk in The Philippines is significant, with many Risk Level 3 volcanoes, and further moderately hazardous volcanoes with large surrounding populations. Whilst monitoring of the majority of the Risk Level 3 volcanoes is at Monitoring Level 3, there are many Risk Level 2, and a few Risk Level 3, volcanoes that are not so closely monitored. There is moderate to high uncertainty surrounding a considerable number of volcanoes, reflecting the need for more geological knowledge.

C14 The Solomon Islands

Description

A fairly complex tectonic setting involving several microplates and two larger plates gives rise to the eight Holocene volcanoes listed for the Solomon Islands in the GVP database. Most, however, are associated with subduction of the Solomon Sea Plate beneath the Pacific Plate. Seven of the eight volcanoes lie in a northwest to southeast trending line, forming islands to the west of the archipelago, with the eighth Solomon Islands volcano, Tinakula, located 600 km distant from this chain.

The Solomon Islands volcanoes are made up of four submarine volcanoes, three stratovolcanoes, and one volcanic field. Two, Savo and Tinakula, have generated pyroclastic flows, and only Savo has triggered lahars. The country's largest population centres are not located on any of the volcanic islands, though the capital, Honiara, could be affected by tsunami generated by Savo, 35 km to the northwest. Two eruptions from Savo have had major impacts, namely those in 1568 and 1840; the 1568 eruption generated pyroclastic flows that killed the island's approximately 1,000 inhabitants, whilst ash and stones killed many during the 1840 eruption.

Other noteworthy volcanoes in the Solomon Islands are Tinakula and Kavachi. Tinakula is the only other Solomon Islands volcano known to have caused fatalities, when a VEI 3 eruption in 1840 produced pyroclastic flows that swept all sides of the island and killed its inhabitants. Kavachi is one of the most active submarine volcanoes in the entire southwest Pacific, with thirty eruptions recorded since 1939. Kavachi has produced twelve island-forming eruptions in this time, though the volcano's isolated position away from major shipping lanes and airport routes reduces the hazard it poses to people and infrastructure.

Location of The Solomon Islands' Volcanoes and Key Cities

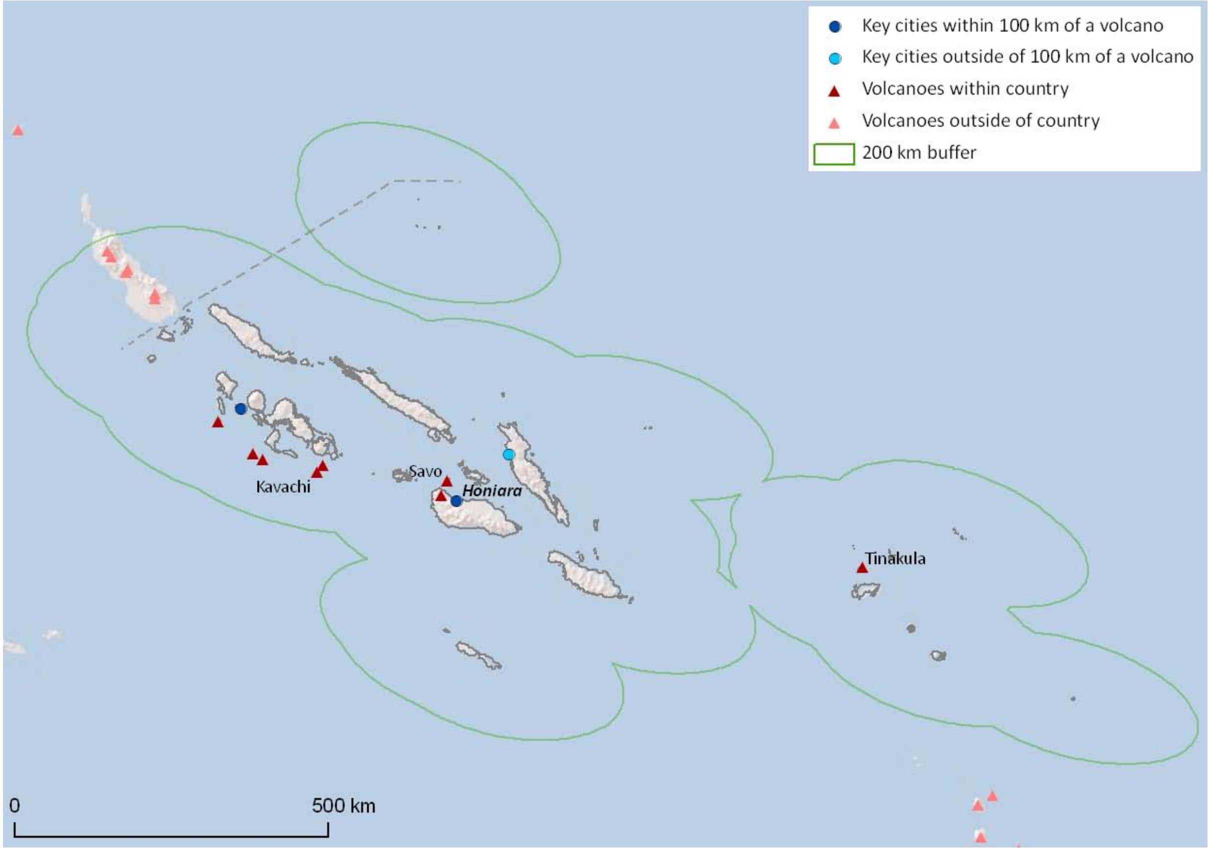


Figure 14.56: Locations of The Solomon Islands' volcanoes, and three largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect The Solomon Islands.

Volcanic Facts

Number of Holocene volcanoes:	8
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	3 and 5 respectively
Number of volcanoes generating pyroclastic flows:	2
Number of volcanoes generating lahars:	1
Number of volcanoes generating lava flows:	2
Number of fatalities caused by volcanic eruptions:	1,418

Socio-Economic Facts

Total population:	535,700
GDP per capita, 2008 PPP US$:	2,546
HDI:	0.494 – Medium

Three largest cities, as measured by population (“Key Cities”), and populations:

- Honiara (capital city)	Population:	52,298
- Gizo	Population:	6,154
- Auki	Population:	4,336

Distance from capital city to nearest volcano:	26 km
Number (percentage) of Key Cities within 100 km of a volcano:	3 (100%)
Number (percentage) of people living within 10 km of a volcano:	4,700 (1%)
Number (percentage) of people living within 30 km of a volcano:	98,000 (16%)
Number (percentage) of people living within 100 km of a volcano:	300,000 (50%)

Hazard and Uncertainty Assessments

The plot on Figure 14.2 shows the classifications of The Solomon Islands’ eight volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 14.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Five of the eight Solomon Islands volcanoes are of Hazard Level 1, and these are split across the three Uncertainty Levels. The lowest Uncertainty Level applies to the two Hazard Level 3 volcanoes.

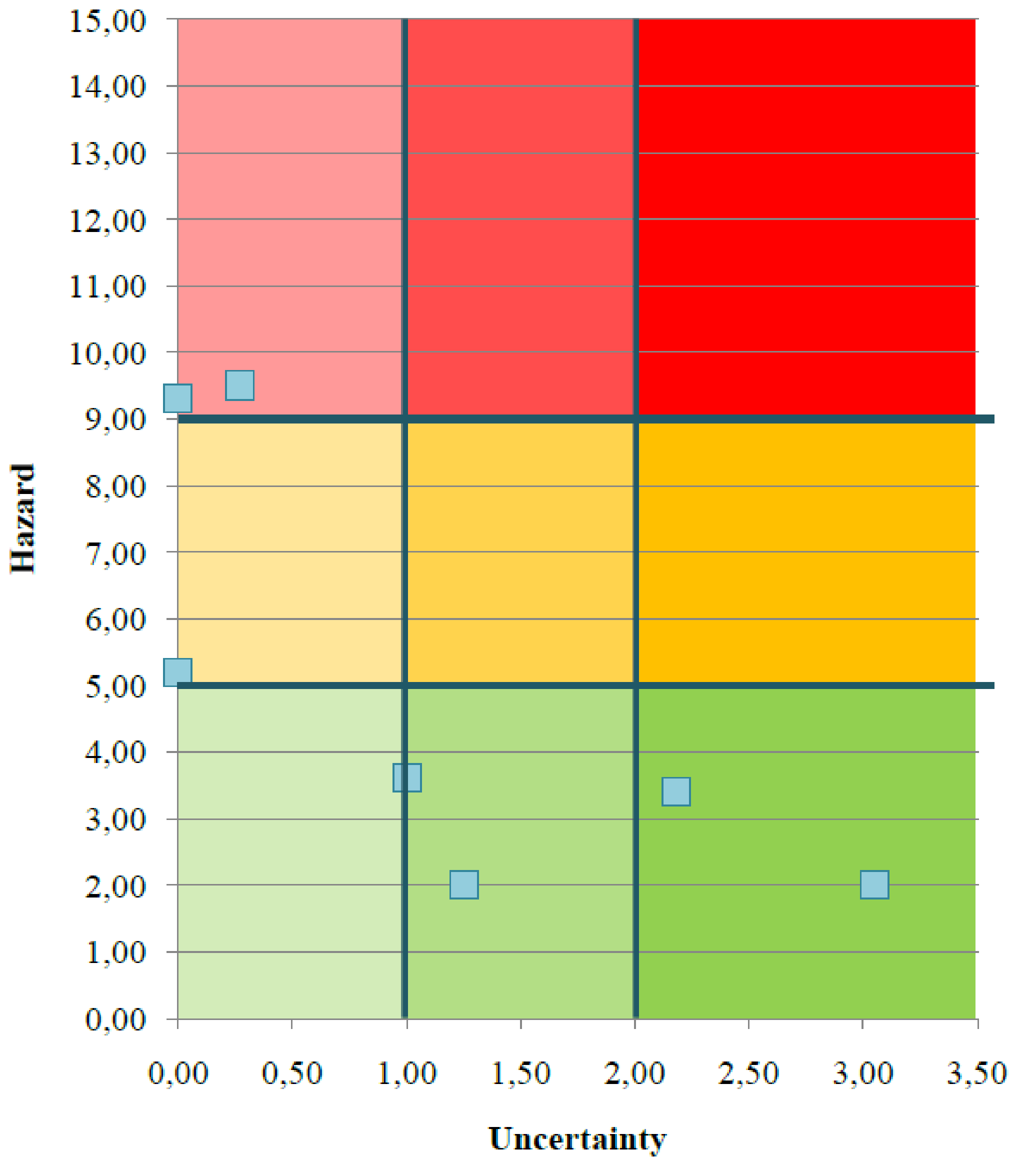


Figure 14.57: Distribution of The Solomon Islands' volcanoes across Hazard and Uncertainty Levels.

Table 14.42 Identities of The Solomon Islands' volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Savo Tinakula		
Hazard Level 2	Kavachi		
Hazard Level 1	Simbo	Coleman Seamount Unnamed (0505-061)	Gallego Kana Keoki
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 14.3 shows the classifications of The Solomon Islands' eight volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 14.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

The Solomon Islands' volcanoes are all of PEI Levels 1 and 2. As such, only one volcano is classed as Risk Level 2; this volcano has Uncertainty Level 1.

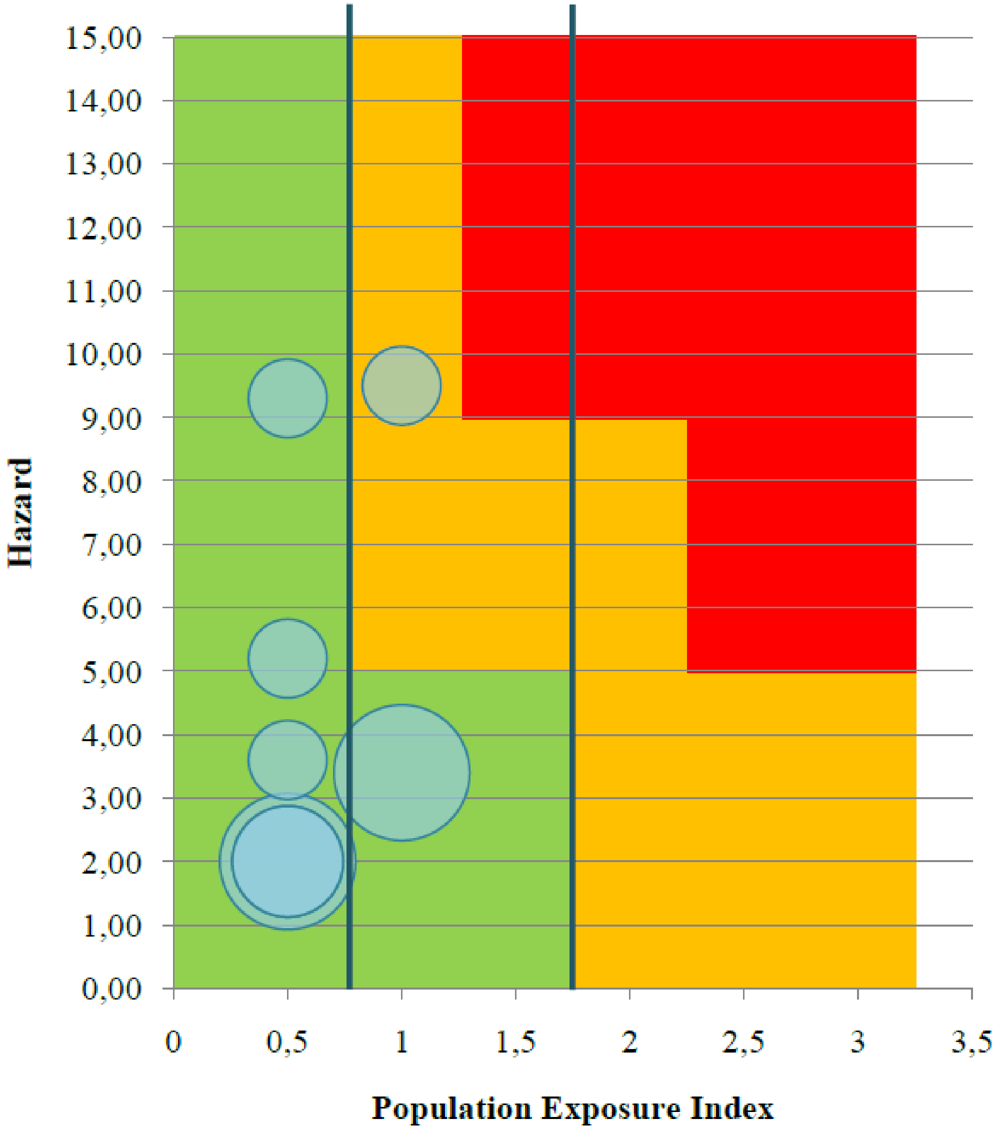


Figure 14.58: Distribution of The Solomon Islands' volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Basic results – Risk assessments

The list below gives the Risk Levels of The Solomon Islands' volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 14.1 and Figure 14.2.

Risk Level 2:

• Savo	Uncertainty Level 1

Risk Level 1:

• Coleman Seamount	Uncertainty Level 2
• Gallego	Uncertainty Level 3

• Kana Keoki	Uncertainty Level 3
• Kavachi	Uncertainty Level 1
• Simbo	Uncertainty Level 1
• Tinakula	Uncertainty Level 1
• Unnamed (0505-061)	Uncertainty Level 2

Of The Solomon Islands’ eight volcanoes, one is Risk Level 2, and seven are Risk Level 1.

Table 14.43 Identities of The Solomon Islands’ volcanoes in each Hazard-PEI cohort.

Hazard Level 3	Tinakula	Savo	
Hazard Level 2	Kavachi		
Hazard Level 1	Coleman Seamount Kana Keoki Simbo Unnamed (0506-061)	Gallego	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Hazard-specific exposure assessments

Table 14.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies. Note that no data, and thus results, were available for all roads, main roads and railways in The Solomon Islands.

Table 14.44 Extent of infrastructure exposure to lahars and pyroclastic flows in The Solomon Islands.

Exposed Elements	Lahars		Pyroclastic Flows	
Key Cities (as defined above)	Number of cities:	0	Number of cities:	0
	Percentage of total number of cities:	0%	Percentage of total number of cities:	0%
Population	Number of people:	1,500	Number of people:	1,600
	Percentage of total number of people:	~ 0%	Percentage of total number of people:	~ 0%
Ports	Number of ports:	0	Number of ports:	0
	Percentage of total number of ports:	0%	Percentage of total number of ports:	0%
Airports	Number of airports:	0	Number of airports:	0
	Percentage of all airports:	0%	Percentage of all airports:	0%

Figure 14.4 shows agriculture and infrastructure elements exposed to ash hazards, and a wind rose indicating prevalent conditions for The Solomon Islands.

Wind direction is variable, low velocity winds are relatively evenly distributed towards the east, south and west sectors, and wind speeds do not typically exceed 20 m/s. Dominant winds, and particularly winds in excess of 10 m/s, are easterly (approximately 18%) and westerly (about 17%). Southerly winds occur least frequently (6-7%). The capital city of Honiara (on Guadalcanal Island) and the Solomon Islands' only international airport (Henderson Field) lie approximately 35 km south southeast of Savo volcano and as such would be vulnerable to ash fall. There is a lower probability of ash impacting the cities of Auki (approximately 100 km east northeast of Savo) or Gizo (about 350 km west northwest). There is agriculture on all islands, but the greatest density of dedicated cropland appears to be on Guadalcanal.

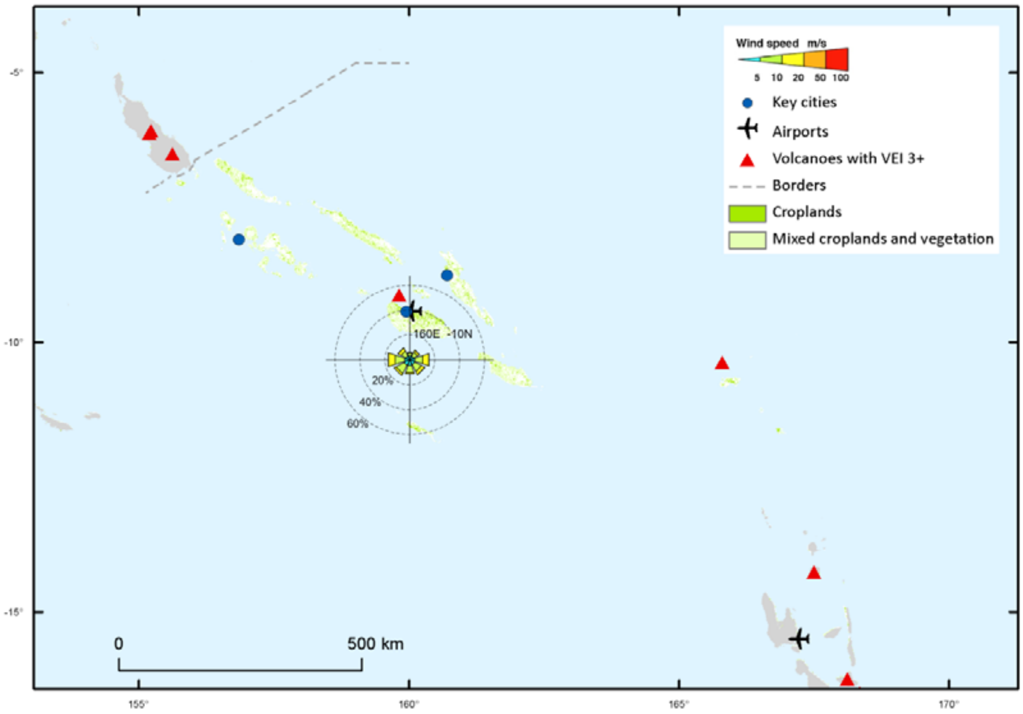


Figure 14.59: Map showing elements exposed to ash hazards in The Solomon Islands, with wind rose indicating dominant wind directions and speeds.

Frequency of Explosive Volcanism

Table 14.4 gives estimated return periods for different magnitude eruptions in the Pacific region, which comprises The Solomon Islands, Papua New Guinea, and Vanuatu in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 14.4 Return periods for different magnitude eruptions in The Solomon Islands.

Magnitude	Return Period (years)
3	4.3
3.5	8.2
4	17
4.5	33
5	60
5.5	150
6	310
6.5	820
7	3,700
8	220,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of The Solomon Islands' volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

Of the eight Holocene volcanoes in the Solomon Islands, one is recorded as being monitored on a regular basis (which is also the only Risk Level 2 volcano), but data collection is limited as there is no dedicated monitoring institution. Four volcanoes do however have either a temporary or permanent seismic network in place, producing an elevated Monitoring Level.

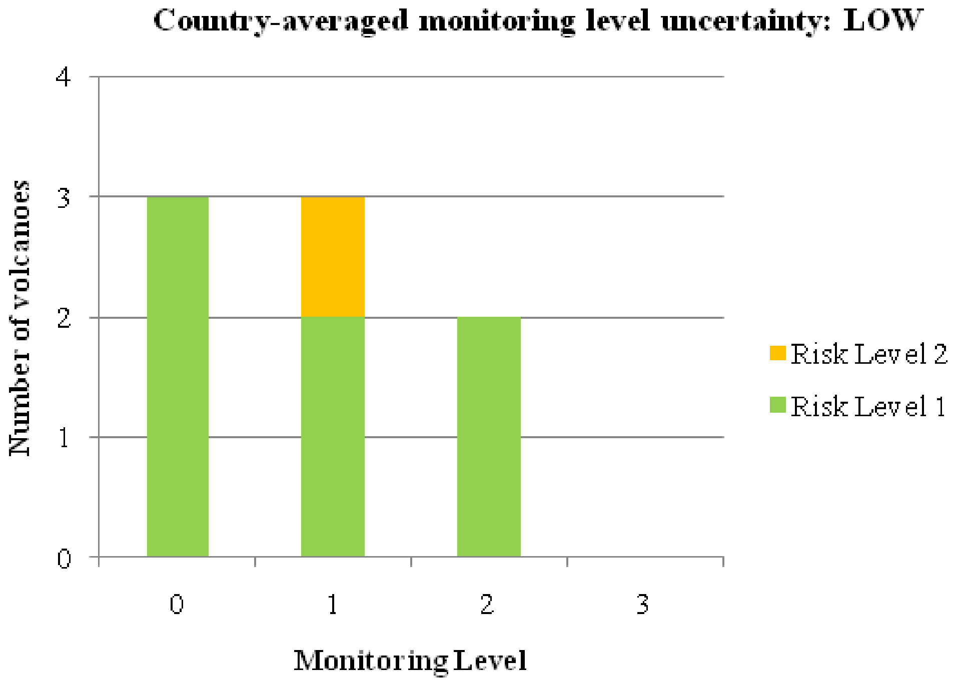


Figure 14.60: Distribution of The Solomon Islands' volcanoes across Monitoring and Risk Levels.

Summary

Volcanic risk in the Solomon Islands is moderate, with one Risk Level 2 volcano; small populations surrounding the volcanoes contribute to these assessments. It should be noted is that these small populations are small with regards to the PEI scale, and may in fact be of significance at the country level. Measuring infrastructure exposure is difficult without further data. Lack of a dedicated monitoring institution means Monitoring Levels for all eight volcanoes are 2 or below. High Uncertainty Levels for several volcanoes reflect lack of geological knowledge.

C15 Vanuatu

Description

The fourteen Holocene volcanoes contained in the GVP database for Vanuatu lie in a north-south trending line that lies between Tinakula volcano in the Solomon Islands in the north, and Matthew and Hunter Islands in the south-western Pacific Ocean in the south. The tectonic setting of Vanuatu is complex and geologically recent; present day volcanism results from subduction of the Australian Plate beneath the Pacific Plate. None of Vanuatu's three largest population centres are located on islands with volcanoes, and two are over 70 km from their nearest volcano.

Thirteen of the fourteen volcanoes of Vanuatu are stratovolcanoes or other normally-explosive edifice types. Four of these thirteen have produced pyroclastic flows, and one has generated a lahar. Though considered a generally effusive volcano type, the country's only shield volcano, Aoba, has in fact produced both pyroclastic flows and lahars. An eruption of Aoba in 1870 triggered a lahar that destroyed villages on the southeast flank and killed over 100 people, whilst a flank eruption in 1670 annihilated populated areas near the western coast.

Lopevi and Yasur, along with Ambrym, are two of Vanuatu's most active volcanoes. Lopevi, located on a small island roughly 135 km north of the country's capital, Port-Vila, has both flank and summit vents that have produced moderate explosive eruptions and lava flows that have reached the coast, as well as numerous pyroclastic flows. Timely evacuation prior to Lopevi's major eruptions in 1939 and 1960 avoided loss of life. Yasur, a stratovolcano situated on an island approximately 230 km south east of Port-Vila, has been almost constantly active since its first observation in 1774. This volcano has produced tsunami and debris avalanches since then, leading to approximately five fatalities. Eruptions of Vanuatu's volcanoes have caused an estimated 750 deaths in total.

Gaua is the most recently active of Vanuatu's volcanoes. An eruption commencing on 27th September 2009 led to explosions and high dense ash plumes on 18th November 2009, with the evacuation of over 300 people following on 26th November. Activity carried on into 2010, and increased in April; plans were made to evacuate a further 3,000 people. Seismic tremors, as well as ash and gas emissions, continued throughout the first 8 months of 2010. The Vanuatu Geohazards Observatory reported on 21st December 2010 that activity from Gaua had been low since September.

Location of Vanuatu's Volcanoes and Key Cities

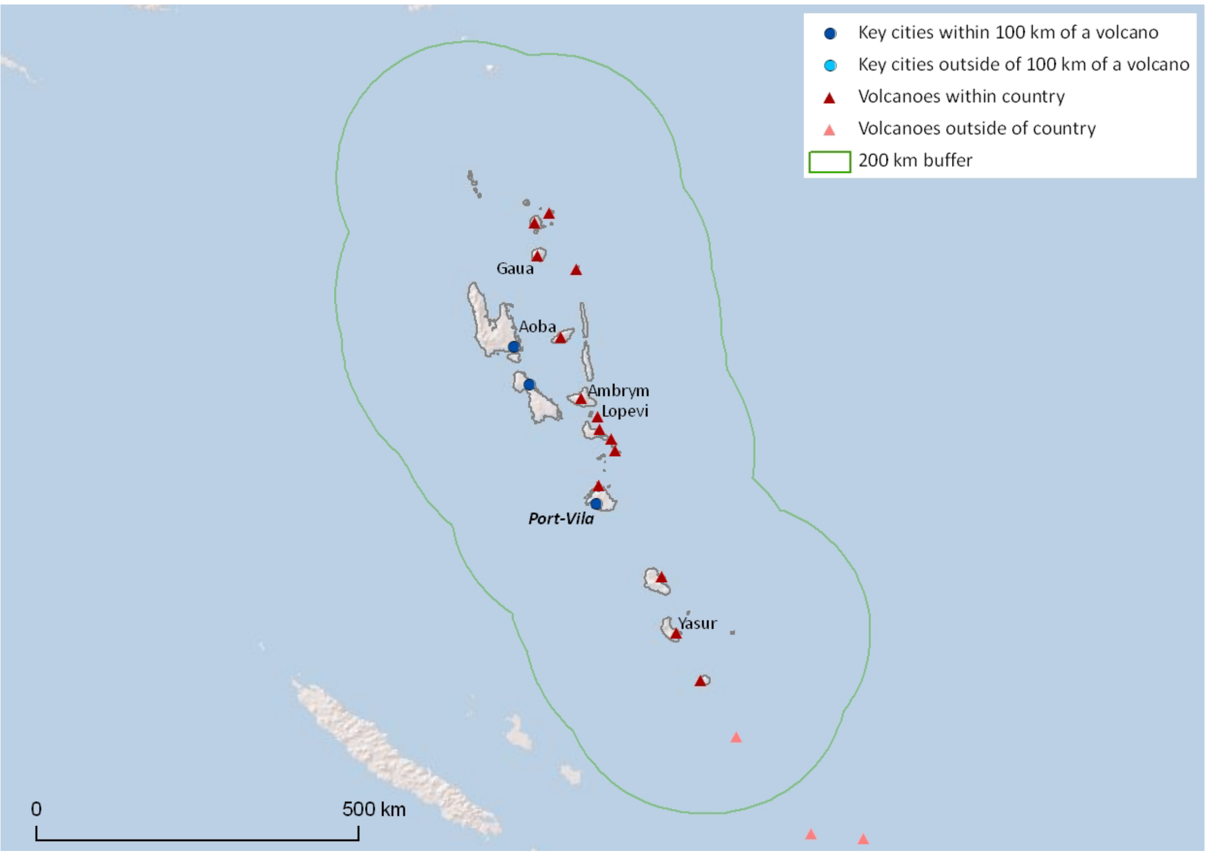


Figure 15.61: Locations of Vanuatu's volcanoes and three largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Vanuatu.

Volcanic Facts

Number of Holocene volcanoes:	14
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	13 and 1 respectively
Number of volcanoes generating pyroclastic flows:	5
Number of volcanoes generating lahars:	2
Number of volcanoes generating lava flows:	3
Number of fatalities caused by volcanic eruptions:	772

Socio-Economic Facts

Total population:	218,519

Vanuatu is not included in the countries covered by the UN Human Development Report, the data source used for total population, GDP per capita and HDI in all other country profiles; total population is thus estimated using the LandScan 2009 data in ArcGIS, and GDP per capita and HDI are not given.

Three largest cities, as measured by population ("Key Cities"), and populations:

- Port Vila (capital city)	Population:	35,901
- Luganville	Population:	13,397
- Norsup	Population:	2,998

Distance from capital city to nearest volcano:	29 km
Number (percentage) of cities within 100 km of a volcano:	2 (67%)
Number (percentage) of people living within 10 km of a volcano:	25,000 (11%)
Number (percentage) of people living within 30 km of a volcano:	97,000 (44%)
Number (percentage) of people living within 100 km of a volcano:	210,000 (94%)

Hazard and Uncertainty Assessments

The plot in Figure 15.2 shows the classifications of Vanuatu's fourteen fifteen volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 15.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Vanuatu's volcanoes display a somewhat polar split over the Hazard and Uncertainty Levels, with most having either Hazard Levels 1 or 3, and Uncertainty Levels 1 or 3. The single two largest Hazard-Uncertainty cohorts are those of Hazard Level 3, Uncertainty Level 1, and Hazard Level 1, Uncertainty Level 3. Such a relationship between hazard and uncertainty is common to many other GFDRR priority countries.

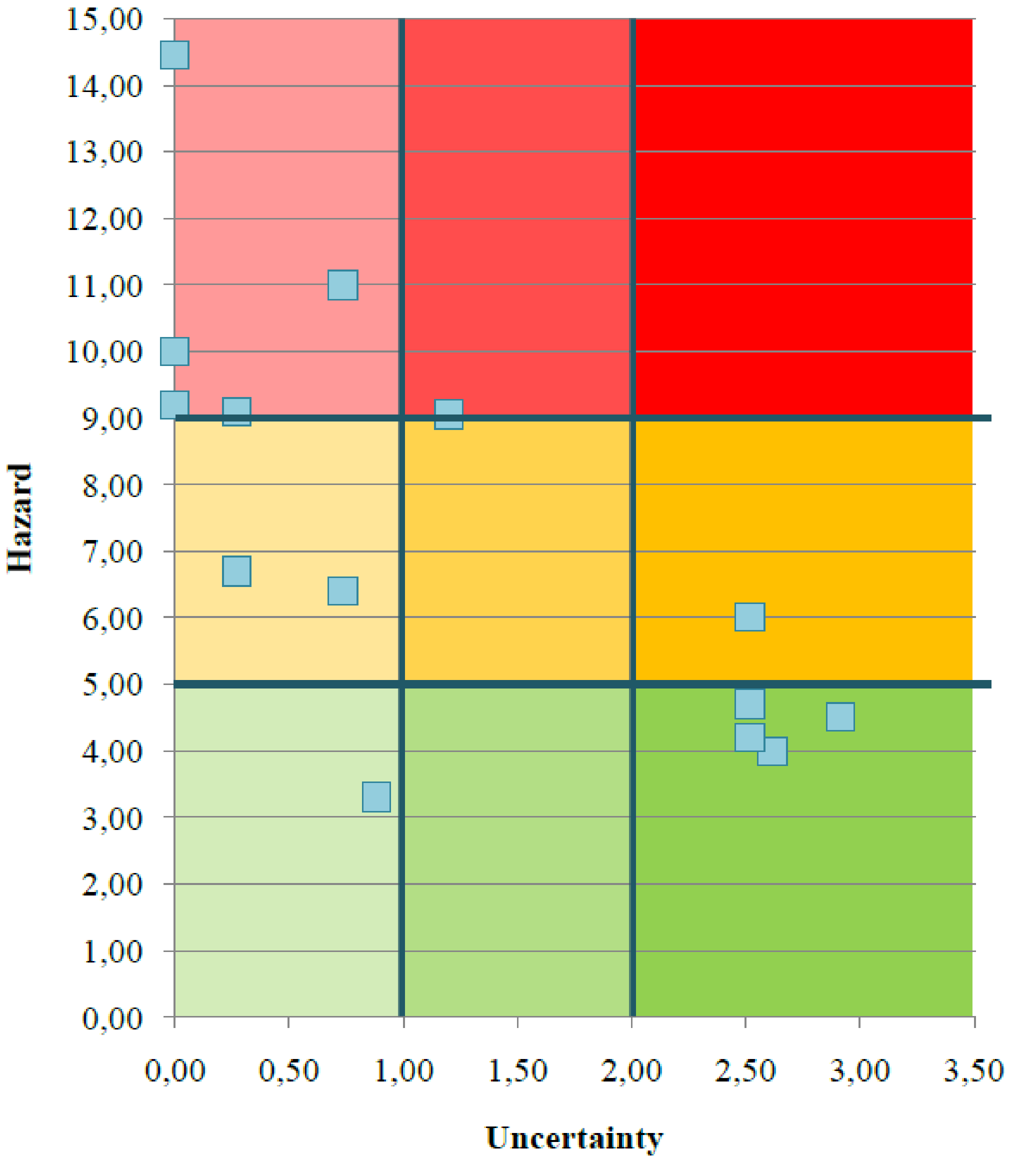


Figure 15.62: Distribution of Vanuatu's volcanoes across Hazard and Uncertainty Levels.

Table 15.45 Identities of Vanuatu's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3	Ambrym Aoba Gaua Kuwae Lopevi	Suretamatai	
Hazard Level 2	Epi Yasur		Unnamed (0507-08-)
Hazard Level 1	Traitor’s Head		Aneityum Mere Lava Motlav North Vate
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 15.3 shows the classifications of Vanuatu’s fourteen volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 15.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

All bar two of Vanuatu’s volcanoes are of PEI Level 1. As a result, even the highest hazard of the fourteen volcanoes is Risk Level 1.

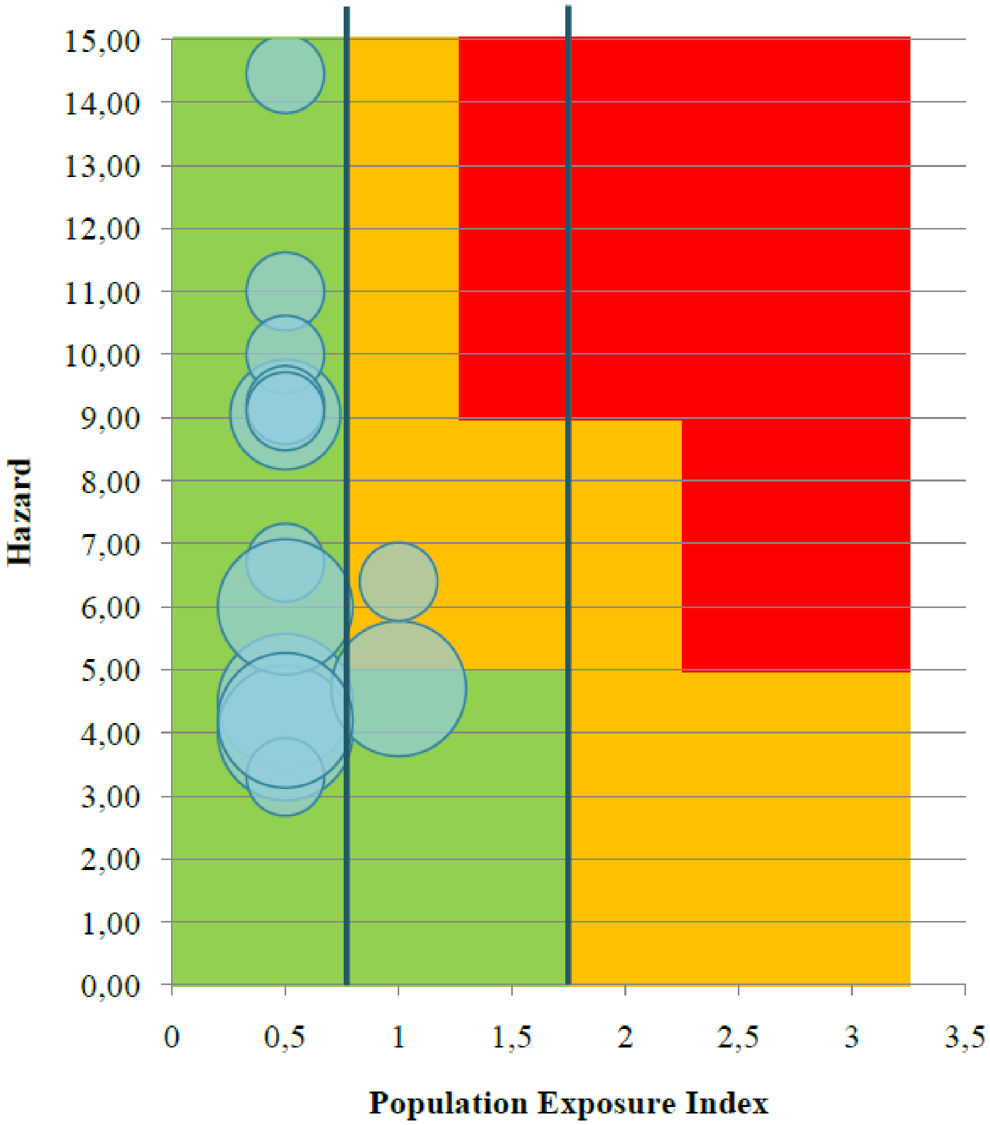


Figure 15.3: Distribution of Vanuatu's volcanoes across Hazard and Uncertainty Levels.

Basic results – Risk assessments
The list below gives the Risk Levels of Vanuatu's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 15.1 and Figure 15.2.

Risk Level 2:

• Yasur	Uncertainty Level 1

Risk Level 1:

• Ambrym	Uncertainty Level 1
• Aneityum	Uncertainty Level 2

Aoba	Uncertainty Level 1
Epi	Uncertainty Level 1
Gaua	Uncertainty Level 1
Kuwae	Uncertainty Level 1
Lopevi	Uncertainty Level 1
Mere Lava	Uncertainty Level 3
Motlav	Uncertainty Level 3
North Vate	Uncertainty Level 3
Suretamatai	Uncertainty Level 2
Traitor’s Head	Uncertainty Level 1
Unnamed (0507-08-)	Uncertainty Level 3

Of Vanuatu’s fourteen volcanoes, one is Risk Level 2, and thirteen are Risk Level 1.

Table 15.46 Identities of Vanuatu's volcanoes in each Hazard-PEI cohort.

Hazard Level 3	Ambrym Aoba Gaua Kuwae Lopevi Suretamatai		
Hazard Level 2	Epi Unnamed (0507-08-)	Yasur	
Hazard Level 1	Motlav Mere Lava Traitor’s Head Aneityum	North Vate	
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Hazard-specific exposure assessments

Table 15.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both kinds of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies. Note that no data, and thus results, were available for main roads and railways in Vanuatu.

Table 15.47 Extent of infrastructure exposure to lahars and pyroclastic flows in Vanuatu.

Exposed Elements	**Lahars**		**Pyroclastic Flows**	
Key Cities (as defined above)	Number of cities: Percentage of total number of cities:	0 0%	Number of cities: Percentage of total number of cities:	0 0%
Population	Number of people: Percentage of total number of people:	6,100 3%	Number of people: Percentage of total number of people:	6,700 3%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	12 2%	Length (km): Percentage of total length:	29 6%
Airports	Number of airports: Percentage of all airports:	0 0%	Number of airports: Percentage of all airports:	0 0%

Figure 15.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Vanuatu.

Westerly winds dominate, and occur around 43% of the time in the north, and 64% of the time in the region of Tanna and Erromango islands in the south. Due to this strongly dominant wind direction there is a relatively low probability of major ash fall affecting the capital city of Port Vila; the nearest volcano is Kuwae, approximately 100km north northeast, and winds from the north or northeast occur about 2 % of the time. However, flights to and from Bauerfield International Airport could be affected. An eruption of Yasur volcano (on Tanna Island) would be expected to affect agriculture on the island. Stronger winds occur in the south, with daily mean wind speeds exceeding 20 m/s around 60% of the time in the 250-100 mbar region.

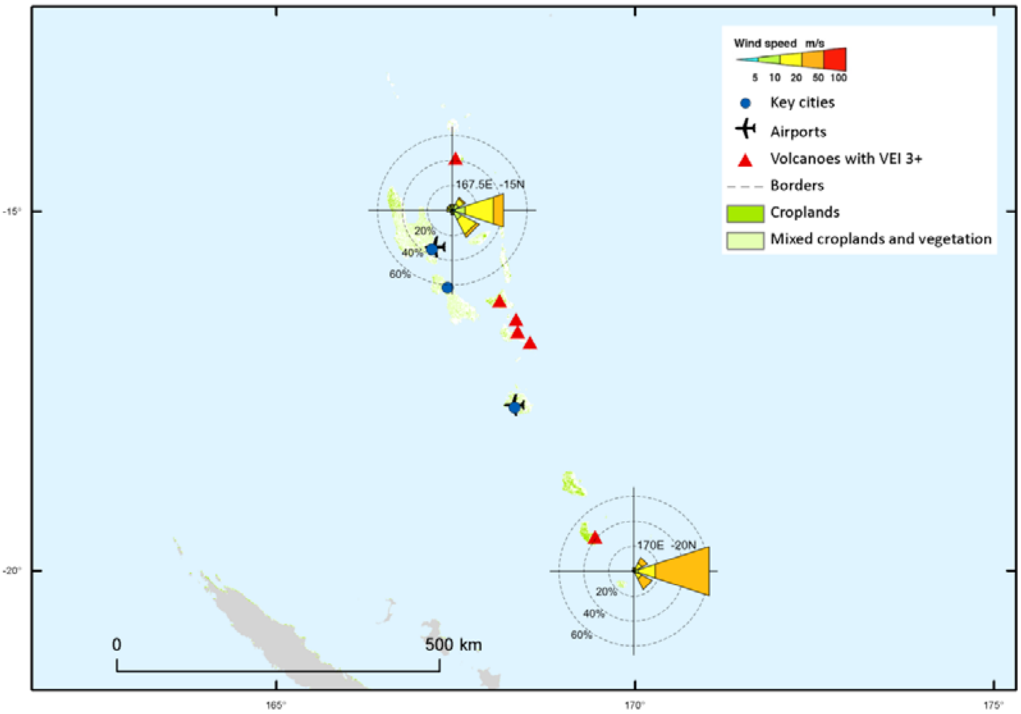


Figure 15.63: Map showing elements exposed to ash hazards in Vanuatu, with wind roses indicating dominant wind directions and speeds.

Frequency of Explosive Volcanism

Table 15.4 gives estimated return periods for different magnitude eruptions in the Pacific region, which comprises Vanuatu, Papua New Guinea, and The Solomon Islands in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present; see Appendix B for more details.

Table 15.48: Return periods for different magnitude eruptions in Vanuatu.

Magnitude	**Return Period (years)**
3	4.3
3.5	8.2
4	17
4.5	33
5	60
5.5	150
6	310
6.5	820
7	3,700
8	220,000

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Vanuatu's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

Six of the fourteen Holocene volcanoes in Vanuatu have been recorded as having regular (monthly-continuous) monitoring conducted by a single institution, five of which are within 15 km of a permanent seismic network. Only one of these fourteen volcanoes has a slightly elevated Risk Level and it has a correspondingly high Monitoring Level of 3.

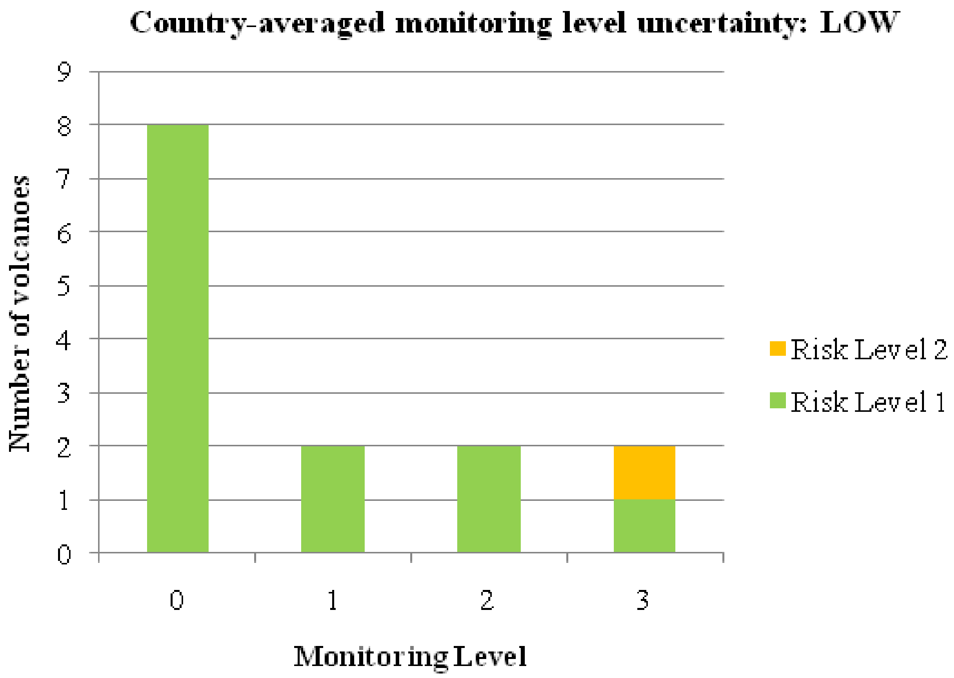


Figure 15.64: Distribution of Vanuatu's volcanoes across Monitoring and Risk Levels.

Summary

The physical threat posed by a number of Vanuatu's volcanoes is significant, though the small populations surrounding them reduces overall volcanic risk. It should be noted is that these small populations are small with regards to the PEI scale, and may in fact be of significance at the country level. Knowledge is adequate for volcanoes that have shown recent or past high magnitude activity, but there are several volcanoes given Hazard Level 1, but with high uncertainty, that reflect the lack of geological knowledge. Monitoring capabilities are greatest for Vanuatu's highest risk volcano.

C16 Vietnam

Description

Situated at the junction between the Eurasian and Philippine Plates, six Holocene volcanic features are contained in the GVP database for Vietnam, though the Holocene age of three of these needs confirmation. All are dominantly basaltic and effusive, categorised as cinder cones, volcanic fields, or submarine. Two of the volcanoes are located towards the centre of the country, with the other four loosely grouped nearer the south. Because of the generally effusive nature of Vietnam's volcanoes, the only hazardous flow they are likely to produce is lava, with potential minor localised explosive activity. A geologic and an historic record of a lava flow exists at Haut Dong Nai and Ile des Cendres respectively. Vietnam's ten largest population centres are sufficiently far from the six volcanic features to face little to no risk of damage or fatalities, though Haut Dong Nai and Bas Dong Nai have over 100,000 people living within 30 km of their summits. There are no historic records of human or socio-economic impacts from volcanoes in Vietnam.

Location of Vietnam's Volcanoes and Key Cities

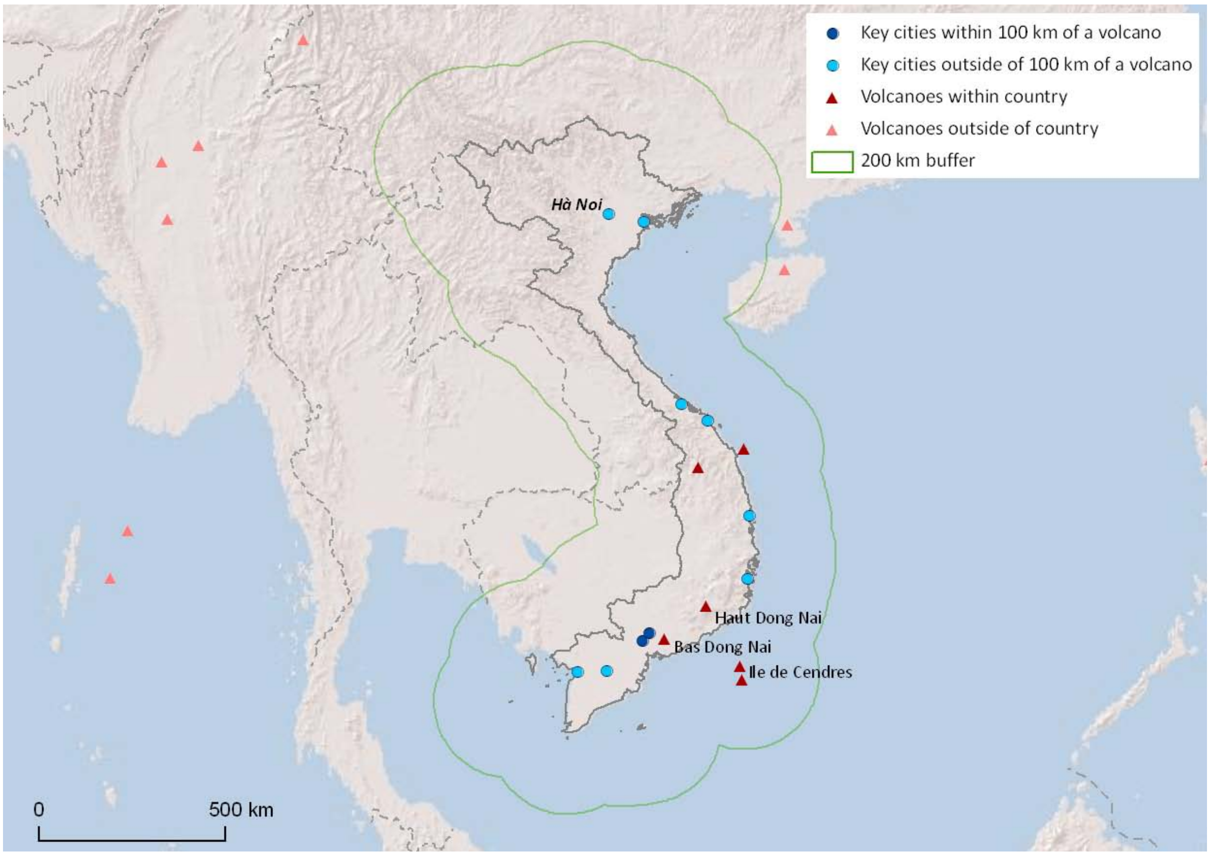


Figure 16.65: Locations of Vietnam's volcanoes and ten largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Vietnam.

Volcanic Facts

Number of Holocene volcanoes:	6
Number of Type 1 (“explosive”) and Type 0 (“effusive”) volcanoes:	0 and 6 respectively
Number of volcanoes generating pyroclastic flows:	0
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	2
Number of fatalities caused by volcanic eruptions:	0

Socio-Economic Facts

Total population:	89,028,700
GDP per capita, 2008 PPP US$:	3,097
HDI:	0.572 – Medium

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Thành phố Hồ Chí Minh	Population:	3,467,331
- Hà Nội (capital city)	Population:	1,431,270
- Đà Nẵng	Population:	752,493
- Haiphong	Population:	602,695
- Biên Hòa	Population:	407,208
- Huếúcuta	Population:	287,217
- Nha Trang	Population:	283,441
- Cần Thơ	Population :	259,598
- Rạch Giá	Population :	228,356
- Quy Nhơn	Population :	210,338

Distance from capital city to nearest volcano:	450 km
Number (percentage) of cities (population over 20,000) within 100 km of a volcano:	16 (22%)
Number (percentage) of people living within 10 km of a volcano:	140,000 (~ 0%)
Number (percentage) of people living within 30 km of a volcano:	1,600,000 (2%)
Number (percentage) of people living within 100 km of a volcano:	19,000,000 (22%)

Hazard and Uncertainty Assessments

The plot in Figure 16.2 shows the classifications of Vietnam’s six volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 16.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Vietnam’s volcanoes are all of Hazard Level 1. They are split across the three Uncertainty Levels.

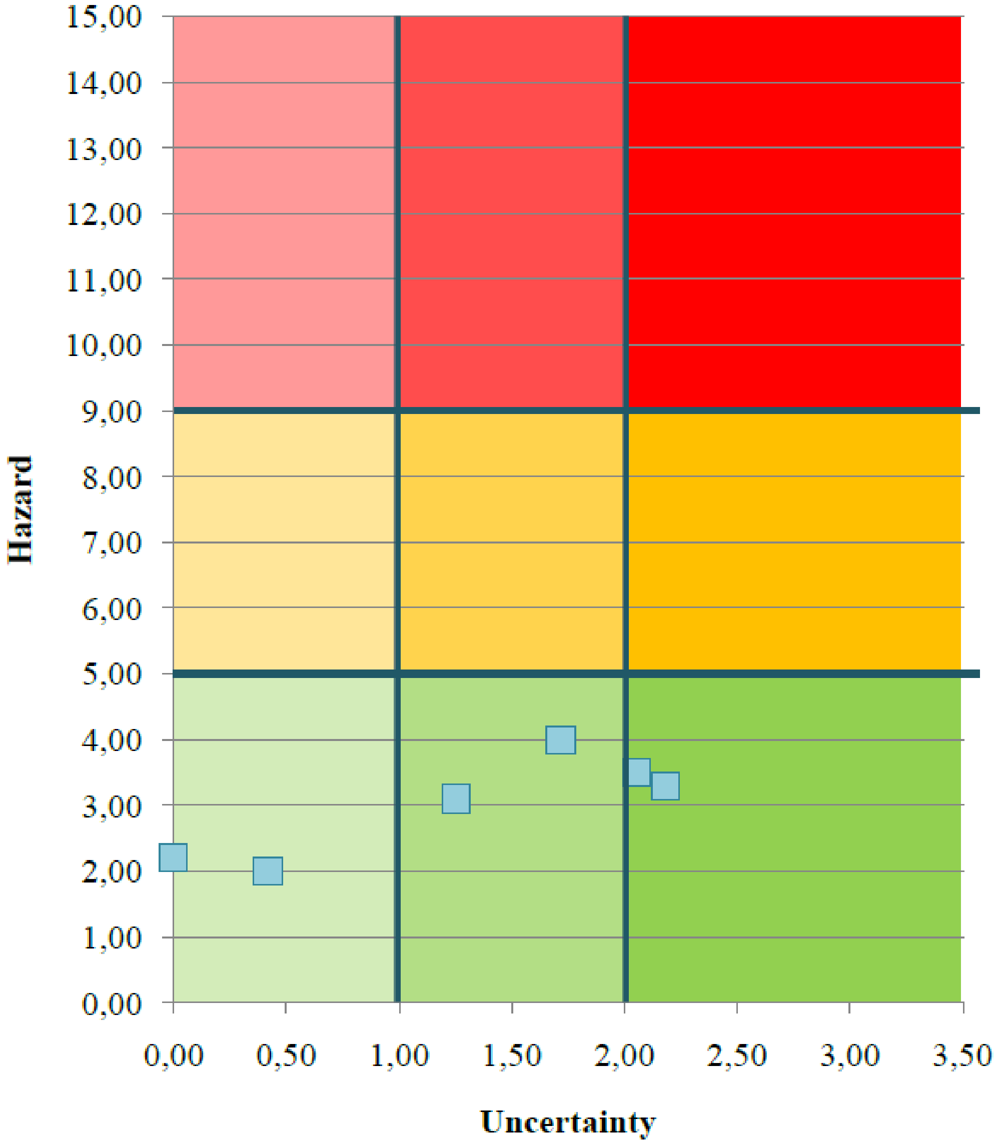


Figure 16.66: Distribution of Vietnam's volcanoes across Hazard and Uncertainty Levels.

Table 16.49 Identities of Vietnam's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1	Cendres, Ile des Veteran	Cù-Lao Ré Group Toroeng Prong	Bas Dong Nai Haut Dong Nai
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 16.3 shows the classifications of Vietnam's six volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 16.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Vietnam's volcanoes are classed as PEI Levels 1, 2 and 3, though their Hazard Level means they are subsequently of Risk Levels 1 and 2 only. Of note is the Level 3 Uncertainty surrounding the two Risk Level 2 volcanoes.

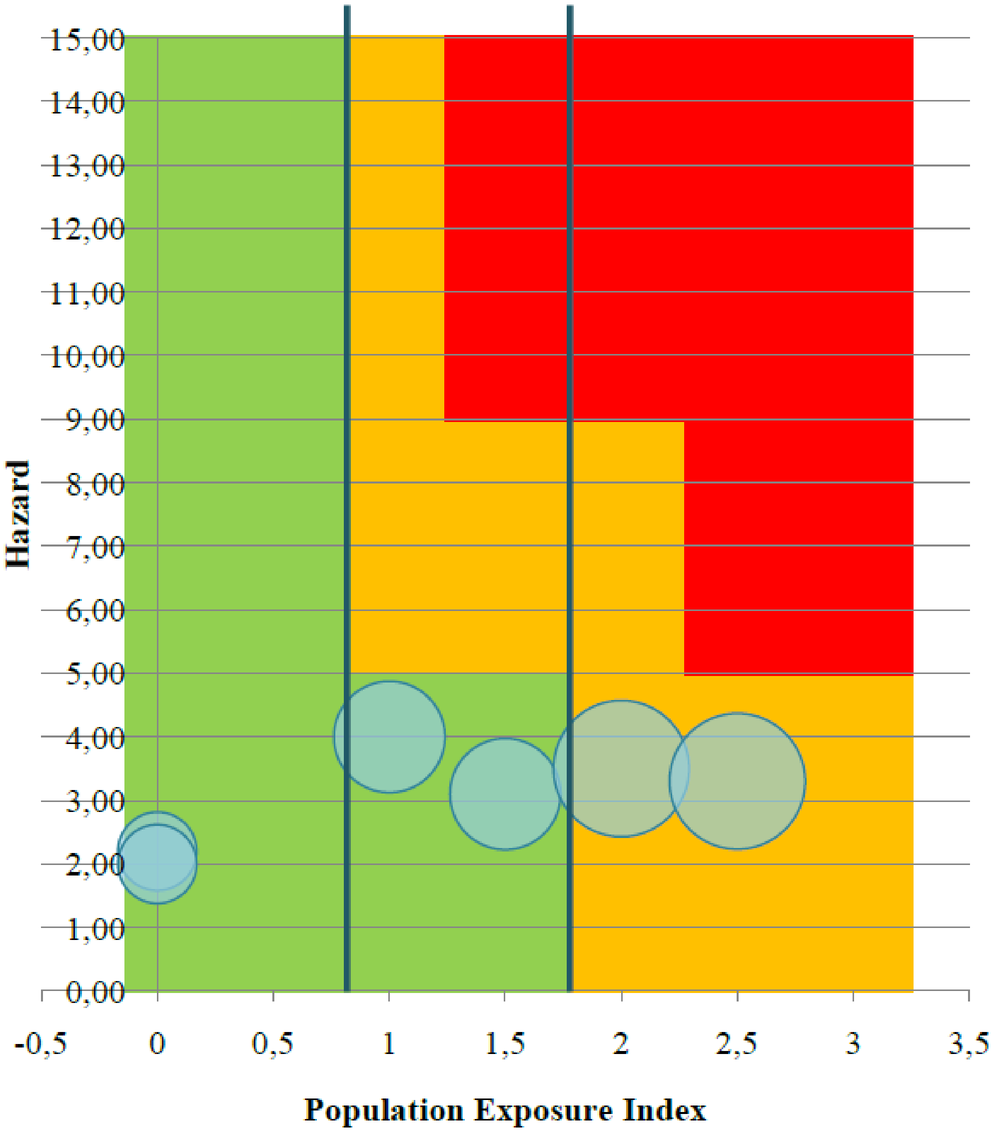


Figure 16.67: Distribution of Vietnam's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Table 16.50 Identities of Vietnam's volcanoes in each Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2			
Hazard Level 1	Cendres, Ile des Veteran	Cù-Lao Ré Group Toroeng Prong	Bas Dong Nai Haut Dong Nai
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Basic results – Risk assessments

The list below gives the Risk Levels of Vietnam's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 16.1 and Figure 16.2.

Risk Level 2:

• Bas Dong Nai	Uncertainty Level 3
• Haut Dong Nai	Uncertainty Level 3

Risk Level 1:

• Cendres, Ile des	Uncertainty Level 1
• Cù-Lao Ré Group	Uncertainty Level 2
• Toroeng Prong	Uncertainty Level 2
• Veteran	Uncertainty Level 1

Of Vietnam's six volcanoes, two are Risk Level 2, and four are Risk Level 1.

Hazard-specific exposure assessments

Table 16.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 16.51 Extent of infrastructure exposure to lahars and pyroclastic flows in Vietnam.

Exposed Elements	Lahars		Pyroclastic Flows	
Cities (population > 20,000)	Number of cities: Percentage of total number of cities:	3 4%	Number of cities: Percentage of total number of cities:	0 0%
Population	Number of people: Percentage of total number of people:	1,400,000 2%	Number of people: Percentage of total number of people:	0 0%
Ports	Number of ports: Percentage of total number of ports:	0 0%	Number of ports: Percentage of total number of ports:	0 0%
All Roads	Length (km): Percentage of total length:	1,600 6%	Length (km): Percentage of total length:	0 0%
Main Roads	Length (km): Percentage of total length:	30 2%	Length (km): Percentage of total length:	0 0%
All Railways	Length (km): Percentage of total length:	47 2%	Length (km): Percentage of total length:	0 0%
Airports	Number of airports: Percentage of all airports:	0 0%	Number of airports: Percentage of all airports:	0 0%

National Capacity for Coping with Volcanic Risk

The plot below depicts the numbers of Vietnam's volcanoes within each of three Monitoring Levels, where proficiency of monitoring increases from Level 0, through 1 and 2, to 3. Volcanoes are colour coded according to Risk Level.

None of the six Holocene volcanoes in Vietnam are monitored due to the lack of a dedicated monitoring institution and resources. There is high uncertainty however surrounding the location of the regions' seismic networks.

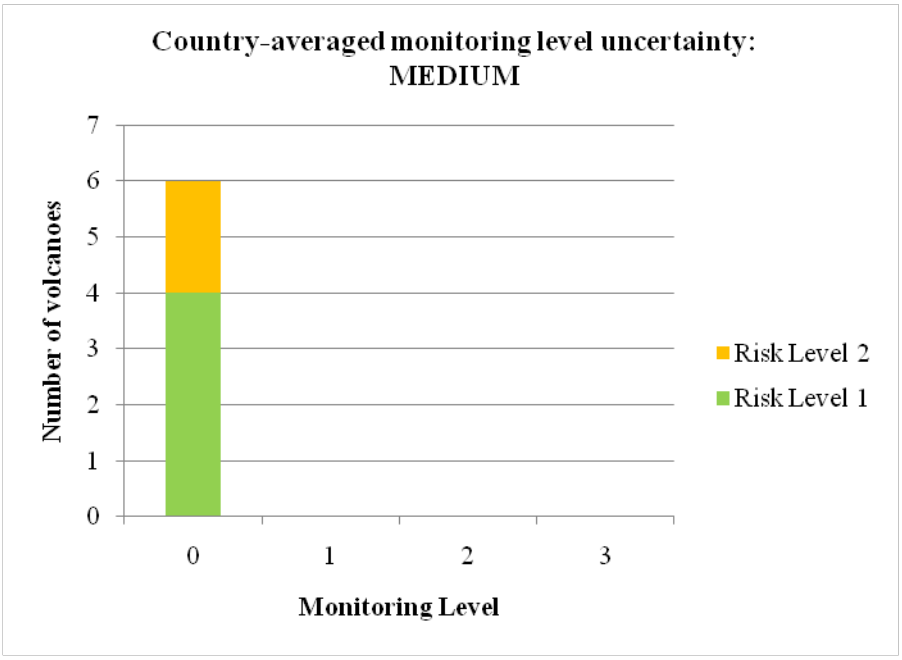


Figure 16.68: Distribution of Vietnam's volcanoes across Monitoring and Risk Levels.

Summary

Although volcanic risk in Vietnam is low compared to other GFDRR priority countries, Hazard and Risk Levels are highly uncertain, reflecting a paucity of geological knowledge. Further research is needed to better constrain these assessments.

C17 Yemen

Description

The GVP database contains twelve Holocene volcanoes for Yemen, formed along the East African and Red Sea Rift Systems, due to divergence of the African and Arabian Plates. Four of Yemen’s twelve volcanoes form islands in the Red Sea to the west of the country, seven are located on land mostly in the southwest, and one is submarine.

With the exception of Jebel at Tair stratovolcano, all of Yemen’s volcanoes are either shield volcanoes or volcanic fields, or some other dominantly-effusive volcano type. None have produced either pyroclastic flows or lahars, and they are mostly of basaltic composition.

The capital city of Yemen, Sana’a, is located 12 km north of Jabal el-Marha, a tuff cone. Though proximate to a large settlement, Jabal el-Marha is known only to have produced a basaltic lava flow which travelled 1.8 km and thus poses a very small threat to Sana’a. Jebel at Tair is located off the western coast of Yemen, roughly 150 km northwest of Yemen’s second most populous city, Al Hudaydah; Jebel at Tair is the only of Yemen’s volcanoes known to have caused any fatalities, when a VEI 3 eruption in September 2007 killed four Yemeni military personnel.

Location of Yemen's Volcanoes and Key Cities

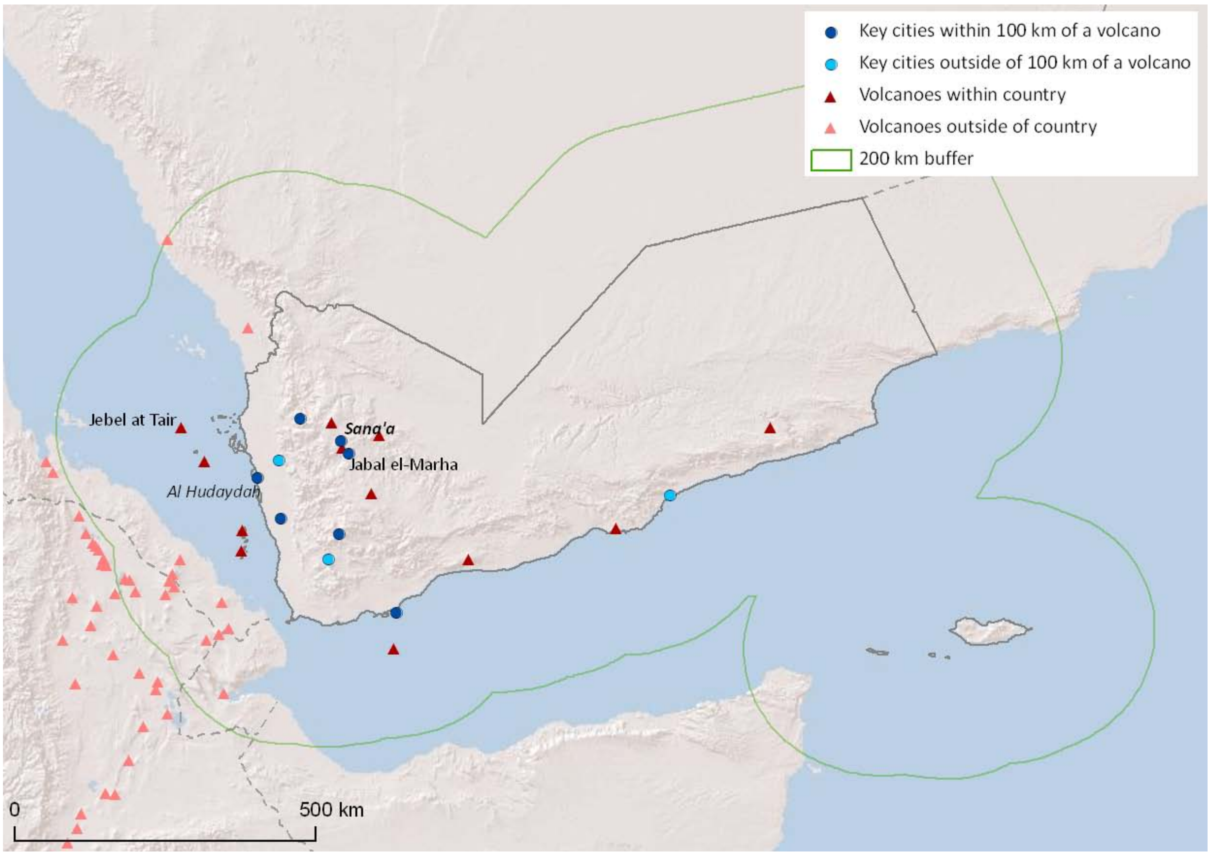


Figure 16.69: Locations of Yemen's volcanoes and ten largest cities. A zone extending 200 km beyond the country's borders shows other volcanoes whose eruptions may affect Yemen.

Volcanic Facts

Number of Holocene volcanoes:	12
Number of Type 1 ("explosive") and Type 0 ("effusive") volcanoes:	1 and 11 respectively
Number of volcanoes generating pyroclastic flows:	0
Number of volcanoes generating lahars:	0
Number of volcanoes generating lava flows:	11
Number of fatalities caused by volcanic eruptions:	4

Socio-Economic Facts

Total population:	24,255,900
GDP per capita, 2008 PPP US$:	2,595
HDI:	0.439 – Low

Ten largest cities, as measured by population (“Key Cities”), and populations:

- Sana’a (capital city)	Population:	1,937,451
- Al Ḩudaydah	Population:	617,871
- Ta‘izz	Population:	615,222
- ‘Adan	Population:	550,602
- Al Mukallā	Population:	258,132
- Ibb	Population:	234,837
- Sayyān	Population:	69,404
- Zabīd	Population :	52,590
- Bājil	Population :	48,218
- Ḩajjah	Population :	43,549

Distance from capital city to nearest volcano: 12 km

Number (percentage) of cities (population over 20,000) within 100 km of a volcano: 14 (88%)

Number (percentage) of people living within 10 km of a volcano: 620,000 (3%)

Number (percentage) of people living within 30 km of a volcano: 3,700,000 (16%)

Number (percentage) of people living within 100 km of a volcano: 16,000,000 (70%)

Hazard and Uncertainty Assessments

The plot in Figure 17.2 shows the classifications of Yemen’s twelve volcanoes across the three Hazard and Uncertainty Levels. Background colouring is used to show Hazard Level, and colour intensity to show Uncertainty Level. Table 17.1 lists the names of these volcanoes and the Hazard-Uncertainty class to which each is assigned.

Ten of Yemen’s twelve volcanoes are classed as Hazard Level 1; these ten are spread across the three Uncertainty Levels, but are mostly Uncertainty Level 1. Yemen’s highest hazard volcano is of Uncertainty Level 1.

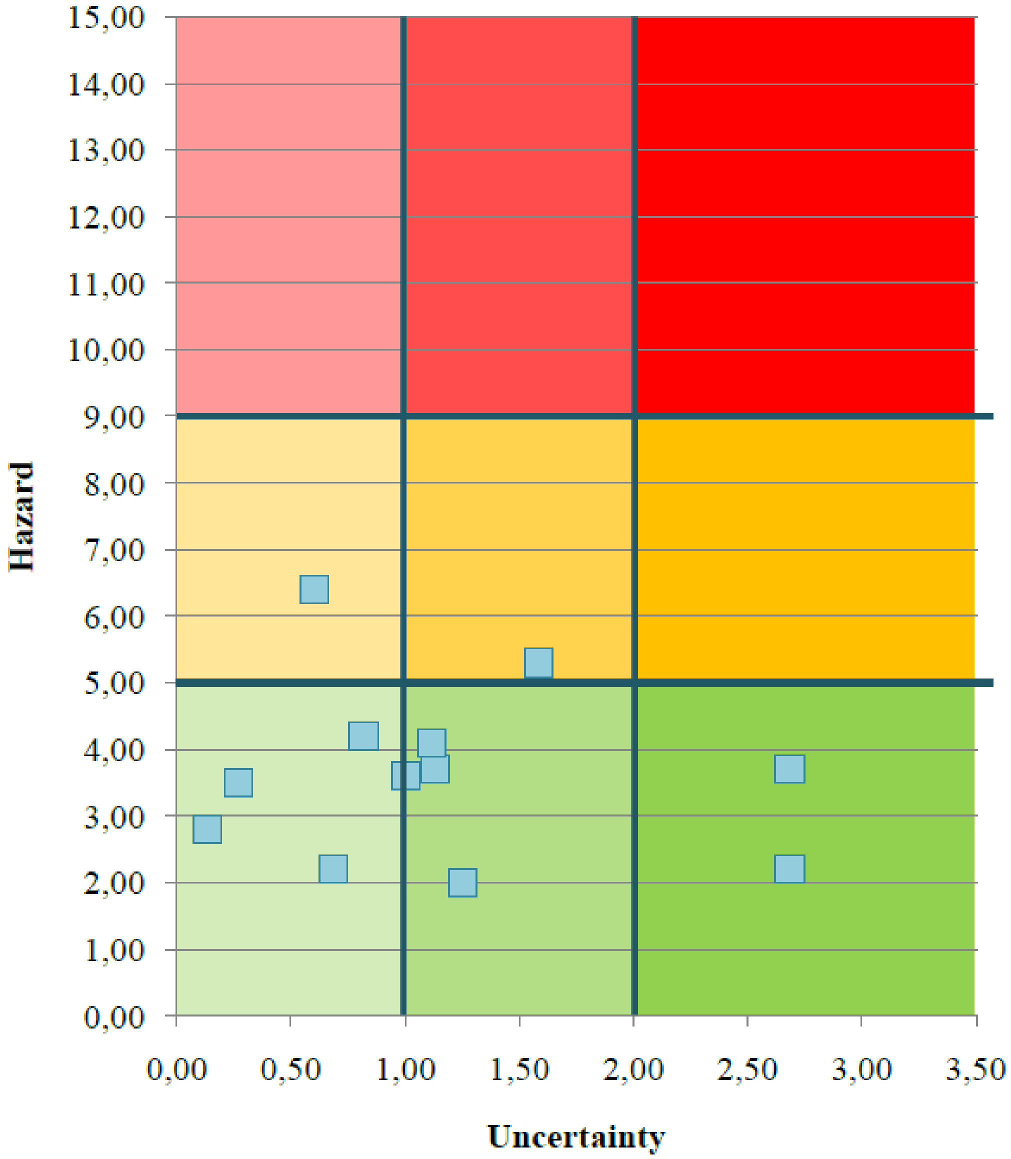


Figure 17.70: Distribution of Yemen's volcanoes across Hazard and Uncertainty Levels.

Table 17.52 Identities of Yemen's volcanoes in each Hazard-Uncertainty cohort.

Hazard Level 3			
Hazard Level 2	Tair, Jebel at	Bal Haf, Harra of	
Hazard Level 1	Arhab, Harra of Bir Borhut Haylan, Jabal Sawâd, Harra es- Zubair, Jebel	Dhamar, Harras of Hanish Unnamed (0301-15-)	Marha, Jabal el-Zukur
	Uncertainty Level 1	**Uncertainty Level 2**	**Uncertainty Level 3**

Exposure Assessments

Basic results – Population Exposure Index (PEI)

The plot in Figure 17.3 shows the classifications of Yemen's twelve volcanoes across the three Hazard and PEI Levels; marker circle size increases with Uncertainty Level. Background colouring is used to show Risk Levels, with red for Risk Level 3, orange for Level 2, and green for Level 1. Table 17.2 lists the names of the volcanoes in each of the Hazard-PEI classes.

Yemen's volcanoes are spread across all three PEI Levels. Their Hazard Levels are such that they fall into Risk Levels 1 and 2 only, however. The volcanoes are of mixed Uncertainty Levels within the two Risk Levels.

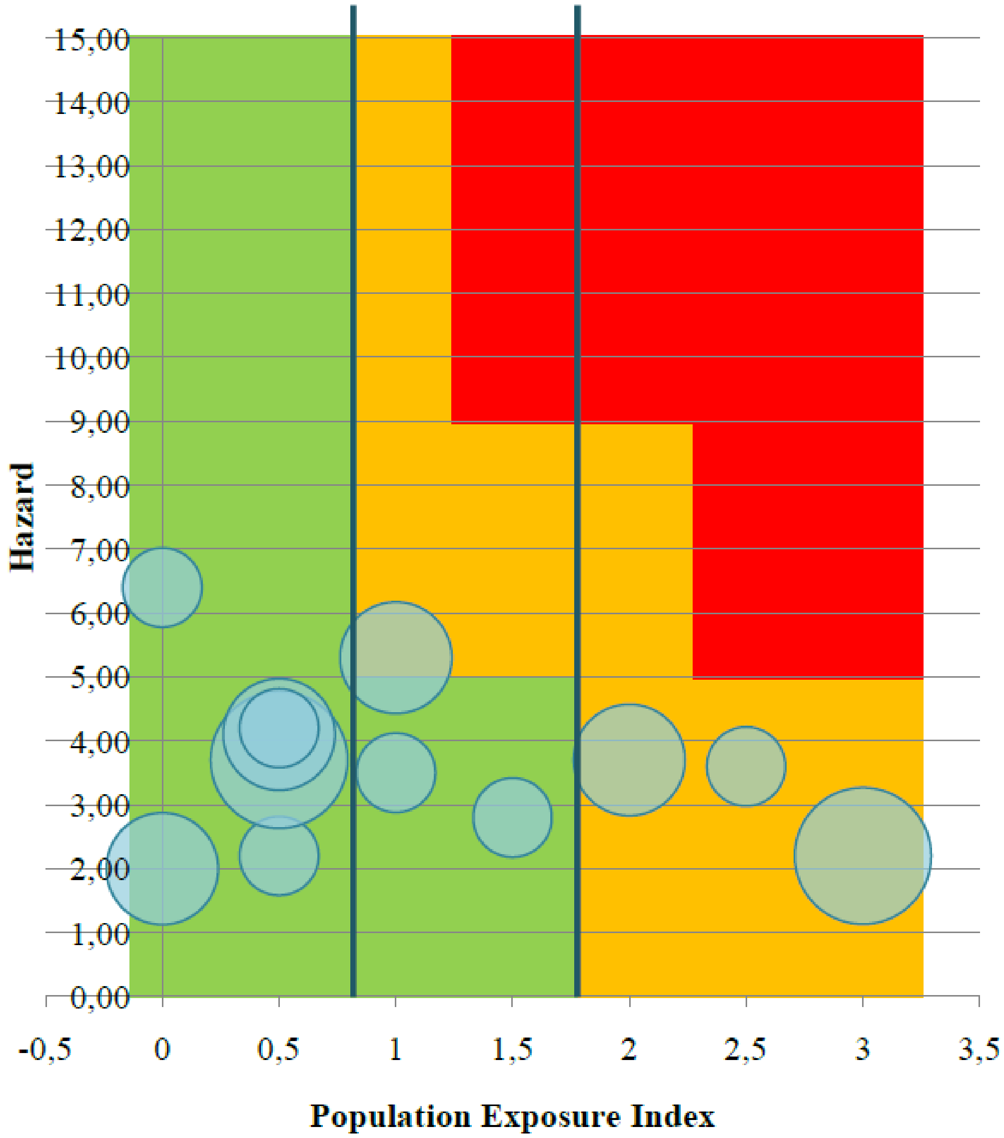


Figure 17.71: Distribution of Yemen's volcanoes across Hazard, Population Exposure Index, and Uncertainty Levels.

Basic results – Risk assessments

The list below gives the Risk Levels of Yemen's volcanoes, a measure that combines Hazard Level and PEI. The Uncertainty Levels quoted are those ascribed during the hazard assessment, as in Table 17.1 and Figure 17.2.

Risk Level 2:

• Arhab, Harra of	Uncertainty Level 1
• Bal Haf, Harra of	Uncertainty Level 2
• Dhamar, Harras of	Uncertainty Level 2
• Marha, Jabal el-	Uncertainty Level 3

Risk Level 1:

- Bir Borhut Uncertainty Level 1
- Hanish Uncertainty Level 2
- Haylan, Jabal Uncertainty Level 1
- Sawâd, Harra es- Uncertainty Level 1
- Tair, Jebel at Uncertainty Level 1
- Unnamed (0301-15-) Uncertainty Level 2
- Zubair, Jebel Uncertainty Level 1
- Zukur Uncertainty Level 3

Of Yemen’s twelve volcanoes, four are Risk Level 2, and eight are Risk Level 1.

Table 17.53 Identities of Yemen’s volcanoes in each Hazard-PEI cohort.

Hazard Level 3			
Hazard Level 2	Tair, Jebel at	Bal Haf, Harra of	
Hazard Level 1	Bir Borhut Hanish Unnamed (0301-15-) Zubair, Jebel Zukur	Haylan, Jabal Sawâd, Harra es-	Arhab, Harra of Marha, Jabal el- Dhamar, Harras of
	Population Exposure Index Level 1	**Population Exposure Index Level 2**	**Population Exposure Index Level 3**

Hazard-specific exposure assessments

Table 17.3 summarises overall national risk exposures determined by a first order assessment of pyroclastic flow and lahar hazards from relevant volcanoes. Note that the hazard from both types of flow is largely confined to river valleys and basins; only a small fraction of the populations listed are thus exposed to these hazards. A larger population may be affected if lahars or pyroclastic flows block off evacuation routes or destroy critical infrastructure, such as power supplies.

Table 17.54 Extent of infrastructure exposure to lahars and pyroclastic flows in Yemen.

Exposed Elements	Lahars	Pyroclastic Flows
Cities (population > 20,000)	Number of cities: 0 Percentage of total number of cities: 0%	Number of cities: 0 Percentage of total number of cities: 0%
Population	Number of people: 6,700 Percentage of total number of people: 0%	Number of people: 0 Percentage of total number of people: 0%
Ports	Number of ports: 1 Percentage of total number of ports: 11%	Number of ports: 0 Percentage of total number of ports: 0%
All Roads	Length (km): 27 Percentage of total length: ~ 0%	Length (km): 0 Percentage of total length: 0%
Main Roads	Length (km): 61 Percentage of total length: 1%	Length (km): 0 Percentage of total length: 0%
All Railways	Length (km): 27 Percentage of total length: ~ 0%	Length (km): 0 Percentage of total length: 0%
Airports	Number of airports: 0 Percentage of all airports: 0%	Number of airports: 0 Percentage of all airports: 0%

Figure 17.4 shows agriculture and infrastructure elements exposed to ash hazards, and wind roses indicating prevalent conditions for Yemen.

Wind direction is strongly bimodal, with easterly winds occurring approximately 33 - 38% of the time and westerlies 24 - 34%. The capital city of Sana'a and the Al Rahaba international airport lie approximately 250 km east of Jebel at Tair volcano and could be affected by ash fall from a major eruption. Sana'a is 280 km northwest of Harra es-Sawâd volcano, although winds in this direction are only expected about 10% of the time and are typically less than 20m/s. The agricultural regions approximately 200-250 km west of Harra es-Sawâd and about 160 km east of Jebel at Tair could also be affected by a large eruption. A number of Ethiopian volcanoes (also within a few hundred kilometres) could also pose a threat to agriculture and air traffic in the event of a large eruption.

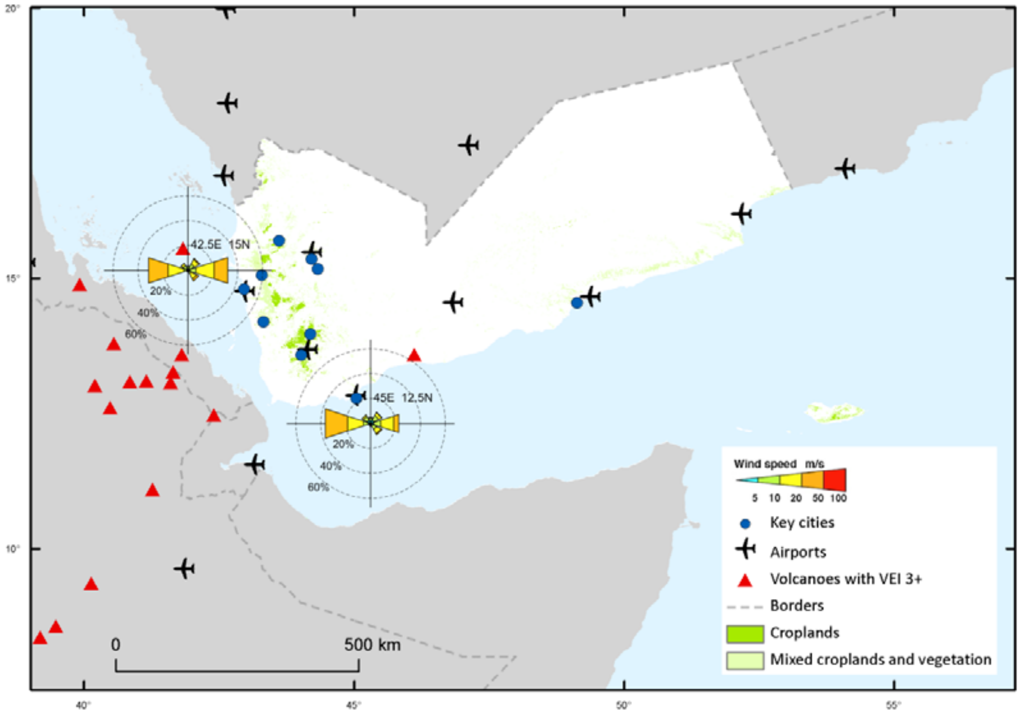


Figure17.72: Map showing elements exposed to ash hazards in Yemen, with wind roses indicating dominant wind directions and speeds.

<u>Frequency of Explosive Volcanism</u>

Table 17.4 gives estimated return periods for different magnitude eruptions in the African region, which comprises Yemen and Ethiopia in this work. The results are based on global return periods calculated using the LaMEVE database, scaled for the number of explosive volcanoes present: see Appendix B for more details.

Table 17.55: Return periods for different magnitude eruptions in Yemen.

Magnitude	Return Period (years)
3	7.3
3.5	14
4	29
4.5	55
5	100
5.5	250
6	530
6.5	1,400
7	6,200
8	380,000

National Capacity for Coping with Volcanic Risk

Graphical display of Yemen’s capacity for coping with volcanic risk is not possible due to a lack of information.

Summary

Volcanic risk in Yemen is moderate, with four Risk Level 2 volcanoes. However, uncertainty is fairly high for these four volcanoes, as well as for several others. Data pertaining to monitoring capabilities could not be obtained, and thus it is inferred that monitoring of all of Yemen’s volcanoes is inadequate.

C18 References

Kalnay et al., (1996): The NCEP/NCAR 40-year reanalysis project, Bull. Amer. Meteor. Soc., 77:437-470. URL http://www.esrl.noaa.gov/psd/data/reanalysis/.

Appendix D - National Capacities

Contents

D1 Introduction

This appendix provides an overview of the national capacities for the sixteen GFDRR priority countries with volcanoes within their borders (so-called Category A countries).

The capacity to deal with volcanic emergencies depends on many factors. Only those factors that are within the realm of scientific institutions are discussed here, recognising that responding to a volcanic emergency depends on many things outside the direct influence of scientific institutions to influence. These include the organisation of emergency services, communication infrastructure, robustness of evacuation plans, and social, cultural, economic factors. Risk perceptions and attitudes amongst public officials and the affected communities are also very important. Scientific institutions play a key role in providing robust evidence based scientific assessments and advice. They can also be more effective if this advice is trusted and delivered in a timely manner. In periods of quiescence scientific institutions can provide sources of authoritative information to raise awareness about volcanic risk for decision-makers and the public, and to inform long-term planning (e.g. land-use and evacuation).

Monitoring is a key task for scientific institutions for active volcanoes. In GFDRR priority countries the focus is typically on monitoring frequently active volcanoes near to densely populated regions and to some extent on volcanoes which, while dormant, have had major eruptions in the past. This priority is reflected in our study results where the majority of volcanoes with high hazard and risk levels are monitored to some extent. Our study has, however, highlighted some examples of high-risk volcanoes, which have either low levels of monitoring or no monitoring at all. Countries with many such volcanoes could be considered as reflecting inadequate institutional capacity to do the necessary scientific work. Long dormant and infrequently active volcanoes are commonly characterised by little or no monitoring, poor geological knowledge and high uncertainty on the hazard level. It is likely that the true hazard level of some of these volcanoes with high uncertainty indices is higher. These volcanoes pose specific problems when they show signs of unrest or impending eruption. Support networks from overseas institutions and programmes, such as the VDAP team of the US Geological Survey are particularly important in many GFDRR priority countries which commonly lack the capacity to deal with a major crisis on a previously unknown and poorly monitored volcano.

The main stalwart of volcano monitoring is the deployment of a permanent seismic network to give early warning. Some form of national seismic network is present in all the study countries, but there are relatively few networks dedicated to specific volcanoes in several of the study countries. Volcanic earthquakes are typically very small in magnitude and may not necessarily be easily detected in national networks. A first order aim would be to have at least one seismometer dedicated to every high risk volcano in GFDRR priority countries with telemetry to the institutional headquarters. Dedicated seismic stations should be augmented by a mobile network and team that can respond rapidly to unrest. This is the strategy in Indonesia and is reasonably successful option with limited resources. We suggest that countries with monitoring levels 1 and 0 on volcanoes with risk levels 2 and 3 display a deficiency of capacity.

Volcano monitoring is greatly enhanced if deformation measurements and gas monitoring is carried out routinely. Traditionally some of the methods have been time-consuming and expensive, but this is changing quite rapidly. Cheaper methods are emerging (e.g. miniDOAS systems for SO_2 monitoring and GPS). The proliferation of regional and national GPS networks is helping but there are still rather few GPS networks in most GFDRR priority countries dedicated to volcanoes. Remote sensing advances are also producing a major new approach with thermal images, gas emission images and InSAR interferometer providing very valuable information. A problem with fully utilising these technologies by GFDRR priority countries institutions is access and expertise. Much of the access to these technologies and expertise in the processing and interpretation of the data resides in the developing world and access is highly varied from one GFDRR priority countries to another. In general there is an urgent need for resources to allow institutions to access images and these new technologies, and training to allow the data processing to be done competently and quickly in house. Very few of the volcanoes in GFDRR priority countries have the full panoply of instrumentation and processing capability that would be regarded as normal in Observatories in the developed world.

A related issue to highlight is access to high quality and high resolution Digital Elevation Models for volcanoes. Hazards maps and hazards assessments, using the state-of-the-art hazard process models, rely on having high resolution terrain models. The publically available models with 30 and 90 metre resolution are simply not good enough for most purposes in hazard assessment. Such terrain models are likely just around the corner, but their utility will depend on GFDRR priority countries having inexpensive access.

Many volcanic emergencies have problems that relate to the institutional and personality issues. Factionalism with lack of communication between rival institutions (e.g. national government science agencies and university groups) can be sources of discord and result in loss of trust and credibility during crises. Very hierarchical systems of management can be problematic, particularly where individuals at lower levels in an organisation are afraid to make decisions for fear of recriminations. Autocratic management systems can work well if the person in charge is astute or perhaps lucky, but can lead to a structure where no-one is willing to raise legitimate alternative interpretations or viewpoints. Complex communication and organisational systems can be a concern, especially if either there are key issues that fall between the gaps between institutional responsibilities or rivalries for a responsibility. Cultural issues may also arise; for example if the hazards and risk assessment is overly deterministic, and uncertainties and alternative conceptual models are not considered. The above are generalisations but unfortunately do characterise national institutional attributes in some GFDRR priority countries.

D2 Sources of information

To assess the coping capacity of each country we collected information on the institution (s) responsible for monitoring volcanoes, which of the volcanoes they monitored, their regularity of monitoring and facilities that they have to do so. Further information included sources of communication such as warning levels, hazard maps and training, to see how well the risks are known or understood, and partnering organisations who contribute to funding, research, maintenance or training.

The information in this report was compiled using a variety of web-based resources, namely the Smithsonian Institute, WOVO (the World Organisation of Volcano Observatories) and institutional websites specific to each country, and supported by a range of internal and external contacts.

The majority of countries with a well-established institution have reliable, up-to-date websites, for example the INGEOMINAS website which has details about the institution, each monitored volcano, facilities and news updates. Similar websites include those for OVSICORI (Costa Rica), IG(EPN) (Ecuador), INSIVUMEH/CONRED (Guatemala) and to a slightly lesser extent, CVGHM (Indonesia) and PHIVOLCS (Philippines). Monitoring within countries with no single dedicated institution is often the responsibility of the local government, although if the risk has not been identified it is often not considered and information, particularly on the Internet, is limited. Alternatively, there are a few institutions who collaborate and are all responsible for different roles within monitoring; for example the Ministry of Mines, the Geological Survey and the National Disaster Council (Solomon Islands) and SENACYT and SINAPROC (Panama). This sometimes results in gaps or contradictions in the information supplied. Websites are a primary resource for the public and other interested parties, but access to and the reliability of information is obviously dependent on the country's Internet availability and staffing and updates can vary across the site.

Information gathering was further substantiated via individual contacts at the local institution, contacts found via websites, local academics, visiting academics and contacts from partnering organisations who have worked in the country. Direct institutional contacts for example, provided very useful and reliable information. These included INGEOMINAS, OVSICORI, IG(EPN), Addis Ababa University, CONRED, OSOP, GNS and VIGMR. External contacts or partnering organisations include contacts from University of Texas, University of Leicester, Michigan Tech University, IPGP and the University of Bristol.

This information is limited to only that which we had access to or sources who we communicated with. For this reason there is an element of uncertainty associated with the reliability of this data, and this is represented in the uncertainty classification that is given next to each country's bar chart.

D3 Colombia

Institution	INGEOMINAS http://www.ingeominas.gov.co
Observatories	Manizales, Papayan, Pasto
Volcanoes continuously monitored	(12) Cerro Bravo Santa Isabel Nevado del Ruiz Nevado del Tolima Machín Nevado del Huila Sotará Puracé Doña Juana Galeras Azufral Cumbal
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(3) Petacas Romeral Cerro Negro de Mayasquer
Facilities available at every observatory	Long-period seismometers Short-period seismometers BB seismometers Inclinometers Flow monitors Magnetometers Cameras/videos
Published hazard information	Accurate, detailed and regular updates via observatory's website: Reports (weekly/monthly/yearly/special bulletins) Traffic light system (I-imminent eruption to IV-active but stable) Seismograms Hazard maps for 10 volcanoes Photos Disaster statistics published on Preventionweb.org
Partnering organisations:	

Notes

INGEOMINAS operate three, well-established volcano observatories in Colombia, based at Pasto, Popayan and Manizales. Each observatory has a group of trained staff members (currently 26, 17, 32 respectively) including geologists, seismologists, technical and administrative staff. Observatories at Pasto and Manizales also have staff trained in geochemistry and GIS or remote sensing. Twelve of the fifteen volcanoes active in the Holocene are monitored continuously by INGEOMINAS through the use of permanent seismic networks, inclinometry, GPS and regular sampling of SO_2. Our classification therefore assigns them a monitoring level of 3, with low uncertainty. The most equipment is established at volcanoes Cerro Machín, Galeras, Nevado del Tolima and Nevado del Huila. Our classification recognises seven of these volcanoes as high risk. Petacas, Romeral and Cerro Negro de Mayasquer are not monitored by INGEOMINAS, but these volcanoes are only identified as low to medium risk.

A colour-coded warning system has been developed. Hazard maps for ten of the volcanoes and daily, weekly and monthly reports are accessible online. There are issues concerning the public understanding of the risks and uncertainty, and who has the responsibility of disseminating this information. The work of INGEOMINAS is augmented by well-established collaborations and assistance from North American and European institutions and research programmes.

A project entitled ‘Natural disaster vulnerability reduction programme’ established by the World Bank and INGEOMINAS in 2005/2006, has successfully provided funding for improved monitoring facilities and equipment in Colombia (phase I). It has also helped contribute towards education and training (phase II).

Colombia has very good institutional capacity with INGEOMINAS being internationally respected as a scientific organisation of high quality. There are training and knowledge transfer needs in areas like remote sensing, gas geochemistry, and risk assessment, but to a large extent these are being addressed in partnerships with foreign institutions.

D4 Costa Rica

Institution	OVSICORI http://www.ovsicori.una.ac.cr/ www.rsn.geologia.ucr.ac.cr
Observatories	
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(7) Arenal Irazu Miravalles Poas Rincón de la Vieja Turrialba Tenorio
Volcanoes not monitored	(3) Orosi Platanar Barva
Facilities available at every volcano	Geochemistry sampling: crater lakes, hot springs, streams and fumeroles Gas analysis: CO_2, SO_2, H_2S GIS Infrared camera Inclinometry Seismometer
Published hazard information	*Accurate University and RSN website:* Publish annual reports and newsletters Active traffic light warning system (1-dormant – 4-eruption imminent) Accurate reports for active volcanoes at level 3-4, published monthly Reports for abnormal activity Host workshops on volcano monitoring Educational site for children and teachers on disaster prevention *OVSICORI website:* Media reports Host natural hazards workshop Disaster statistics are published on Preventionweb.org
Partnering organisations:	University of Costa Rica UCR, Oficina de Sismología y Vulcanología (OSV) Instituto Costarricense de Electricidad (ICE) RSN Red Sismológica Nacional (national seismological network) Instituto Costarricense de Electricidad - Area Hazard and Hazard and Seismic and Volcanic Auscultation

Notes

There are three key institutions involved in monitoring in Costa Rica, which are all part of the National Seismological Network:

1. Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI)
2. Universidad de Costa Rica UCR, Oficina de Sismología y Vulcanología (OSV)
3. Instituto Costarricense de Electricidad (ICE)

The main observatory, OVSICORI, currently has nine professional or academic staff and seven technical or clerical staff. The Red Sismológica Nacional (RSN) is an institution formed collaboratively by the Instituto Costarricense de Electricidad (ICE) and the Seismology and Volcanology department at the University of Costa Rica (OSV). They predominantly conduct research and some temporary monitoring.

Six of the volcanoes active in the Holocene are currently monitored regularly by OVSICORI and RSN; Arenal, Irazu, Poas, Rincon de la Vieja, Turrialba and Tenorio. This is through regular water and gas analysis, deformation and seismic studies. Miravelles volcano is reported to be monitored irregularly through deformation studies and dry inclinometry, but it is within 15km of the seismic network that also includes the six other previously mentioned volcanoes. Each station in the network has between one and six seismometers, the most being at Arenal and Miravelles volcanoes. Four of the seven monitored volcanoes are classified as high risk. Barva volcano is also classified as high risk but currently believed to be only monitored through a temporary seismic station. There is also a strong motion seismic array in northwest Costa Rica, which includes 10-13 sites with a range of accelerographs, Ref-Tek dataloggers and Kinemetric Episensors.

Orosi and Platanar, both risk level 2 volcanoes, are not currently monitored by any of the institutions in Costa Rica.

D5 Djibouti

Institution	Centre d'Etude et Recherche de Djibouti (CERD) http://www.cerd.dj/
Observatories	L'observatoire géophysique d'Arta http://www.jpb-imagine.com/djibgeol/obsarta/present.html
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(1) Ardoukôba (seismic monitoring)
Volcanoes not monitored	(0) None
Facilities available at seismic stations with 15km of Ardoukôba	Seismometer GPS
Published hazard information	
Partnering organisations:	Institut de Physique du Globe de Paris (IPGP) University of Utah

Notes

L'observatoire géophysique d'Arta (OGA) is a part of CERD, the Centre d'Etude et Recherche de Djibouti (Institute of Earth Sciences at Djibouti's Centre for Studies and Research) and is the main institution involved in the assessment of volcanic and seismic hazard and risk. There are currently five staff members working at OGA. They work in collaboration with the Institut de Physique du Globe de Paris (IPGP) to maintain a seismic network of 12 short-period seismic stations (plus any temporary IPGP stations) to monitor both seismic and volcanic activity, focusing in particular around the Asal-Ghoubbet Rift. Four of the seismic stations and four permanent GPS stations are within approximately 15km of Ardoukôba. Other monitoring of Ardoukôba volcano is highly uncertain but it is not believed to be directly monitored by any other means (gas or deformation) and it is a low risk volcano.

The Geophysical Observatory at Arta record data from all seismic stations in the network. There is an accelerometer and seismometer that are checked daily and summaries are provided weekly. Every station has at least one seismometer and the equipment necessary to transmit details to the main observatory. There are no longer distance and levelling meters for deformation measuring or inclinometers at the local stations near Ardoukôba.

There is no known publication of hazard or risk information associated with the volcanoes or volcano seismicity.

D6 Ecuador

Institution	Instituto Geofisico, Escuela Politécnica Nacional (IG) EPN http://www.igepn.edu.ec/	
Observatories	(3) Levels 1-3	
Volcanoes continuously monitored	*Ecuador:* (4) Tungurahua Reventador Cotopaxi Guagua Pichincha	
Volcanoes monitored at monthly-yearly intervals	*Ecuador:* (7) Cayambe Antisana Sangay Chimborazo Quilotoa Socha Cuicocha	*Galapagos Islands:* (11) Ecuador Fernandina Wolf Darwin Alcedo Sierra Negra Cerro Azul Marchena Santiago San Cristobal Santa Cruz
Volcanoes not monitored	*Ecuador:* (9) Chachimbiro Imbabura Mojanda Pululagua Atacazo Chacana Illiniza Sumaco Licto	*Galapagos Islands:* (2) Pinta Genovesa

Facilities available at *ECUADOR* observatories	**Level 1:** Seismometers BB seismometers Accelerometers Inclinometers, EDM Electronic tiltmeters Continuous (telemetered) GPS Infrared camera Gas monitoring (SO_2)	**Level 2:** Seismometers Electronic inclinometers, GPS Gas monitoring (SO_2)	**Level 3:** Seismometers GPS Gas monitoring
Facilities available on *GALAPAGOS ISLANDS*	Gas monitoring Global Network of Seismographs based in Santa Cruz 5 seismic stations (currently not functioning) BB stations (Sierra Negra)		
Published hazard information	Accurate and up-to-date IGEPN website: - Produces summary publications of volcanic activity: daily-weekly for level 1 volcanoes, weekly-monthly for level 2 volcanoes and yearly (or not at all) for level 3 voclanoes. - Publications include: Recent seismicity General observations Gas emissions data Deformation - Information for the public including general information about each volcano, what to do in emergency, training and risk management ideas (currently in place at Tungurahua and Cotopaxi) Disaster statistics published Preventionweb.org		
Partnering organisations:	Japan International Cooperation Agency Institute of research and development VDAP USGS		

Notes

The monitoring of volcanoes in Ecuador and the Galapagos Islands is undertaken by the Instituto Geofisico, Escuela Politécnica Nacional (Geophysical Institute of the National Polytechnic School, Ecuador (IG)EPN) - a part of the National Network of Volcano Observatories, based in Quito. They have an established group of trained staff including ten seismologists (including four specifically volcano seismology), seven volcanologists and 23 technicians and administrators, responsible for real-time surveillance, data processing, instrumentation and training and hazard assessment.

Eleven of the twenty volcanoes in Ecuador active in the Holocene are currently monitored by (IG)EPN. Each monitored volcano in Ecuador is assigned a level from 1 to 3 and grouped accordingly, based on the amount of monitoring that is undertaken or necessary at each volcano (Please note: This is separate from, but does influence, the monitoring level that we have assigned). The network thus consists of three observatories at a level 1 (corresponding to those volcanoes continually monitored or currently active: Tungurahua, Cotopaxi and Guagua Pichincha), two observatories at level 2 (corresponding to those volcanoes regularly monitored: Cayambe and Reventador) and those at level 3 (the basic level of surveillance: Antisana Cuicocha, Cerro Negro, Soche, Quilotoa and Chimborazo).

The network covers approximately 70% of the country and consists of 47 telemetric stations (all located on volcanoes), 40 accelerographs, 25 continual GPS (for tectonic-related deformation) and 9 new seismic stations located mainly along the coast. There are two broadband stations in Imbabura that are within two active volcanoes. Most equipment is located on Cotopaxi, Tungurahua, Reventador and Antisana, Cuicocha, Quilotoa, Cayambe, Guagua Pichincha, Atacazo, and Pululagua.

Our classification assigns six of the eleven monitored volcanoes a monitoring level of 3 due to their regularity of monitoring and proximity to the seismic network. Three of these are high risk (Guagua Pichincha, Cotopaxi, Tungurahua). Half of the remaining six high risk volcanoes in Ecuador have no or little established monitoring (Imbabura, Atacazo, Pululagua).

(IG)EPN also monitor nine of the volcanoes in the Galapagos Islands, with assistance from the Galapagos National Park. Monitoring is largely reactive than pre-emptive and based on visual observations by tourists and locals. However, yearly thermal monitoring missions are carried out on all volcanoes and qualitative ‘special reports’ are published approximately every week when there is a sign of activity, yearly if not. There are operating broadband seismic stations on Sierra Negra but the five seismic stations installed on Fernandina, Isabela and Bartholomew islands are no longer functioning due to a lack of funds. All of the volcanoes on the Galapagos Islands are low risk, and have a monitoring level between 0 and 2.

A current project entitled "Project for Strengthening the Geophysical Institute, expansion and modernization of the National Seismology and Volcanology", funded by the SENACYT (Panama), is installing GPS stations on volcanoes Antisana, Pululahua, Quilotoa and Chimborazo and four additional stations on Chimborazo, Cayambe, Antisana and Cuicocha. There is also soon to be operating real-time CO_2 gas measurements on Cotopaxi and Tungurahua volcanoes.

Volcanic activity in Ecuador has been quite high for the last 15 years or so, resulting in challenges to the scientific capacity in emergency managements, especially for the activity at Tungurahua and Guagua Pichincha. They have been supported from time to time by the VDAP team of the USGS and other overseas institutions and programmes. The Instituto Geofisico is well respected for these efforts and has a strong reputation internationally.

D7 Ethiopia

Institutions	Institute of geophysics, space science and astronomy (IGSSA) Addis Ababa University, Department of Earth Sciences (geochemistry & structural geology) Ministry of mines - Geological Survey of Ethiopia (economics)
Observatories	Geophysical Observatory, IGSSA http://www.aau.edu.et/index.php/geophysical-observatory
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(65)
Facilities available at every volcano	
Published hazard information	Information is available from the World-Wide Seismographic Station Network (WWSSN) (5 seismic stations are a part of this network) Seismic research published by the Afar consortium – seismic monitoring : http://www.see.leeds.ac.uk/afar/
Partnering organisations:	Institut de Physique du Globe de Paris (IPGP) Afar consortium (UK)

Notes

Due to a lack of resources and capabilities none of the volcanoes in Ethiopia are currently being monitored. There is however a seismic network established by the Geophysical Observatory at the Institute of Geophysics, Space Science and Astronomy (IGSSA), Addis Ababa University (AAU). Researchers at the AAU are also known to have strong interests in geohazards. The IGSSA is predominantly involved in geophysical and geodectic research, whereas the Ministry of Mines, part of the Geological Survey of Ethiopia, oversees general environmental affairs and economical issues. There are currently five scientists and one administrator at the Geophysical Observatory.

The IGSSA is part of the World-Wide Seismographic Station Network (WWSSN) and currently maintains two permanent seismic centres in Ethiopia, four regional seismic stations and thirteen continuous GPS stations (although some of these are project-related and temporary), as well as a global navigation satellite system. The two permanent stations at Furi and the AAU are both broadband seismic stations and the only two recorded in real-time; the other stations record continuous data but are serviced when information is needed. Four volcanoes (Dofen, Fentale, Bishoftu and Corbetti Caldera) are within 40 km of one of these seismic centres, but there are none within 15 km. Two of these have been identified as high risk volcanoes (Bishoftu and Corbetti Caldera), along with three others in Ethiopia.

There are a number of other arrays currently working or having previously worked in Ethiopia, for example the IPGP in the Afar and Djibouti, a US array (Missouri University) and the AFAR consortium (Leeds and Bristol University).

There is only limited institutional capacity to meet the challenge of future volcanic crises. Historically eruptions have occurred well away from centres of population but this study shows that some active volcanoes are close to populated areas. Inexperience at dealing with a future volcanic emergency could be another concern. There are clear needs for better equipment, training and improved baseline knowledge of the countries many volcanoes. How authorities might interact with the scientific institutions in an emergency is another unknown on the basis of information gathered in this study.

D8 Guatemala

Institution	Instituto Nacional de Sismologia, Vulcanología, Meteorología, e Hidrologia National (INSIVUMEH) http://www.insivumeh.gob.gt/ Coordinadora Nacional para la Reducción de Desastres (CONRED) http://conred.gob.gt/
Observatories	(4) Santiaguito observatory (OVSAN) OVFUEGO I, in the village of Panimache, on the slopes of Fuego OVFUEGO II, on the slopes of Fuego Pacaya observatory
Volcanoes continuously monitored	(3) Pacaya Santiaguito Fuego
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(19) Tajumulco Almolonga Atitlán Tolimán Acatenango Agua Cuilapa-Barbarena Jumaytepeque Tecuamburro Moyuta Flores Tahual Cerro Santiago Suchitán Chingo Ixtepeque Ipala Chiquimula Volcanic Field Quezaltepeque

Facilities available at every observatory	At least one short period seismometer Weather station DOAS and COSPEC instruments for gas monitoring (SO_2) Radio link to central offices of INSIVUMEH Visual observation team
Published hazard information	Accurate, detailed and regular updates via INSIVUMEH website: Alert level 1 (green) to 4 (red) Publish seismic records and bulletins Produce bulletins every few days on the current conditions of the active volcanoes During crisis time, they also publish "special" bulletins Downloadable educational brochures on volcano facts & hazards - specific to the 3 active volcanoes including glossaries and eruptive histories Disaster statistics published on Preventionweb.org CONRED Offer courses in risk management
Partnering organisations:	Japanese International Cooperation Agency (JICA) Proteccion Civil del Estado de Chiapas (Mexican Governmental Agency)

Notes

CONRED (Guatemala National Disaster Reduction Agency) and INSIVUMEH (the National Institute for Seismology, Volcanology, Meteorology and Hydrology) are the two monitoring institutions that conduct volcanic monitoring, forecasting and crisis management in Guatemala. Together, they monitor only three of the twenty-two active volcanoes in Guatemala.

CONRED encompasses all the governmental and non-governmental organisations (including INSIVUMEH) and individuals. It has a hierarchical structure with a national level based in Guatemala City (CONRED), a departmental level (CODRED), a municipal level (COMRED) and a local level (COLRED). Only some of the communities near active volcanoes (particularly Pacaya, Santiaguito and Fuego) have a local COLRED, who during a crisis or emergency are in charge of hazard and risk management.

Generally, CONRED perform risk analysis and the interpretation of the data provided by INSIVUMEH and the CONRED volunteers. The group currently includes trained staff in seismology (one person), geology (two persons) and engineering, as well as technicians and administrators. INSIVUMEH operate via four observatories that are staffed with people from the local villages who have received basic training from INSIVUMEH. Each observatory has one or two staff members who report to INSIVUMEH headquarters. There are also between five and fifteen voluntary observers in the 'at risk' communities around a number of the active volcanoes. They report visual observations to the CONRED headquarters.

There are currently two working permanent seismic stations at Santiaguito, one at Fuego and one seismometer at Pacaya. These are also within 15 km of Acatenango, Agua, Almolonga (Cerro Quemado) volcanoes. Five other regional stations at Moyuta, El Jato, Las Nubes, Ixpaco and Marmol are able to monitor Tecuamburro, Cuilapa-Barbarena and Moyuta seismically and are recorded once a month. Tacana, which lies on the border of Mexico and Guatemala, is monitored by the Mexican Governmental Agency (Proteccion Civil del Estado de Chiapas) who informs INSIVUMEH of any changes.
These three monitored volcanoes are all high risk volcanoes. There are five other risk level 3 volcanoes in Guatemala, two of which have no recorded monitoring facilities. The remaining nineteen volcanoes in Guatemala have a risk level of 2, eleven of which also have no recorded monitoring facilities.

Whilst a colour-coded warning system was officially set up in 2004, it has not been fully operational and has reportedly been a source of confusion to both the institution staff and the public. Communication has improved due to the structure of CONRED and the local COLRED involvement, but it has led to a more reactive response and something that is left largely up to local individual's own interpretation. There are therefore still issues with the communication and education of risks between CONRED and INSIVUMEH, and these are also complicated by political and economic aspects. CONRED is currently running a project with funding from the Japanese International Cooperation Agency (JICA) in order to organise an early warning system at Fuego volcano.

Guatemala is a country with many active volcanoes and a dense population. Its institutional capacity seems limited and basic, with several high risk volcanoes with little monitoring and a significant knowledge gap about the geology of many volcanoes. It seems likely that Guatemala will rely heavily on overseas assistance in the event of a major volcanic crisis. There are needs for improved equipment, training and general institutional strengthening.

D9 Indonesia

Institution	Pusat Vulkanogi dar Mitigasi Bencana Geologi (CVGHM), Geological Survey of Indonesia http://pvmbg.bgl.esdm.go.id/ http://www.bgl.esdm.go.id/
Observatories	(76 but not all are operational)
Volcanoes monitored	(67)
Volcanoes not monitored	(75)
Facilities available at every volcano	Seismometer Observation post (1-2 local staff)
Published hazard information	Up-to-date CVGHM website – - volcano status (traffic light); from levels 1-4 - activity reports of key active volcanoes - published reports of changes in volcano status and warnings - publish data and maps of potential soil movement MEMR website - - Create hazard and risk maps, geological maps and fault maps - Provide advice and counselling to public, community and school exhibitions - Publish yearly geology reports and news volumes 3-4 times a year Disaster statistics published on Preventionweb.org
Partnering organisations:	National Disaster Agency (BNBP) Volcano Disaster Assistance Programme of the US Geological Survey (VDAP) Disaster Prevention Research Institution (DPRI) of Kyoto University, Japan

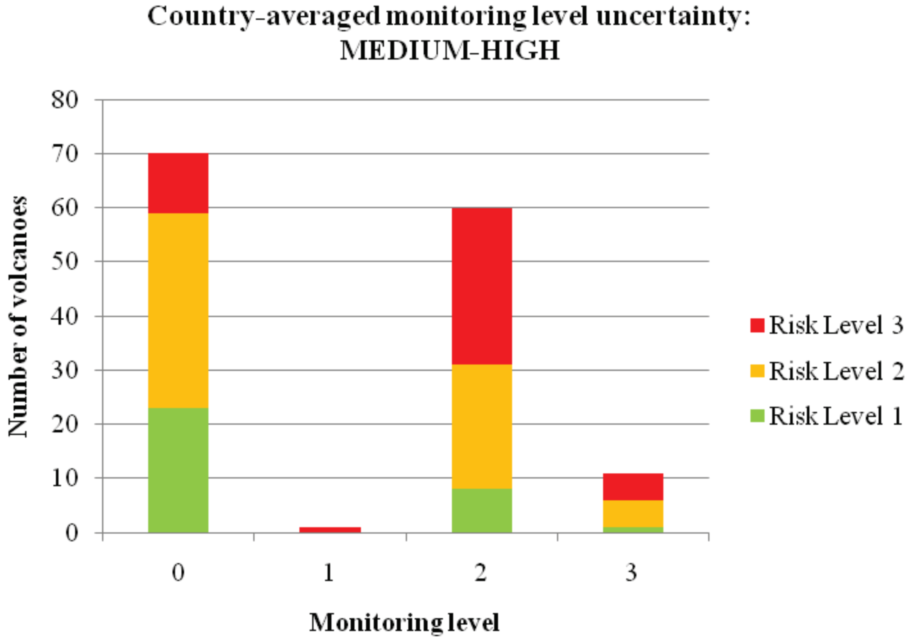
Notes

Pusat Vulkanogi dar Mitigasi Bencana Geologi is the Centre for Volcanology and Geological Hazard Mitigation (CVGHM) and one of the five sections of the Geological Survey of Indonesia. It falls under the authority of the governmental, national Ministry of Mines. The CVGHM (previously called the VSI) is a well-established institution with large numbers of scientific and technical staff who maintain the volcano database of Indonesia and are responsible for monitoring, volcanic hazard mapping and responding to crises.

The CVGHM classifies volcanoes into three types:

(i) Type A (volcanoes that have erupted after 1600 AD);
(ii) Type B (volcanoes have not erupted after 1600 AD); and
(iii) Type C (volcanoes that exhibit geothermal systems, without any eruption history)

67 of the 78 Type A volcanoes are currently monitored, but only about ten of these have more than one seismometer. Typically each observation post has a dedicated building, one member of CVGHM and two or three local observers. Any elevated recordings by the local observation post are reported to the headquarters in Bandung and a team is sent out to them with extra monitoring equipment. About 20 of the volcanoes have seismic data telemetered directly to the CVGHM offices in Bandung. There are few ground deformation networks, though Lokon-Empung has permanent GPS monitoring; any monitoring of gas emissions is predominantly carried out by foreign research groups and organisations. CVGHM is currently producing volcanic hazards maps for Type A volcanoes. CVGHM do not currently monitor the 29 Type B or 21 Type C volcanoes, or the other 14 volcanoes active in the Holocene listed by the SI. Only five of the 56 volcanoes that have been classified as high risk in Indonesia are well monitored at level 3.



The work of CVGHM is augmented by work of overseas research teams, notably from the USA (VDAP), Japan (the Disaster Reduction Research Institute, Kyoto), Singapore (Earth Observatory of Singapore) and Europe. Sabo works (Japan) have built Sabo dams on many volcanoes to protect from lahar and pyroclastic flows, but these have recently proved to be ineffective for large volcanic events, as at Merapi in 2010.

A lack of basic geological data, baseline geophysical data and technical equipment limit the ability to assess volcanic hazards in Indonesia. There are also added complications due to the shared responsibility of different hazards; for example floods and lahars are the responsibility of the Ministry of Public Works and ash hazards are under the auspices of the Darwin Volcanic Ash Advisory Centre in Australia. This creates problems in lines of communication.

With over 20% of the World's volcanoes, including some of the most dangerous types and with very dense populations around many of them, volcanic risk is high. Some long dormant volcanoes of type B and C, such as Sinabung in Sumatra that erupted in 2010, pose problems when they erupt (becoming type A) because they previously had low priority and little is known about them. Although there are several hundred staff within CVGHM institutional capacity is stretched, especially when there are several simultaneous volcanic eruptions and episodes of unrest. CVGHM has limited equipment in gas and deformation monitoring. Enhancement of equipment, further integration of monitoring networks with telemetering of data, training and knowledge transfer in some key science areas would all improve institutional capacity. The lack of basic geological knowledge on many potentially high risk volcanoes is an impediment to rapid assessment of long dormant volcanoes when they show signs of unrest.

D10 Madagascar

Institution	
Observatories	Institut et Observatoire Géophysique d'Ambohidempo IOGA, Université d'Antananarivo http://takelaka.dts.mg/ioga-ctbto/index.html
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(4) Ambre-Bobaomby Nosy-Be Ankaizina Field Itasy Volcanic Field Ankaratra Field
Facilities available at every volcano	(0) None - Only Itasy is within 15km of a seismometer
Published hazard information	No disaster statistics available on Preventionweb.org
Partnering organisations:	EOST - Ecole et Observatoire des Sciences de la Terre, University Strasbourg BGS Joint Center for Resources in Geomatics (CCRG) – GIS and Remote Sensing

Notes

There is no dedicated volcano monitoring institution in Madagascar, although local seismic and geophysical research is conducted by the Institut et Observatoire Géophysique d'Ambohidempo IOGA, at the Université d'Antananarivo. They have four centres in Seismology, Electro- and Geomagnetism, Geophysics and Remote sensing, with a total of approximately

25 staff including directors, researchers and technicians. The seismic observatory maintains seven seismic stations around Madagascar, although only one of these is within 15 km of one of the active volcanoes- the Itasy Volcanic field.

The Ecole et Observatoire des Sciences de la Terre (EOST) are in charge of the Antananarivo Magnetic Observatory, although no data has been acquired since 2008 due to acquisition failure and political instability in the country. They plan to reinstall equipment in May 2011. The youngest volcanics in Madagascar are mostly stabilised lava deposits and are considered to represent only a low a threat to the inhabitants; with the highest risk of all four volcanoes a level 2.

D11 Mali

Institution	Ministry of Internal Security and Civil Protection (civil defence, disaster management) http://www.primature.gov.ml
Observatories	None
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(1) Tin Zaouatene
Facilities available at every volcano	None
Published hazard information	No disaster statistics available on Preventionweb.org
Partnering organisations	Unknown

Notes

There is no single dedicated monitoring institution in Mali, but disaster management is believed to fall under the authority of the Ministry of Internal Security and Civil Protection, the governmental branch who manage civil defence. For this reason there is not believed to be any facilities available for volcanic hazard monitoring, but there is a relatively high degree of uncertainty associated with this. Tin Zaouatene has been identified as only being at risk level 1 and is not considered high risk.

D12 Panama

Institution	Secretaría Nacional de Ciencia, Tecnología e Innovación (SENACYT) http://www.senacyt.gob.pa/ Sistema Nacional de Protección Civil (SINAPROC) http://www.sinaproc.gob.pa/
Observatories	For seismic network at Volcán Barú: Observatorio Sísmico del Occidente de Panamá (OSOP) http://www.osop.com.pa/ For the rest of Panama: Universidad de Panama Instituto de Geociencias
Volcanoes continuously monitored	(1) Volcán Barú
Volcanoes monitored at monthly-yearly intervals	(0)
Volcanoes not monitored	(1) El Valle
Facilities available at monitored volcano	Permanent seismic network (Barú): - 4 BB digital seismograph stations - seismometer - accelerometer Digital radio system Inclinometers Lahar detection facilities Webcam Digital telemetry (real-time monitoring)

Published hazard information	SINAPROC maintain an accurate and up-to-date website on emergency and risk management: - Local news items about recent eruptions or earthquakes - Publish leaflets, brochures and organise workshops and training - Civil warning system SENACYT run an education system for the local schools in the Volcán Barú region No disaster statistics available on Preventionweb.org
Partnering organisations:	USGS (hazard mapping for Volcán Barú) USGS VDAP (training and software exchange, installation of seismic network, BB stations) Michigan Tech University ACP (Installation and maintenance of seismic stations and data exchange) UPA (Seismic station installation and maintenance in UPA network, seismic data exchange)

Notes

The Institute of Geosciences at the University of Panama is in charge of both seismic and volcanic monitoring at the national level in Panama. They exchange data with local networks in Panama and the national networks of Colombia and Costa Rica. There are a total of 43 seismic stations across Panama, owned by the University of Panama and the Authority of Panama Canal but OSOP manage the four that are within 15 km of Volcán Barú, a risk level 2 volcano. OSOP (Seismic Observatory of Western Panama) collaborate closely with SINAPROC (civil protection) to maintain this seismic network at Volcán Barú, which is the only site with established monitoring facilities and hazard assessment reports. They share data with the university and gain funding from the government through SENACYT. The network stores data continuously and it is sent to the university on a daily basis. No monitoring is performed at El Valle, but the University of Panama plans to monitor La Yeguada in the near future. El Valle is a low risk volcano and there has been no recorded eruption of La Yeguada in the Holocene period. There has been a recent programme of assistance from the VDAP team of the USGS.

Whilst monitoring at Volcán Barú is fairly established (corresponding monitoring level of 3), it is predominantly concentrated around seismicity than volcanological hazards due to frequent tectonic earthquakes and recent seismic activity there. There is no known record of fumarolic activity, ash or degassing in panama and as such, little volcanic gas or deformation monitoring is performed.

D13 Papua New Guinea

Institution	Rabaul Volcanological Observatory (RVO) - Geological Survey of Papua New Guinea
Observatories	Rabaul Volcanological Observatory (RVO)
Volcanoes continuously monitored	(6) Rabaul Manam Ulawun Langila Karkar Pago
Volcanoes monitored at monthly-yearly intervals	
Volcanoes not monitored	(50)
Facilities available at every volcano	Seismometer Water-tube or Electronic tiltmeters GPS Gas monitoring (COSPEC)
Published hazard information	The PNGNDC website is fairly informative but not very up-to-date. It publishes news articles about recent volcanic activity (last update Aug 2010) -Active volcanoes are assigned an Alert (warning) level Disaster statistics are published on Preventionweb.org
Partnering organisations:	Department of Mining: Papua New Guinea Geological Survey Papua New Guinea National Disaster Centre (PNG)NDC http://www.pngndc.gov.pg/ USGS VDAP (technical assistance) AusAid

Notes

The Rabaul Volcanological Observatory is operated by the Geological Survey of Papua New Guinea who currently monitor six of the active volcanoes in Papua New Guinea. They currently have approximately 25 staff members, including volcanologists, seismologist and technicians, and five part-time observers. There are eleven seismic stations in Papua New Guinea, including ones at Langila, Manam, Ulawun, Port Moresby and Karkar, which are linked to the main headquarters of the RVO in Rabaul. Some stations also have tiltmeters, GPS and gas monitoring facilities although these are not believed to be very many. Problems with social unrest and a lack of funding have led to some of the monitoring equipment not being maintained.

The six monitored volcanoes are monitored to level 3 due to the known proximity to the seismic networks and regularity of monitoring. There is a higher degree of uncertainty however around the facilities available for gas or deformation monitoring. Manam, Karkar, Pago and Tavui volcanoes are risk level 2, whilst Rabaul is recognised as high risk. There are no other high risk volcanoes in Papua New Guinea.

Generally at times of increased risk, the RVO communicate with and provide data to the Provincial Disaster Committee at the National Disaster Centre (NDC). The NDC are a part of the Department of Provincial & Local Government Affairs and are responsible for preparedness, education and crisis management. They also conduct their own research through their Risk Management division whilst the Community Government Liaison manages emergency planning.

D14 Philippines

Institution	Philippines Institute of Volcanology and Seismology (PHIVOLCS) http://www.phivolcs.dost.gov.ph/
Observatories	(9) Taal Volcano Observatory, Buco Mayon Resthouse Observatory (MRHO) Buang, Albay Lignon Hill Observatory (LHO) Tagas, Albay Kanlaon Volcano Observatory (KVO) La Carlota City College Campus, Bgy. Cubay, Cabagnaan Volcano Observatory (CaVO) Cabagnaan, Negros Oriental Bulusan Volcano Observatory San Benon, Irosin, Sorsogon Quiboro Volcano Observatory Mambajao, Camiguin Province Pinatubo Volcano Observatory Clarkfield, Pampanga Gen.Santos Volcano Observatory, MSU campus
Volcanoes continuously monitored	(8) Bulusan Hibok-Hibok (Camiguin de Babuyanes) Kanlaon Mayon Pinatubo Taal Matutum (seismics) Parker (seismics)
Volcanoes monitored at monthly-yearly intervals	(1) Biliran
Volcanoes not monitored	(38)
Facilities available at every observatory	Seismometer Tiltmeter Precise leveling lines and EDM Water sampling Gaseous SO_2 monitoring (COSPEC) Thermometers GPS

Published hazard information	Informative and up-to-date PHIVOLCS website publishes: - Education tools; e.g. list of volcanic hazards and their precursors, tsunami and earthquake preparedness guide - Daily active volcano bulletins, including data on seismicity, SO_2, ground deformation and general observations - Hazard maps - Alert levels 1 - 5 - Evacuation zones (A,B,C), Permanent Danger Zone (4-6km radius of active volcano) and Extended Danger Zone (EDZ) Disaster statistics are published on Preventionweb.org
Partnering organisations	Mindanao State University (MSU) VDAP, USGS Earth Observatory of Singapore (EOS)

Notes

The Philippines Institute of Volcanology and Seismology (PHIVOLCS), part of the service institute of the Department of Science and Technology (DOST), operate nine volcano observatories throughout the Philippines. Through these observatories they continuously monitor eight of the 47 volcanoes active in the Holocene. Of these, Parker and Matutum volcanoes are monitored seismically only. The variety in seismic monitoring results in only six of these eight volcanoes having a monitoring level of 3 and five other volcanoes in the Philippines being assigned level 3 monitoring; Pocdol, Masaraga, Banahaw, San Pablo and Laguna. Nine of these eleven volcanoes are high risk. The remaining three other high risk volcanoes in the Philippines (Cabalían, Parker and Paco) are monitored at level 2.

DOST-PHIVOLCS is a large, established institute with approximately 25 trained staff members at the head office in Quezon City, and at least two staff members (with at least one trained resident volcanologist) at each of the observatories. Each observatory monitors the local volcano continuously through the use of permanent seismic stations (between four and eight stations each), deformation equipment, water and gas sampling facilities and permanent GPS stations. There is also a remote seismic network at Parker and Matatum volcanoes. The Philippines has a total of 65 seismic stations, 29 of which are manned. All information is received at the Data Receiving Center (DRC) at the PHIVOLCS head office, which is operated continuously by the Seismological Observation and Prediction Division (SOEPD).

DOST-PHIVOLCS are responsible for advising the public of hazard information, monitoring fallout and volcanic hazards, wind directions and advising civil aviation authorities. They also have a quick response team to respond to any increased activity.

There are partnerships with overseas institutions and programmes, which augment research and monitoring of Philippine volcanoes in co-operation with PHIVOLCS. The VDAP team of the USGS, for example, has had a close and positive relationship with PHIVOLCS and played a notable role in crises at Pinatubo in 1991 and Mayon.

PHIVOLCS gained a deserved high reputation during the eruption of the Pinatubo in 1991 when over 300,000 people were successfully evacuated and it seems likely that a few tens of thousands of lives were saved. Nonetheless, many of Philippines volcanoes are not monitored and there is large deficit in basic geological knowledge.

D15 Solomon Islands

Institution	Ministry of Mines, Energy and Rural Electrification/Geology and Seismology Divisions, Solomon Islands Geological Survey National Disaster Council, Ministry of Home Affairs
Observatories	
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(1) Savo
Volcanoes not monitored	(7) Kana Keoki Coleman Seamount Simbo Unnamed Gallego Kavachi Tinakula
Facilities available at every volcano	(0) None
Published hazard information	The National Disaster Council, SOPAC and SIGS have all undertaken a range of community outreach sessions, in the form of workshops in Honiara, Savo and Simbo. No disaster statistics available on Preventionweb.org
Partnering organisations:	SOPAC (South Pacific Applied Geoscience Commission) – now part of the South Pacific Commission assists the SIGS. University of Wellington, New Zealand University of Leicester University of Austin, Texas National Taiwan University British Geological Survey BGS

Notes

The monitoring of the volcanoes on the Solomon Islands is under the authority of the Solomon Islands Geological Survey (SIGS) Ministry of Mines, Energy and Rural Electrification/Geology and Seismology Divisions, but financial and technical restraints prevent them from establishing a reliable network or regular monitoring. SIGS is based in Honiara on Capitol Territory, where there is one broadband seismograph that feeds into the USGS' World Wide Standard Seismological Network (WWSSN). Ministry staff includes a permanent secretary, a seismologist and geologist.

Savo volcano is the highest risk volcano on the Solomons but still only classified as level 2. Visits there are regular but data collection is reported to be limited to observation of the geothermal areas. There is no seismometer or monitoring equipment on Savo, or any other volcano on the Solomons.

Volcanic hazards are not addressed by the SIGS, or by any other partnering organisation. The National Disaster Council in the Ministry of Home Affairs and SOPAC however, undertake community outreach sessions and educational workshops and have worked with SIGS to develop an evacuation plan of Savo. In common with many GFDRR priority countries, there is a lack of baseline geological knowledge.

There are 4 continuous GPS stations in the Western Province, on the islands of Simbo, Ranongga, Nusatupe, and on central Rendova. Temporary GPS stations have also been established at the Munda airfield on New Georgia, on southern Vella Lavella and in the southeast of Rendova, but none are within 15 km of any volcanoes. National Taiwan University (NTU) has five broadband seismographs on Simbo, Vella Lavella, Nusatupe, northwestern New Georgia and on central Rendova (within 15km of Gallego volcano). This caused an increase in the monitoring levels at Simbo and Gallego to level 2. They plan to add more continuous GPS and seismographs in 2011, one of which will be within 20 km of Kavachi volcano.

D16 Vanuatu

Institution	Geohazards Observatory, Vanuatu Meteorological and Geosciences Department http://www.geohazards.gov.vu/
Observatories	
Volcanoes continuously monitored	(2) Yasur Ambrym
Volcanoes monitored at monthly-yearly intervals	(4) Lopevi Ambae (Aoba) Gaua Suretamatai
Volcanoes not monitored	(8) Motlav Mere Lava Epi Kuwae Unnamed North Vate Traitor's Head Aneityum
Facilities available at monitored volcano	At least one seismic monitoring station
Published hazard information	The Geohazards Observatory website publishes: Activity bulletins of active volcano published online approximately every other month Map of monitoring network, satellite pictures Resources site with information about volcano hazards, eruptions and monitoring Active traffic light monitoring system (1-4) for 6 monitored volcanoes Disaster statistics published on Preventionweb.org

Partnering organisations:	IPGP Institut de Physique du Globe de Paris CRV Volcanology Research Centre (Clermont Ferrand, France) CTIV Centre for computerised remote observation of volcanoes IRD Institute of Development Research (Clermont Ferrand, France) GNS, Geology and Nuclear Science, New Zealand CTBTO, Vienne GA, Geoscience Australia NOAA/MODIS, Satellite information services

Notes

The Geohazards Observatory within the Vanuatu Meteorological and Geosciences Department monitors six of the fourteen active volcanoes in Vanuatu. Thirteen of these fourteen volcanoes in Vanuatu are classified as low risk; Yasur is a risk level 2 volcano but also monitored at level 3.

The Observatory, based in Port-Vila, Vanuatu, currently has nine trained staff members and is the centre of the Vanuatu volcano network (and also the Efate Seismic Network). The centre receives the real-time/near real-time data sent from the four temporary (Ambae, Gaua, Ambrym, Lopevi) and two permanent (Ambrym, Yasur) seismic stations in the network, plus three permanent stations at Port Vila itself. The Vanuatu volcano network also includes two permanent GPS stations and three acoustic temporary stations. One permanent seismic station at Santo/Malekula is part of the North Vanuatu Seismic Network.

There are plans for at least two more permanent sites to be installed at Ambae and Gaua and one at Santo/Malekula to become part of the Geoscope programme (Global Network of Broad Band Seismic Stations, monitored by IPGP). Mapping of SO_2 gas emissions from active volcanoes are also occasionally produced. The CRV and IRD help in the real-time transmission of this data. They actively use the Geohazards Observatory website to publish educational tools, updated volcano bulletins and volcano alert levels, although the level of public engagement and disaster management is unknown.

D17 Vietnam

Institution	Vietnam Institute of Geosciences and Mineral Resources (VIGMR)
Observatories	None
Volcanoes continuously monitored	(0) None
Volcanoes monitored at monthly-yearly intervals	(0) None
Volcanoes not monitored	(6) Cù-Lao Ré Group Toroeng Prong Haut Dong Nai Bas Dong Nai Ile des Cendres Veteran
Facilities available at every volcano	(0) None
Published hazard information	None
Partnering organisations:	AusAid

Notes

None of the six volcanoes in Vietnam are currently monitored, and there is no single dedicated volcano observatory. The surveying of volcanic hazards in Vietnam theoretically falls under the authority of the Geological sector of the Vietnam Institute of Geosciences and Mineral Resources (VIGMR) (part of the Ministry of Natural Resources and Environment (MONRE)). The VIGMR have previously conducted a ‘geohazard assessment and prediction’, which included volcanic hazards in Central Vietnam and noted evidence of active faulting, fumeroles and mud eruptions. Historical records in Vietnam also show evidence of offshore volcanic activities along the 109° meridian; Cù-Lao Ré Group, Ile des Cendres, Veteran, all which are low risk volcanoes. Due to this recorded evidence, concern seems to be focussed predominantly around the submarine volcanoes, but complications arise as to whom has the responsibility of monitoring the associated hazard – whether it is the Marine Geology Centre (also a part of the Ministry of Natural Resources and Environment), the Geological sector of the VIGMR, the Institute of Global Physics, (who is in charge of monitoring earthquakes) or the National Centre for Hydrology and Meteorology Forecast (who are responsible for monitoring possible tsunamis). There is, however, a National Committee of Rescue and Emergency who would provide service in disaster/crisis management. There are no high risk volcanoes in Vietnam, but the two with moderate risk (Haut Dong Nai and Bas Dong Nai) are located inland.

D18 Yemen

Institution	National Seismological Observatory Center (NSOC) http://www.nsoc.org.ye
Observatories	
Volcanoes monitored	Unknown
Volcanoes not monitored	Unknown
Facilities available at every volcano	Unknown
Published hazard information	None
Partnering organisations:	Yemen Geological Survey and Mineral Board Yemen Ministry of Water and Environment http://www.ygsmrb.org.ye/MYDEFAULT.asp German Ministry of Foreign Affairs/German Red Cross

Notes

Following the eruption of Jebel at Tair in 2007, the National Seismological Observatory Center (NSOC) became the National Seismological and Volcanological Observatory Center, creating Yemen's first volcano monitoring network. It was established in collaboration with the Germany-Indonesian Tsunami Early Warning System and is has previously been supported by the German Ministry of Foreign Affairs who led projects on disaster risk reduction. It has not been able to assess the current status of the Observatory or whether any of the twelve volcanoes in Yemen are monitored as there are no reports on their status or activity levels since that eruption in 2007. Four of the twelve volcanoes have a risk level 2, whilst the remaining eight are classified as low risk.

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