Chapter 22

Development of a new global Volcanic Hazard Index (VHI)

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22.1 Background

Globally, more than 800 million people live in areas that have the potential to be affected by volcanic hazards, and this number is growing [Chapter 4]. The need for informed judgements regarding the global extent of potential volcanic hazards and the relative threats is therefore more pressing than ever. There is also an imperative to identify areas of relatively high hazard where studies and risk reduction measures may be best focussed. Various authors have tackled this task at a range of spatial scales, using a variety of techniques. At some well-studied volcanoes, the geological record has been used in combination with numerical modelling to create probabilistic hazard maps of volcanic flows and tephra fall [Chapter 6 and 20]. Such sources of information can be hugely beneficial in land use planning during times of quiescence and in emergency planning during times of unrest. Unfortunately, creating high-resolution probabilistic hazard maps for all volcanoes is not yet feasible. There is therefore a need for a methodology for volcanic hazard assessment that can be applied universally and consistently, which is less data- and computing-intensive. The aim of such an approach is to identify, on some objective overall basis, those volcanoes that pose the greatest danger, in order that more in-depth investigations and disaster risk reduction efforts can then be focused on them.

22.2 Previous methods

An index-based approach to volcanic hazard assessment involves assigning scores to a series of indicators, which are then combined to give an overall hazard score. Indicators typically include measures of the frequency of eruptions, the relative occurrence of different kinds of eruptions and their related hazards, the footprints of these hazards, and eruption size. Indices are well suited to the problem of volcanic hazard assessment, as they allow the decomposition of the complex system into a suite of volcanic system controls and simple quantitative variables and factors that jointly characterise threat potential.

Ewert (2007) presented an index-based methodology for assessing volcanic threat (the combination of hazard and exposure) in the USA, to permit prioritisation of research, monitoring and mitigation. The study formed part of the development of the National Volcano

Early Warning System (NVEWS). The NVEWS method scores and sums twelve hazard indicators, with the result then assigned to one of five levels. Whilst representing a significant improvement on past indices, the use of a largely binary scoring system obscures much of the complexity of volcanic hazard. For example, the occurrence of Holocene lava flows and Holocene pyroclastic flows are assigned the same weighting, though the latter is far more hazardous, particularly from a loss of life perspective (Auker et al., 2013, Witham, 2005). The inclusion of indicators for historical unrest and unsatisfactory treatment of missing data make application of the NVEWS system problematic in many jurisdictions outside of the USA, where data may be scarce or absent.

Aspinall et al. (2011) developed a method for volcanic hazard assessment for application to the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) priority countries (16 developing countries). The GFDRR method uses eight indicators to assess hazard; uncertainty indicators, used to describe the quality of information, are attached to six of the eight indicators. The summed hazard and uncertainty scores are each assigned to one of three levels.

The time period over which volcanic hazards are being assessed is not explicitly stated in the NVEWS and GDFRR methods. However, hazard assessments are more valuable if the time is specified and indeed the informativeness of the results depends on the time-frame. For example, an assessment over ten years will likely yield a very different outcome to an assessment over 10,000 years, in which very large but rare eruptions may be the dominant peril. Both the NVEWS and GFDRR methods are based on the entire Holocene eruption record. The new method developed here gives more weight to recent activity patterns, as these are more likely to indicate the character of future eruptions.

22.3 Development of a new methodology

Here, we address limitations in the NVEWS and GFDRR approaches and build on their strong points to develop an improved volcanic hazard assessment approach, which we call the Volcanic Hazard Index (VHI). We aim to assess global volcanic hazard for the next 30-year period using our indicator-based VHI method on a volcano-by-volcano basis.

The main data source is the Volcanoes of the World 4.0 (VOTW4.0) database (Siebert et al., 2010) from which we only consider 'confirmed' eruptions. There is evidence for severe under-recording of events over the entire Holocene period, which diminishes towards the present (Deligne et al., 2010). The fatalities database of Auker et al. (2013) is used in conjunction with VOTW4.0 to provide evidence that justifies indicator choices and their weightings.

22.3.1 Indicator choices

Indicators used in both the NVEWS and GDFRR methods provide a useful starting point for development of an improved methodology. These are:

- eruption frequency
- eruption magnitude
- pyroclastic flow occurrence
- mudflow (lahars and jökulhlaups) occurrence
- lava flow occurrence.

Eruption magnitude and frequency are intuitive indicators of volcanic hazard. The Volcanic Explosivity Index (VEI) is based on the size of eruptions according to volume of tephra produced; higher VEI eruptions have larger footprints and are thus more hazardous. Modal VEI and largest recorded VEI are used as magnitude indicators, aiming to capture a volcano's 'typical' and 'extreme' eruption size, based on what is known from the record. A future eruption greater than the largest recorded VEI cannot of course be excluded.

With regard to eruption frequency, given identical volcanoes producing eruptions of identical style, magnitudes and intensities, if one erupts twice as often as the other then the former is twice as hazardous as the latter. This notion suggests that eruption frequency should be used multiplicatively rather than additively, as was done in previous methods. Taking AD 1900 as base year, because recording of eruptions is almost complete after this date (Furlan, 2010), four frequency classes are defined: active (one or more eruptions since AD 1900); semi-active (historical (post-AD 1500) eruptions with or without unrest recorded since AD 1900 or Holocene (pre-AD 1500) eruptions and unrest since AD 1900); semi-dormant (Holocene (pre-AD 1500) eruptions with no post-1900 unrest or no Holocene eruptions but recorded unrest); fully-dormant (no Holocene eruptions or unrest recorded since AD 1900). Unrest is identified from Bulletin Reports which accompany VOTW4.0, and is defined subjectively as activity above background levels (for example, the presence of fumaroles does not constitute unrest, however descriptions of periods of intensified emissions does).

The fatalities database of Auker et al. (2013) can be used to infer the relative hazard posed by different eruption phenomena. Pyroclastic flows and mudflows have caused the greatest proportions of fatalities (44% and 22%, respectively), and are therefore deemed very hazardous. Lava flows have caused a relatively small proportion of fatalities (1%) but are recorded in approximately 30% of eruptions. As such, their economic impact could be large and an indicator is used to reflect this. The occurrence of pyroclastic flows, mudflows and lava flows should form part of a volcano's hazard assessment when these are common hazards (rather than rare, extreme events). We define a phenomenon as a significant contributor to overall hazard potential if it has occurred in 10% or more of a volcano's eruptions.

Indicators should capture distinct components of volcanic hazard, and problems known to affect volcanic eruption data, namely under recording, should be compensated for. Testing for the concurrence and under-recording of pyroclastic flows, mudflows, and lava flows was undertaken to identify any potential issues; no corrections were required. Further, the relationship between the occurrence of pyroclastic flows, mudflows and lava flows, and modal and maximum VEI was investigated. However, these aspects are not simply correlated, and thus VEI cannot be used as a catch-all representation of hazard. Separate indicators for pyroclastic flows, mudflows, and lava flows are required. For example, pyroclastic flows due to dome collapse and volcanic blasts can occur in eruptions with quite low VEI, and mudflow occurrence is dependent on external factors such as rainfall and the presence of crater lakes, which are unrelated to VEI.

22.3.2 Time dependence

Exploration of the global under-recording of volcanic eruptions shows two significant improvements in recording completeness, at approximately AD 1500 and AD 1900 (at which

point the record becomes largely complete; Furlan (2010)). These findings can inform the length of time over which data are drawn for the hazard assessment, referred to henceforth as the 'counting period', and are useful in characterising each volcano's 'recent' history. The ideal counting period start date would be AD 1900 because of the near completeness of the volcanic eruption record after this date. However, some volcanoes have not erupted frequently enough for this time period to be representative of their recurrence statistics. Consequently we develop a simple approach where the definition of 'recent', and thus the length of the counting period, is specific to each volcano. For active volcanoes (those with at least one year in eruption recorded since AD 1900) a sliding scale is used. The counting period for an individual volcano begins in the year defined by the equation: AD Year = $1500 + \left[\left(\frac{N}{113}\right) \times 400\right]$, where N is the number of years in which the volcano is recorded as erupting between AD 1900 and AD 2013. AD 2013 is the end year of the counting period for active volcanoes. AD 1500 is used as the base year for active volcanoes' counting periods because of the significant improvement in recording at this time. The entire Holocene is used as the counting period for semi-active, semi-dormant and fully-dormant volcanoes, to maximise the amount of eruption data available for hazard assessment.

The modal VEI and pyroclastic flow, mudflow and lava flow occurrence indicators are each scored based on eruptions within the counting period only. The maximum recorded VEI is calculated using data for all Holocene eruptions (regardless of the volcano's frequency status), to maximise the likelihood of capturing the volcano's extreme events.

22.3.3 Hazard indicator scores

Modal and maximum recorded VEI are used as a reference in assigning numerical scores to the pyroclastic flow, mudflow, lava flow, and eruption frequency indicators. Comparison of the percentage of fatalities caused by the three phenomena with the percentage of fatalities caused by eruptions of each VEI suggests that pyroclastic flows and eruptions of VEI 4 generate similar impacts; pyroclastic flows have caused 44% of fatalities, whilst VEI 4 eruptions have caused 37%. This comparison leads to assigning a score of 4 to pyroclastic flow occurrence, when 10% or more of eruptions within the counting period have recorded pyroclastic flows. The total number of fatalities caused by mudflows is 50% those caused by pyroclastic flows, and by lava flows 2%. These proportions yield scores of 2 and 0.1 for mudflows and lava flows, respectively, when 10% or more of eruptions within the counting period have these flows recorded. A score of 0 is given for each of the pyroclastic flow, mudflow and lava flow indicators if the relevant phenomenon is recorded in fewer than 10% of eruptions.

Eruption frequency is used multiplicatively rather than additively in our method. As such, scoring of the frequency indicator need not be proportional to the scores of the other indicators; the only requirement is that active volcanoes are scored highest and fully-dormant volcanoes lowest, and that the scores for the four frequency status classes are proportional to each other in terms of their representation of hazard. A score of 1 is used for fully-dormant volcanoes, 1.5 is used for semi-dormant volcanoes, 2 for semi-active volcanoes, and a sliding scale from 2 to 3 is used for active volcanoes, calculated using $2 + \left(\frac{N}{113}\right)$, where N is the number of years in which the volcano is recorded as erupting since AD 1900.

22.3.4 Calculating the hazard score

Scores for the indicators are combined to give a volcano-specific hazard score using the following conceptual structure:

[eruption frequency × ('frequent' characteristics of volcano's eruptions)] + extreme characteristics

This can be expressed in terms of the aforementioned indicators as:

[frequency status score × (modal VEI + PF score + mudflow score + lava flow score)] + maximum recorded VEI

with indicators for modal VEI, pyroclastic flow occurrence, mudflow occurrence and lava flow occurrence calculated using data for eruptions from the counting period only; maximum recorded VEI is calculated using all available Holocene data.

Maximum VEI is the only indicator score not multiplied by the frequency status score. Testing showed that multiplicative use of the maximum recorded VEI score gave distorted results and very high overall scores for some volcanoes that have particularly large maximum recorded VEIs. Simply adding on the maximum recorded VEI score moderates this propensity, and dilutes the weight associated with infrequent extreme eruptions.

The full method is as follows:

Indicator	Class	Criteria	Scoring
Eruption frequency	Fully dormant	- No time in eruption recorded since AD 1900 and No recorded unrest since AD 1900	1
	Semi-dormant	- No Holocene eruptions but unrest recorded since AD 1900 Or - Holocene (pre-AD 1500) eruptions but no recorded unrest since AD 1900	1.5
	Semi-active	- Holocene (pre-AD 1500) eruptions and unrest since 1900 Or - Historical (AD 1500-1900) eruptions with or without unrest since AD 1900	2
	Active	- One or more years with eruptions recorded since AD 1900	$2 + \left(\dfrac{N}{113}\right)$ where N is the number of years in which the volcano is recorded as erupting since AD 1900
Pyroclastic flow occurrence	Pyroclastic flows are a significant hazard	Pyroclastic flows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	4

Indicator	Class	Criteria	Scoring
	Pyroclastic flows are not a significant hazard	Pyroclastic flows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0
Mudflow occurrence	Mudflows are a significant hazard	Mudflows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	2
	Mudflows are not a significant hazard	Mudflows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0
Lava flow occurrence	Lava flows are a significant hazard	Lava flows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	0.1
	Lava flows are not a significant hazard	Lava flows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0
Modal VEI	N/A	The modal VEI of eruptions recorded with a known VEI within the volcano's counting period is X. A minimum of four such eruptions are required. Where there is no mode, the mean is used	X
Maximum recorded VEI	N/A	The greatest VEI of any eruption recorded within the volcano's Holocene eruptive history is Y	Y

22.3.5 Applicability and data constraints

For many volcanoes in VOTW4.0, data are scarce. The hazard assessment methodology requires enough data for scores to be assigned to all components of the index algorithm. The minimum amount of data required to apply the index is four or more eruptions within the volcano's counting period with a known VEI.

Volcanoes with insufficient data, i.e. those with fewer than four eruptions of known VEI within the counting period are unclassified as a classification would be accompanied by such large uncertainties as to make this irrelevant.

There are 328 volcanoes that satisfy this threshold for sufficient data to apply the scoring method fully. Such volcanoes are termed 'classified'. For the 1,223 volcanoes that do not meet these data requirements, termed 'unclassified', an alternative method that includes an assessment of the uncertainty related to lack of data must be used.

The calculation of VHI can be skewed by the inclusion of an unrepresentative modal VEI or prevented by the description of few events due to the persistent nature of activity at some

volcanoes. Typically, activity separated by less than three months of apparent repose is considered an ongoing eruption. This persistent activity typically comprises small explosions or continuous effusions with infrequent bursts of larger activity. In VOTW4.22, the VEI for a persistent period of activity is taken as the maximum attained in that time. This can skew the calculation of the modal VEI upwards and result in an anomalously high VHI. These issues are accounted for through the identification of long eruptions, specifically those where the number of years in eruption in the counting period is greater than twice the number of eruptions in that period. Detailed bulletin reports accompanying VOTW4.22 have been studied to better constrain common activity and individual events. This approach will be improved and refined to ensure objectivity.

22.4 VHI application for GAR15

VHI scores have been determined for the Holocene volcanoes of VOTW4. The scores for classified volcanoes range from 0 to 30. The volcanoes' hazard scores are divided into the three hazard levels: VHI Level I (Scores 0 to <8; 134 volcanoes), VHI Level II (Scores 8 to <16; 106 volcanoes), and VHI Level III (Scores 16+; 88 volcanoes). These hazard levels are used to reflect the semi-qualitative nature of some of the data used and the approximations employed in creating and applying the method.

Ultimately, the Hazard Levels must be combined with measures of exposure in order to make statements about risk. For example, VHI Level I volcanoes may cause huge impacts if located sufficiently close to vulnerable populations or infrastructures. At this stage both the VHI and PEI are semi-quantitative, being presented as levels based upon numerical values, and risk cannot therefore be calculated as a strict product of hazard and exposure. However, plots of hazard levels against the Population Exposure Index (PEI, see Chapter 4) for each volcano in each country provide a useful visualisation of a risk matrix. This matrix is derived using a qualitative assessment of the product of the VHI and PEI, amended to consider the potential impact of hazardous phenomena within highly populated areas regardless of the hazard level. Risk is defined at three levels, I, II and III with increasing risk, shown by the warming of the colours (Figure 22.1).
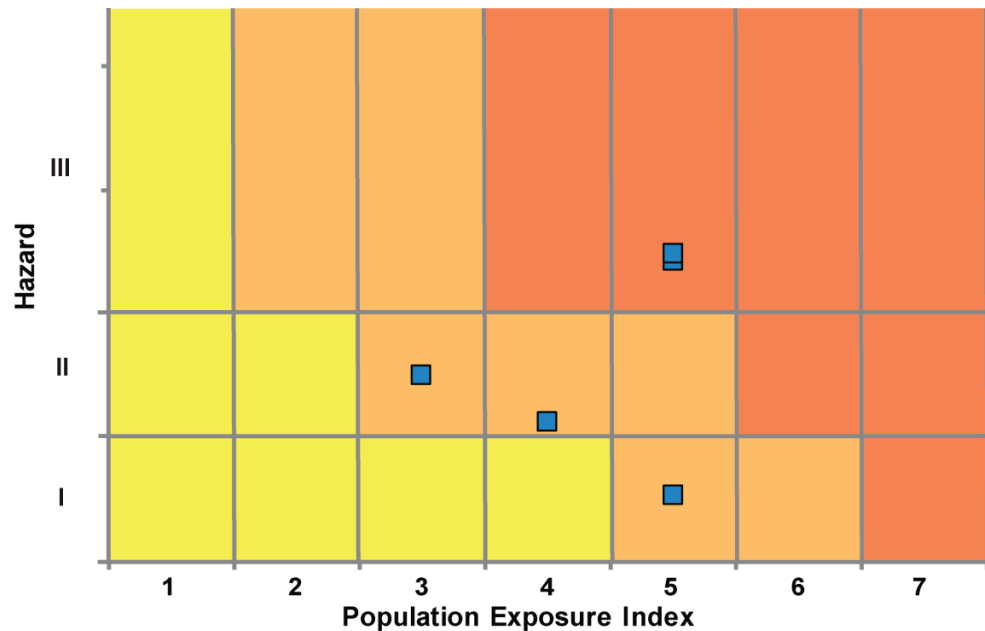
Figure 22.1 An example matrix combining VHI and PEI levels to indicate level of risk. Each volcano is represented by a point plotted using its hazard score and PEI level. The warming of the colouring of the matrix squares represents increasing risk (Risk Level I is yellow; Risk Level II is orange; Risk Level III is red).

The granularity within the matrix prevents detailed assessment and the matrix is therefore intended as a tool for the relative ranking of volcanoes. It should not be seen as a quantitative tool, as it comprises two ordinal rating scales which could be considered qualitative descriptors. This should not be used to undertake further calculations.

Unclassified volcanoes are presented with the PEI and are grouped according to their eruption record to permit an indication of known activity and for the use of PEI for an approximation for risk.

This globally applied assessment of VHI, PEI and ultimately risk does not substitute for focussed, local assessments. The PEI, for example, considers the population within concentric circles around a volcano, though in reality the exposed population will be governed by a number of factors (e.g. topography, which can shield a population on one side of the volcano and channel hazardous flows towards populations on the other). The impact on the human population is also determined by vulnerability, which is not considered here. The assessment of risk is based on these broad hazard and exposure assessments and therefore does not capture the full complexity of the situation. However, the ranking of volcanoes using this method can help identify volcanoes where monitoring and mitigation resources may need to be focussed and where localised hazard and risk assessments may be a priority.

This information is presented in the Country Profiles report (Appendix B), where the distribution of volcanoes across Hazard Levels, PEI and Risk Levels is briefly discussed for each country. Volcanoes which, at present, lack sufficient data to properly constrain their Hazard Levels should receive attention.

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