Chapter 4

Populations around Holocene volcanoes and development of a Population Exposure Index

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A way of ranking the risk to life from volcanoes is to establish how many people live in their vicinity. In addition to being an indicator of lives under threat, population exposure is a proxy for threat to livelihoods, infrastructure, economic assets and social capital. This report uses two indicators of population density around volcanoes to assess the current global exposure and as a risk indicator for individual volcanoes, and discusses this in combination with the Human Development Index (HDI) as a proxy for vulnerability.

4.1 Background

Ewert & Harpel (2004) introduced the Volcano Population Index (VPI), which estimates the number of people living within 5 and 10 km radii of volcanoes (VPI5 and VPI10). These population statistics, and VPI30 and VPI100 (population within 30 and 100 km of Holocene volcanoes) are reported in the VOTW4.0 (2013) database (www.volcano.si.edu; Siebert et al. (2010)). The Population Exposure Index, (PEI), was developed by Aspinall et al. (2011) for a study of volcanic risk in the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) priority countries. Here, populations within 10 and 30 km radii were estimated and combined using weightings that reflect how historic fatalities vary with distance from volcanoes.

The VPI was developed on the basis that most eruptions are small to moderate in size (VEI ≤3), with footprints of less than 10 km. The VPI therefore represents the population exposures for most eruptions. Indeed, eruptions of VEI2 occur at a rate of approximately one every few weeks, and VEI3 several times a year (Siebert et al., 2010). Eruptions of larger magnitudes (VEI≥4) are less frequent, but often cause fatalities at distances well beyond 10 km (Auker et al., 2013). Hazard footprints from such eruptions commonly extend to tens of kilometres. The PEI thus complements the VPI, accounting for the high threat from large eruptions and potentially distal hazard types. An advantage of PEI is that only a single indicator parameter captures the exposure of populations around each volcano with the various VPI populations all contributing to the index and weighted according to historical evidence on the distribution of fatalities with distance. Here we develop and apply an amended version of the PEI, which correlates quite well with VPI_{10}.

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4.2 Population

The location and total population within circles of radius 10, 30 and 100 km of each volcano is derived from the VOTW4.0 (2013) database. Due to overlapping radii from multiple volcanoes, these population figures cannot simply be summed, therefore country-level data counting populations in the vicinity of multiple volcanoes only once were calculated by the Norwegian Geotechnical Institute (NGI) using the Oak Ridge National Laboratory LandScan 2011 dataset of Bright et al. (2012).

Holocene volcanoes are located in 86 countries. The total population within 100 km of these volcanoes is over 800 million (Table 4.1). With 142 volcanoes Indonesia has the greatest total population located within all distance categories (>8.6 million at 10 km, >68 million at 30 km and >179 million at 100 km). After Indonesia, the Philippines and El Salvador have the largest populations living within 10 km, both at >2 million.

Table 4.1 The total global population living within given radii of volcanoes, derived using volcano location data from VOTW4.0 and 2011 LandScan data. Populations within each country were calculated and summed: no population was counted twice.

Total population within 10 km	Total population within 30 km	Total population within 100 km
29,294,942	226,267,790	801,833,245

Indonesia, the Philippines and Japan have the greatest numbers of people living with 100 km of their volcanoes (Figure 4.1; left). The populations of small volcanic island nations, such as Tonga and Samoa, are almost all resident within 100 km. The percentage of the population living within 100 km of volcanoes is therefore calculated for those countries with an area of more than a circle of 100 km radius (Figure 4.1; right). These populations may be affected by volcanoes in bordering countries.

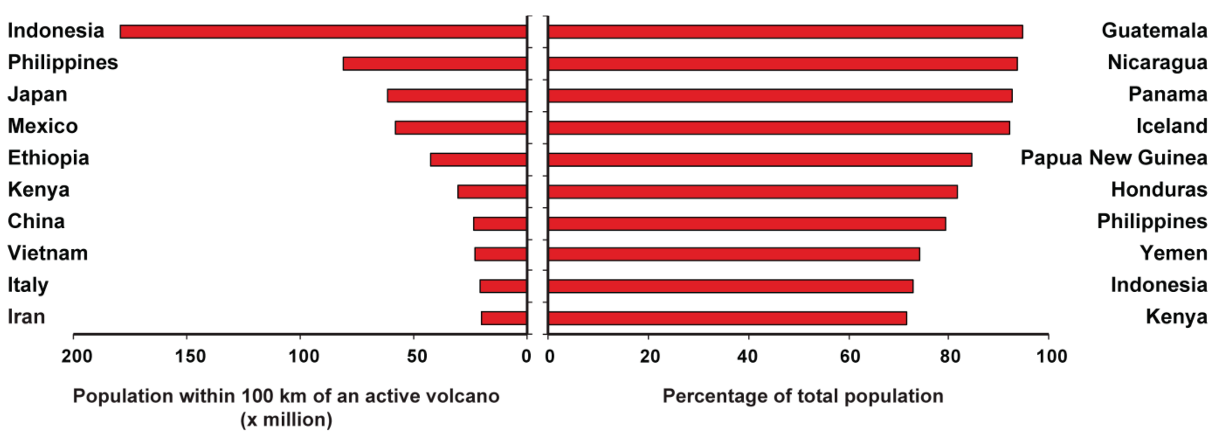

Figure 4.1 The top 10 countries for population within 100 km of a volcano (left) and the top 10 countries (area over 31,415 km^2) for percentage of the total population (right).

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Capital cities are frequently located close to volcanoes. The capitals of American Samoa, Wallis and Futuna islands, Montserrat, Dominica, Guadeloupe, Saint Kitts and Nevis and Nicaragua all lie within 10 km of volcanoes. A further 20 capitals lie between 10 and 30 km; 32 lie between 30 and 100 km.

Countries without Holocene volcanoes within their borders may also have populations within 100 km of a volcano (Table 4.2).

Table 4.2 Countries with populations living within 100 km of volcanoes beyond their borders. No populations in these countries live within 10 km of volcanoes.

Country	Population within 30 km	Population within 100 km
Jordan	48,278	5,690,340
Israel	1,056	1,884,367
Lebanon	0	3,141,870
Laos	0	26,512
Cambodia	0	1,409

The largest populations within 10 km of volcanoes are those around Michoacán-Guanajuato, Mexico (>5.7 million), Tatun Group, Taiwan (>5 million) and Leizhou Bandao, China (>3.2 million) (Table 4.3). These and many other volcanoes with high populations in their vicinity have poorly understood eruptive histories; the age or magnitude, in some cases both, of their last eruption are often unknown. Poorly constrained eruptive histories make hazard assessment at these volcanoes difficult.

The volcanoes with largest populations within 100 km differ considerably from those with largest populations within 10 km, illustrating variation in population distribution (Table 4.3). Indeed, Small & Naumann (2001) explored regional trends in population density around volcanoes, showing a globally averaged decrease in population density with increasing distance from volcanoes, dominated by tropical areas such as SE Asia and Central America. The opposite relationship is present in Japan and Chile. Eight of the ten most populous volcanoes at 100 km are located in Indonesia and Mexico; of these, only Chichinautzin and Popocatépetl have eruptions of VEI≥4 recorded in the Holocene.

The eruptive histories of almost half of the most populated volcanoes are poorly constrained (Table 4.3). The Holocene records for three volcanoes: Salak; Perbakti-Gagak; Tangkubanparahu (all Indonesia), solely contain VEI ≤2 eruptions, suggesting there is a low probability of significant effects beyond 10 km. However, large eruptions of M or VEI ≥4 often have long recurrence intervals, for which the Holocene may not be statistically representative. The volcanoes with largest proximal populations that have produced VEI≥4 eruptions in the Holocene are shown in Table 4.4.

Table 4.3 The top ten volcanoes by population size within the given radii and details of their last recorded eruptions. As magnitude affects the extent of the hazard footprint, the maximum recorded Holocene VEI and model VEI are given, and the occurrence of a Pleistocene record (in the LaMEVE database) of M≥4 eruptions is shown.

Radius	Volcano, Country	Population within given radius	Year of last eruption (VEI of last eruption)	Maximum recorded Holocene VEI and modal Holocene VEI	Pleistocene record of M≥4 events
10 km	Michoacán-Guanajuato, Mexico	5,783,287	1943 (VEI 4)	VEI 4. Modal 3.	
	Tatun Group, Taiwan	5,084,149	4100 BC (VEI 1)	VEI 1.	
	Leizhou Bandao, China	3,230,167	? (VEI ?)	Unknown	
	Kars Plateau, Turkey	3,067,709	1959? (VEI 2?)	VEI 2?	
	Malang Plain, Indonesia	2,397,210	? (VEI ?)	Unknown	
	Campi Flegrei, Italy	2,234,109	1538 (VEI 3)	VEI 5. Modal 4	Yes
	Ilopango, El Salvador	2,049,583	1879 (VEI 3)	VEI 6.	Yes
	Hainan Dao, China	1,731,229	1933 (VEI ?)	Unknown	
	Jabal ad Druze, Syria	1,487,860	? (VEI ?)	Unknown	
	San Pablo Volcanic Field, Philippines	1,349,742	1350 (VEI ?)	Unknown	
100 km	Gede, Indonesia	40,640,105	1957 (VEI 2)	VEI 3. Modal 2.	
	Salak, Indonesia	38,154,252	1938 (VEI 2)	VEI 2. Modal 2.	
	Perbakti-Gagak, Indonesia	36,630,568	1939 (VEI 1)	VEI 1. Modal 1.	
	Tangkubanparahu, Indonesia	32,855,731	2013 (VEI 2)	VEI 2. Modal 1.	Yes
	Hakone, Japan	30,282,197	1170 (VEI ?)	VEI 3. Most unknown.	Yes
	Papayo, Mexico	28,677,002	? (VEI ?)	Unknown	
	Chichinautzin, Mexico	28,030,794	400 (VEI 3)	VEI 4. Modal 3.	Yes
	Iztaccíhuatl, Mexico	27,276,280	? (VEI ?)	Unknown	
	Arayat, Philippines	27,216,491	? (VEI ?)	Unknown	
	Popocatépetl, Mexico	26,509,510	2013 (VEI 2)	VEI 5. Modal 2.	Yes

Table 4.4 The top ten volcanoes by population size with a Holocene record of VEI ≥4 eruptions.

Rank	Volcano, Country	Rank	Volcano, Country
1	Popocatépetl, Mexico	6	Merapi, Indonesia
2	Chichinautzin, Mexico	7	Galunggung, Indonesia
3	Fuji, Japan	8	Tengger Caldera, Indonesia
4	Kelut, Indonesia	9	Pinatubo, Philippines
5	Taal, Philippines	10	Izu-Toba, Japan

4.3 Population Exposure Index

A multitude of factors determine a population's vulnerability to volcanic hazards. Most volcanoes have the potential for a spectrum of eruption magnitudes and styles, with

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consequently varied footprints. In most cases, hazard and threat decreases with distance from the volcano. This is particularly true of pyroclastic density currents and lahars (the cause of almost 70% of all directly caused fatalities (Auker et al., 2013)), which are commonly confined to valleys. A maximum distance for consideration of population exposure of 100 km likely captures the majority of these hazards. However, the effects of the largest eruptions may extend beyond this distance.

The location and population within 10, 30 and 100 km of each volcano is derived from VOTW4.0. These populations are weighted on the basis of the area of each ring, and the number of fatal events recorded since 1600 AD within each distance category, using data from VOTW4.0 and the Smithsonian fatalities database described and analysed in Auker et al. (2013). Fatal incidents attributed to direct hazards (e.g. pyroclastic density currents, lahars, lava flows) are included, whilst indirect fatalities (e.g. famine) are excluded.

The fatality weighting is calculated based on the numbers of fatal incidents from direct hazards at each extent. The distance of fatalities from the volcano is only available for 27 of the 533 fatal incidents listed in Auker et al. (2013). These numbers differ from those used in Aspinall et al. (2011) due to the slight change in selection criteria. A total of 17 fatal incidents are recorded at 0-9 km, six fatal incidents at 10-29 km, and four fatal incidents at 30-100 km, giving proportional weightings of 0.63, 0.22 and 0.19 respectively.

The increase in area of each circle moving away from the volcano decreases the population density for any given population size. The area of the 10 km radius circle is nine times smaller than that of the 30 km circle, and 100 times smaller than the 100 km circle, giving weightings of 0.91, 0.08 and 0.01, respectively. These two sets of weights are combined and scaled, yielding a weighting of 0.967 for the 10 km ring, 0.03 for the 30 km ring, and 0.003 for the 100 km ring.

For each volcano, the population within each distance category is multiplied by the appropriate weighting, and the three figures are summed. These final weighted populations are then assigned one of seven index scores, from 1 to 7 (Table 4.5; amended from the scale of 0 to 3 of Aspinall et al. (2011). We refer to these seven index scores as the Population Exposure Index (PEI).

Table 4.5 Population Exposure Index (PEI), amended after Aspinall et al. (2011).

Weighted summed population	Population Exposure Index
0	1
<3,000	2
3,000 – 9,999	3
10,000 – 29,999	4
30,000 – 99,999	5
100,000 – 300,000	6
>300,000	7

There are inherent uncertainties in the population statistics and in the accuracy of volcano locations. The fatality weighting may be refined through further study of the historic record and improvement in the evidence on distances of fatalities.

4.3.1 Global PEI

The PEI is calculated for all volcanoes in VOTW4.0. Over 40% of volcanoes have a PEI of 2; with the exception of PEI 7 there is an approximately even spread across all other PEI classes. The division of the total global population within 100 km (Table 4.1) across PEI classes is also examined (Table 4.6). Analysis shows that 60% of the population living within 100 km are located around just 4% of volcanoes: the PEI 7 volcanoes. About a quarter of volcanoes are PEI ≥5, yet 96% of the total population are located here. The data indicate that most exposure (>95%) to volcanic hazards is distributed in volcanoes with PEI values of 5 to 7.

Table 4.6 The number of volcanoes in each PEI category globally and the percentage of the total number of volcanoes. The percentage of the total weighted population is also provided.

Population Exposure Index	Number of volcanoes (%)	Percentage of total weighted population
1	197 (12.7%)	0%
2	642 (41.4%)	0.4%
3	157 (10.1%)	1.0%
4	178 (11.5%)	3.5%
5	188 (12.1%	11.4%
6	128 (8.3%)	23.8%
7	61 (3.9%)	59.9%

There are 61 PEI 7 volcanoes, of which 16 are in Indonesia. Africa and the Red Sea and Mexico and Central America have 11 PEI 7 volcanoes each, with all other regions having <10. Indonesia, Mexico and Central America and Africa and the Red Sea have the greatest numbers of PEI ≥5 volcanoes. The regions with the greatest proportions of PEI ≥5 volcanoes are Philippines and SE Asia (70%), Mexico and Central America (64%), and Indonesia (55%). Alaska, Antarctica, and the Kuril Islands have no PEI ≥5 volcanoes (Figure 4.2).

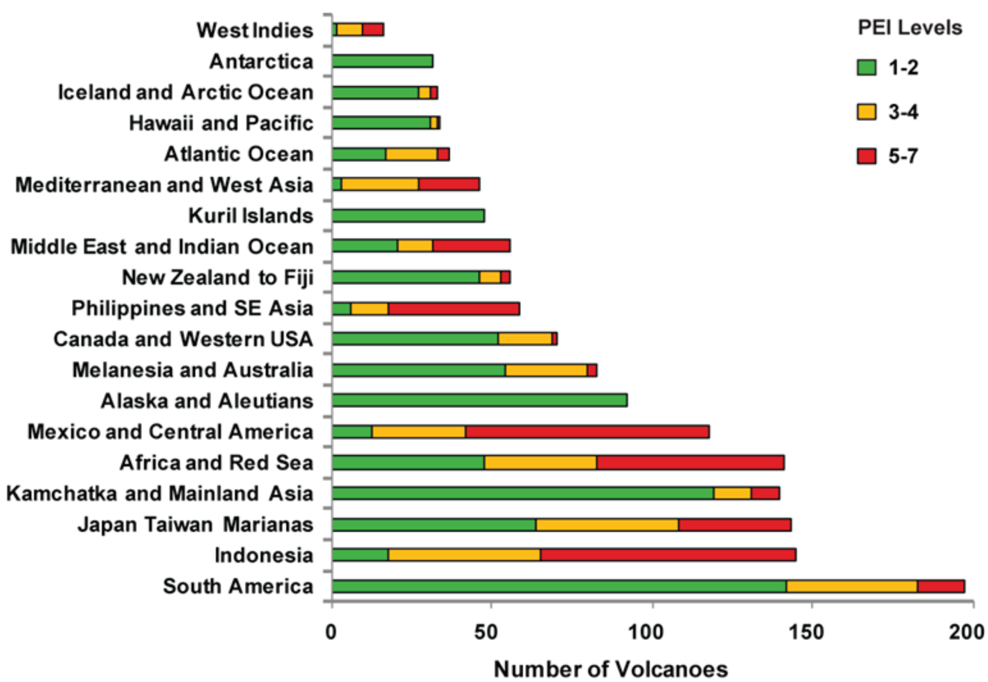

Figure 4.2 Number of volcanoes per region and their PEI classification.

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4.3.2 PEI and VEI

Eruptions of M or VEI ≥4 are less frequent than smaller events, but have the potential for greater losses over larger areas. VOTW4.0 includes 864 volcanoes which have no recorded eruptions of known VEI. Of the remaining 687, 438 have no eruptions of VEI >3; 249 volcanoes have one or more eruptions of VEI ≥4, of which 61 have a PEI of 5-7. There is clearly the potential for far-reaching hazards to affect large populations.

4.3.3 PEI and HDI

The Human Development Index (HDI) combines details of life expectancy, education and income to provide a measure of social and economic development, calculated by the United Nations Development Programme (United Nations Development Programme (UNDP), 2013) and categorised as Low, Medium, High or Very High. HDI is available for most, though not all countries; notable exceptions are overseas territories and island volcanoes. HDI and other metrics such as Gross Domestic Product (GDP) provide an indication of the wealth and development of a country. A low HDI does not always reflect the resources dedicated to disaster preparedness and response; however, there is a general relationship between the wealth of a country and the losses sustained in disasters (Toya & Skidmore, 2007). Toya & Skidmore (2007) and references therein explained that populations of wealthier nations have greater expectations regarding safety and are therefore more likely to use expensive precautionary measures to improve safety. They found that disaster losses and the underlying socio-economic fabric within a country are also correlated.

There are 530 volcanoes located in countries of Very High HDI (dominantly in Japan, Chile and the USA, which account for 391 of these volcanoes; Figure 4.3). Countries of Low HDI have fewer volcanoes (218), though there is a broad negative correlation between HDI and PEI. Significant examples include Ngozi in Tanzania (Low HDI), which has a PEI of 7 and a Holocene eruption of VEI 5; and Masaya in Nicaragua (Medium HDI) which also classifies at PEI 7 and has a Holocene record of eruptions of VEI 5 and 6 and frequent eruptions of VEI 1 and 2. The 142 volcanoes of Indonesia dominate the distribution of PEIs amongst the 355 volcanoes in medium HDI countries.

Fewer than 20% of volcanoes in High and Very High HDI countries are PEI≥5, and over 60% are classed as PEI 1 or 2. Notable examples of PEI 7 volcanoes in Very High HDI countries are Vesuvius and Campi Flegrei. Both border Naples in Italy and have Holocene records of VEI 5 eruptions and the potential to generate far-reaching hazards. The Auckland Field in New Zealand (Very High HDI) is also PEI 7, due to its situation under the city of Auckland. The low relief of this volcanic field makes large explosive eruptions with volcanic flows that extend to tens of kilometres unlikely.

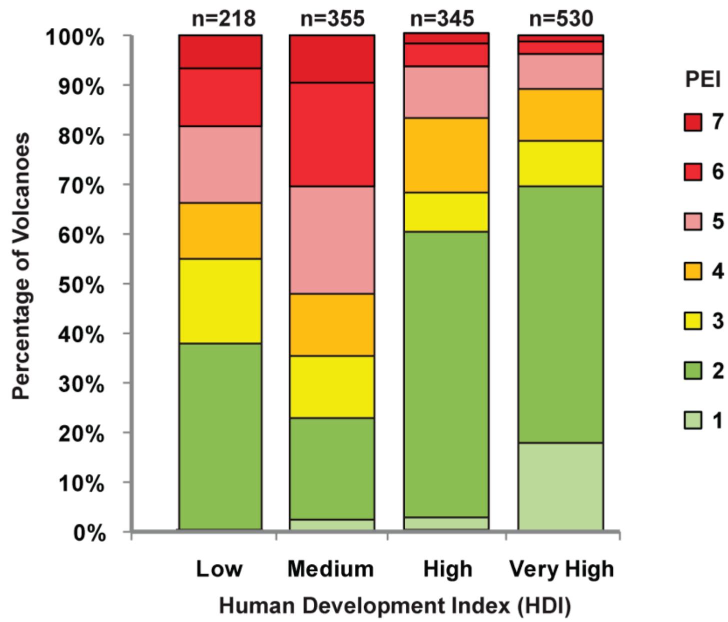

Figure 4.3 The four categories of the HDI and the proportion of volcanoes in each PEI band.

Combining PEI and HDI provides an indicator of the number of people in harm's way and societal and economic capacity to handle disasters. Volcanoes with large proximal populations in relatively low HDI countries may be more vulnerable and suffer greater relative losses. However, factors such as local prioritisation of resources or experience with natural hazards may counter this, and PEI and HDI do not account for differences in eruption styles or recurrence rates. Three main regions have high HDI x PEI rankings: Africa, SE Asia (dominated by Indonesia and the Philippines) and Central America (Figure 4.4).

4.4.4 Implications and use of PEI

The VPI and PEI enable volcanoes close to large populations to be identified. The PEI's weighting of populations at different extents aims to capture the factors that control the number of people exposed.

We show that the majority of people exposed to volcanic hazards live around the 61 PEI 7 volcanoes. Indonesia has the greatest number of PEI 7 volcanoes (16), and subsequently the greatest total number of people living within 100 km of volcanoes. PEI and HDI are generally negatively correlated, suggesting larger populations are situated close to volcanoes in developing countries, compared to developed. There are 61 volcanoes with recorded VEI ≥4 Holocene eruptions and a high PEI (PEI 5-7). Similarly large eruptions from these volcanoes have the potential to cause significant disruption and loss. Many other high PEI volcanoes may produce VEI ≥4 eruptions over longer time scales.

The PEI may be used as a basis for disaster risk reduction resource management decisions. However, population exposure is not the only component of volcanic threat, and use of a hazard index for volcanoes provides a fuller picture. The PEI is also not a substitute for in depth assessments of exposure and vulnerability at specific volcanoes. Indeed it is certain that volcanoes with the same index value may have very different exposed populations. Topographic factors in particular will have a large role in determining exposure. For example, many

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volcanoes have craters or flank collapse scars open in one direction that will channel flows and produce directed hazards that threaten populations on one side of the volcano to a far greater degree than the other. Also, populations close to river valleys and on flood plains are very vulnerable to lahars and pyroclastic flows, and populations in the dominant downwind direction are more exposed to ash fall hazards. Full assessment based on local factors may lead to different conclusions about priorities.

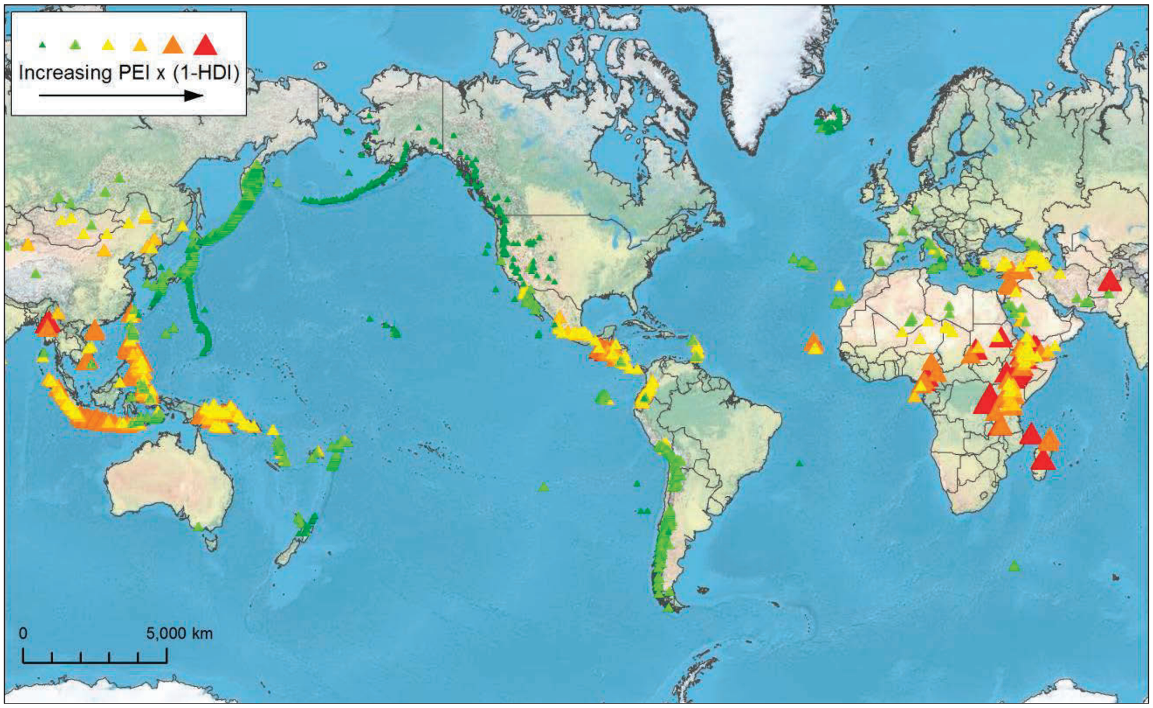

Figure 4.4 Global distribution of volcanoes coloured and scaled by PEI x (1-HDI), illustrating the locations of volcanoes with high proximal populations and lower HDI scores.

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