https://doi.org/10.5194/nhess-2024-219
Preprint. Discussion started: 29 January 2025

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Cities near volcanoes: Which cities are most exposed to volcanic hazards?

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https://doi.org/10.5194/nhess-2024-219
Preprint. Discussion started: 29 January 2025

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1. Abstract

Cities near volcanoes expose dense concentrations of people, buildings, and infrastructure to volcanic hazards. Identifying cities globally that are exposed to volcanic hazards helps guide local risk assessment for better land-use planning and hazard mitigation. Previous city exposure approaches have used the city centroid to represent an entire city, and to assess population exposure and proximity to volcanoes. But cities can cover large areas and populations may not be equally distributed within their bounds, meaning that a centroid may not accurately capture the true exposure. In this study, we suggest a new framework to rank global city exposure to volcanic hazards. We assessed global city exposure to volcanoes in the Global Volcanism Program database that are active in the Holocene by analysing populations located within 10, 30, and 100 km of volcanoes. These distances are commonly used in volcanic hazard exposure assessment. City margins and populations were obtained from the Global Human Settlement (GHS) Model datasets. We ranked 1,106 cities based on the number of people exposed at different distances from volcanoes, the distance of the city margin from the nearest volcano, and by the number of nearby volcanoes. Notably, 50% of people living within 100 km of a volcano are in cities. We highlight Jakarta, Bandung, and San Salvador, as scoring highly across these rankings. Bandung, Indonesia ranks highest overall with over 8 million people exposed within 30 km of up to 12 volcanoes. South-east Asia has the highest number of exposed city populations (~162 million). Jakarta (~38 million), Tokyo (~30 million), and Manila (~24 million) having the largest number of people within 100 km. Central America has the highest proportion of its city population exposed, with Quezaltepeque and San Salvador exposed to the most volcanoes (n=23). Additionally, we ranked the 1,283 Holocene volcanoes by the city populations exposed within 10, 30, and 100 km, the number of nearby cities, and distance to nearest city. Tangkuban Parahu, San Pablo Volcanic Field, and Tampomas score highly across these rankings. Notably, Gede-Pangrango (~48 million), Languna Caldera (~8 million), and Nejapa-Miraflores (~0.8 million) volcanoes have the largest city populations within 100, 30, and 10 km, respectively. We developed a web app to visualise all the cities with over 100,000 people exposed. This study provides a global perspective on city exposure to volcanic hazards, identifying critical areas for future research and mitigation efforts.

2. Introduction

As of 2023, more than half (57%) of the world's population reside in cities (World Bank, 2023). These dense urban clusters of buildings, infrastructure, and populations are particularly vulnerable to natural hazards (Degg, 1992; Godschalk, 2003), as urban residents are heavily reliant on city infrastructure (UNDP, 2021). Such susceptibility exposes cities to high potential losses and cascading systematic impacts that can affect the wider region, country, or world (Thouret, 1999; Chester et al., 2000; Heiken, 2013; Mani et al., 2021). Recent rapid urbanisation into hazardous areas escalates the threat to cities (Pelling, 2012; Freire et al., 2019; Iglesias et al., 2021), driving increasing disaster impacts globally (Gu, 2019). Identification of the most exposed cities and analysis of the spatio-temporal patterns of urban hazard exposure is crucial for guiding effective land-use planning and mitigation efforts. This focus will help prioritise cities that need focussed attention for sustainable development and improved preparedness and resilience against future disasters (Ariyanti et al., 2020).

Cities situated near volcanoes face a variety of direct threats from volcanic hazards resulting from eruptions of various intensities. Historically, volcanic flows have destroyed whole cities; for example, pyroclastic density currents (PDCs) emplaced within 10 km of their volcano destroyed Herculaneum, Italy, in 79 CE (Volcanic Explosivity Index, VEI 5), Saint Pierre, Martinique, in 1902 CE (VEI 4), and Plymouth, Montserrat, in 1997 CE (VEI 3). Some cities are repeatedly impacted, such as Goma, Democratic Republic of Congo (DRC), less than 30 km from the volcano, which was partially inundated by lava flows in 1977 CE, 2002 CE, and 2021 CE. Lahars (volcanic mudflows) destroyed the city of Armero, Colombia, approximately 50 km from the Nevado del Ruiz volcano in 1985 CE (VEI 3), and the city of Lumajang, Indonesia, 35 km from Semeru volcano, in 1909 CE (VEI 2). Some cities are built on old lahar deposits, suggesting they are likely to be impacted again (e.g., Arequipa, Peru; Mexico City, Mexico; San Salvador, El Salvador). The more widely dispersed hazard of tephra falls has destroyed the city of Akrotiri, Greece, around 1600 BCE (VEI 7), and disrupted and damaged the cities of Kagoshima, Japan in 1914 CE (VEI 4), Anchorage, USA in 1989 CE (VEI 3), and Angeles City, the Philippines in 1991 CE (VEI 5).

In order to reduce the risks faced by cities situated close to volcanoes, we first must identify which cities are most exposed to volcanic hazards. Some past studies have used a localised approach, whereby they identify exposed urban areas close to case study volcanoes (e.g., Thouret et al., 2001; Sandri et al., 2014; Strader et al., 2015; Magill & Blong, 2005; Alberico et al., 2011; Delgado Granados & Jenkins, 2015; Torres et al., 2022). However, a more systematic regional or global approach based on the location of all cities would reveal which cities are most exposed. For example, taking a regional multi-volcano approach, Jenkins et al. (2018) evaluated the potential impact of tephra fall on 16 major cities

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in the Asia-Pacific region, highlighting Tokyo, Japan; Jakarta, Indonesia; and Manila, Philippines as being most exposed. Ranking cities or volcanoes by city population exposure would allow us to identify global exposure hotspots which may be missed by a more localised approach.

Whilst global city analyses have been conducted for other hazards such as coastal flooding (Hanson et al., 2011), earthquakes (Bilham, 2009), and multi-hazards (Degg, 1992; Brecht et al., 2013; Gu, 2019), for volcanic hazards, reports or studies often focus on growth rates or total population numbers of case study cities, based on the location of city centroids close to volcanoes. For example, in 1989 CE, the UN estimated that of the top 50 fastest growing cities, only four were exposed to volcanic hazards (UN, 1989). Three years later, it was estimated that 10 of the world's most populated cities were located within 30 km of an active volcano (Degg, 1992). Pelling (2012) and Blaikie (1994) highlight Jakarta as a major city at risk from volcanic activity. Heiken (2013) identified 67 cities (with populations greater than 100,000), home to a total of ~116 million people, located on or near to active volcanoes. Other studies considered the city's distance and direction from volcanoes. Donovan and Oppenheimer (2014) list 49 cities within 100 km of a volcano with recognised Quaternary activity and Erfurt-Cooper (2014) provided a list of 25 cities in close proximity to active volcanoes. Chester et al. (2000) and subsequently Auker et al. (2013) plotted polar charts with examples of highly populated cities in relation to the distance and direction of the city centroid from nearby volcanoes, within 200 km and 50 km of volcanoes, respectively. Brown et al. (2015) identified seven capital cities globally within 10 km of volcanoes, 37 within 30 km, and 69 within 100 km. A systematic approach quantifying all global city populations at specific distances from volcanoes would better capture the variable distribution of populations across cities and exposure~~ed~~ to volcanoes.

Key cities identified as exposed to volcanic hazards can then be targeted for more localised research and mitigation efforts. For example, Jenkins et al. (2022) ranked volcanoes in South-East Asia by population and physical exposure, and proposed that populations near Guntur volcano, Indonesia, are highly exposed and thus require further study. For identified highly exposed cities, combining high resolution exposure with hazard maps or footprints can identify key areas in a city on which to focus future mitigation, such as structural adaptations (e.g., to tephra fall in Kagoshima: Durand, 2001) and/or land-use planning efforts (e.g., Nieto-Torres et al., 2021; Strader et al., 2015; Thouret et al., 2001).

In this study, we propose a new framework to quantify and rank global cities exposed to volcanoes situated within varying proximity thresholds (10, 30, and 100 km), based on three variables: population exposed; distance to nearest volcano; and the total count of volcanoes each city is exposed to. Leveraging high-resolution updated population data allows for assessment of the spatial variation of population exposure within each city. Instead of looking at the total population of the city as presented in past studies, this approach more accurately identifies the proportion of the city population within each distance threshold. Furthermore, our framework also ranks volcanoes by city exposure based on their proximity to city populations, considering the total count of cities and their respective populations within the specified distances from volcanoes.

2.1 Measuring population exposure around volcanoes

To quantify global population exposure around volcanoes, studies typically count the number of people residing within concentric radial buffers of certain sizes around the volcanic vent (e.g., Small & Naumann, 2001; Ewert, 2007; Aspinall et al., 2011; Brown et al., 2017; Freire et al., 2019; Nieto-Torres et al., 2021; Guimarães et al., 2021). For example, Freire et al. (2019) calculated total populations living within 10, 30, 50, and 100-km radial buffers around active volcanoes between 1975 and 2015 CE. The concentric radial buffer size approach allows for a conservative estimate of exposure at each volcano so that the cities can be compared and ranked, especially useful for volcanoes without historical eruptions or high-resolution topography data (Biass et al., 2024). The radius sizes of buffers around the volcanic vent used to calculate exposure are determined by the maximum distances of primary volcanic hazards and the extents of potential Volcano Explosivity Index (VEI) events. For instance, the emplacement of the majority of primary hazards in a VEI <4 eruption are within a 10-km radius around the volcano, including extents of ballistic projectiles and most dome collapse pyroclastic density currents (PDCs) (Biass et al., 2024). A 30-km radius generally represents the extent of the majority of VEI <5 eruption hazard extents, while a 100-km radius signifies the extent of the majority of VEI <6 eruption hazard extents. However, larger eruptions, secondary hazards, or eruptions occurring from fields or fissures beyond the vent might extend beyond these maximum hazard distances. For example, shown by modelling of a VEI 5 scenario in Biass et al. (2024), tephra loads exceeding 1 km/m^2 could extend as far as 600 km away.

These exposure counts can be assigned to specific indices for comparison across volcanoes. For example, the Volcanic Population Index (VPI) estimates the number of people living within 5 and 10 km of volcanoes (Ewert & Harpel, 2004). Aspinall et al. (2011) developed this methodology to assess populations within 10, 30, and 100 km of volcanoes. To calculate the Population Exposure Index (PEI), the population counts are weighted according to evidence on historical distributions of fatalities within a given distance from the vent and each volcano is assigned to one of seven PEI indices (Brown et al., 2015). On a local or regional scale, past studies combined these population counts with physical exposure (e.g., Etna volcano, Italy: Del Negro et al., 2022; Rainier volcano, USA: Wood & Soulard, 2009) and/or hazard factors to understand localised volcanic threat (e.g., Ewert et al., 2018; Mangan et al., 2018; Nieto-Torres et al., 2021). Nieto-Torres et al. (2021) developed a volcanic risk index for Central America considering 41 different factors related to hazards and exposure, assessing population risks within distances of 5, 10, 30, and 100 km from volcanoes. Researchers used various buffer sizes in ongoing efforts to accurately assess the risks that volcanic hazards pose to total populations. No studies conducted exposure analysis based on population exposure by urban type, such as city populations. In this study, we quantify and rank global cities exposed to volcanoes situated within 10, 30, and 100 km of volcanoes.

3. Methods

We developed a framework designed to quantify, rank, and assess city exposure to volcanoes (see Fig. 1 and Fig. 2). In this study, *exposed populations* refer to populations in cities within 100 km (unless the distance is specified) from at least one volcano active in the Holocene, as explained in Section 2.1. Below we detail how we prepared the city outlines, extracted populations, and ranked the cities and volcanoes. The R code used to generate the results of this study is provided at: https://github.com/vharg/VolcCities. The Fig.s presented in this study focus on the top 10 cities or volcanoes. We developed a web app to comprehensively present results of this study, including the population exposure and maps of city polygons for all the cities with over 100,000 people exposed, which is available at: https://nteng.shinyapps.io/ExposureOfCities/.

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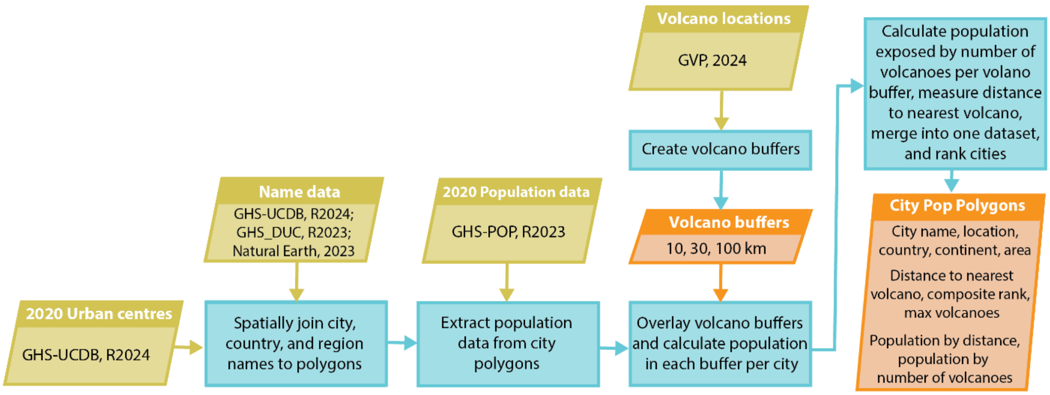

Fig. 1: A flowchart of our framework to assess city exposure to volcanoes. Input datasets (yellow rectangles) are fed into the GIS process (blue rectangles) to collate city polygons (left orange rectangle) and attribute data, clipped by radial buffers (central orange rectangle), into the exposed population polygon dataset (right orange rectangle). For input datasets from the Global Human Settlement For the 2020 urban centres the GHS-UCDB (2024) dataset was used, and the spatially joined centroids of this dataset were used for names. GHS_DUC (2023) Name_2 column was used for city names if they were not available. The cities were ranked by the population size, the distance to nearest volcano, and the maximum number of volcanoes exposed to, and the average of these was presented as the composite rank. The volcanoes chosen are those active in the Holocene epoch. GVP stands for the Global Volcanism Program and GHS stands for Global Human Settlement. The code used in this paper is provided at: https://github.com/vharg/VolcCities

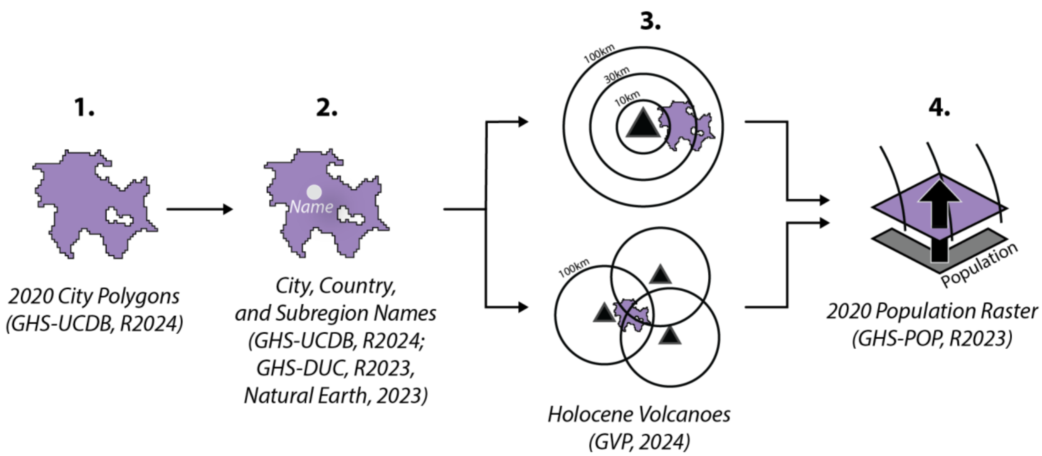

Fig. 2: A schematic of our framework for assessing city exposure to volcanoes. The framework includes the following steps: 1) obtaining city polygons for 2020 CE from the GHS-UCDB (2024) urban centre polygons dataset, 2) joining

city and country names from GHS-UCDB (2024) centroids, otherwise GHS_DUC polygons were used, and Natural Earth (2023) was used for subregion names, 3) conducting distance analysis by clipping city polygons within 10, 30, and 100-km buffers from volcanoes, and analysing the number of volcanoes by counting overlaps of 100-km volcano buffers across city polygons, and 4) extracting the population of city polygons within volcano buffers using a population raster. Cities were ranked by population size and the maximum number of exposed volcanoes. Volcanoes included are those active in the Holocene, as per the Global Volcanism Program (GVP). The code used in this paper is provided at: https://github.com/vharg/VolcCities

3.1 Preparing the exposed city population polygon dataset

We obtained city area outlines from the 2024 CE release of the Global Human Settlement Layer - Settlement Model (GHS-UCDB; Marí Rivero et al., 2024). This dataset is in the World Mollweide (EPSG:54009) projection and we did not reproject it. This dataset identifies the *urban centres,* classified as having a population density of ≥ 1500 inhabitants/km^2 and a total population size of at least 50,000 people (Marí Rivero et al., 2024). These city areas will be referred to from here, as *city polygons*. We identified the centroid co-ordinates and the areas of the *city polygons*.

We selected only those polygons that had all or part of their area within 100 km of a volcano resulting in 1,158 *city polygons*. Volcano locations in this study were based on coordinates from the 1,283 Holocene Volcano List from the Volcanoes of the World (VOTW) v4.11.1 database (Global Volcanism Program, 2024). Co-ordinates of the Holocene volcanoes in the database are positioned either at the summit for volcanoes with a distinct primary edifice, or close to known vents. For volcanic fields with multiple vents, the database presents the most prominent or active vent, most recently erupting vent, or centre of the volcanic field, depending on information availability. Only the 958 volcanoes that are located within 100 km of a *city polygon* are used within this study.

The *city polygons* generated from the raster lacked attribute data, therefore, we spatially joined each polygon with the city and country names of the 2025 CE projected *city polygons* from the 2024 CE release of the Global Human Settlement Layer - Settlement Model, Urban Centre Database (GHS-UCDB; Marí Rivero et al., 2024). The spatial join was based on the overlap of the centroids with the *city polygons*. For the 30 cities that did not have city names (as they are not in the 2025 CE dataset), we spatially joined the *city polygons* to the 2023 CE release of the GHS Degree of Urbanisation

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Classification (GHS-DUC; Schiavina et al., 2023a) polygons dataset and selected the name from the Name_2 column, and for one case, the Name_1 column as Name_2 was empty. For the 35 cities that did not have any country names, these were added from the spatially joined GHS_DUC dataset. The spatial join was based on the location of the *city polygons'* centroids. For the subregions, we spatially joined the *city polygons* to the Natural Earth (2023) country polygons and selected the subregions, based on the location of the nearest polygon. This dataset was chosen as there were more subregions included than the GHS-UCDB dataset. We then grouped the *city polygons* by city name in each country, resulting in a dataset of 1,106 cities.

We made other calculations for the other columns in the dataset shown in Table 1, we included the *city polygon* centroid co-ordinates based on the largest polygon, calculated the *city polygon* area (km^2), and measured the shortest distance (km) of the *city polygon* margin that lies closest to the nearest volcano. To calculate the total population of the city, we extracted the 2020 CE population from Global Human Settlement Layer - Population (GHS-POP; Schiavina et al., 2023b) 100-m population rasters within each of the *city polygons* using the *exactextract* function in R (Levine, 2022). This population dataset is in the World Mollweide (EPSG:54009) projection and we did not reproject it.

Table 1: *The results collated in this study are set out in a dataset with the columns named as in this table. One row represents one city.*

Column Name		
Total city polygon	Name	
	Centroid co-ordinates	Latitude, Longitude
	Country	
	Continent	
	Subregion	
	Total city area (km^2)	
	Total city population	
	Nearest volcano	
	Distance to nearest volcano (km)	
	Rank by distance	
	Maximum number of volcanoes exposed by	
	Composite rank	
Results by distance	Rank (by <100 km)	
	Population by distance	<10 km, <30 km, <100 km, >100 km (not exposed), 30 – 10 km, 100 – 30 km

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Results by number of volcanoes	Rank (by max <100km)	
	Population by number of volcanoes <100 km	1, 2-5, 6-10, 11-20, 20+
	Population by number of volcanoes <30 km	1, 2-5, 6-10, 11-20, 20+
	Population by number of volcanoes <10 km	0, 1, 2-5, 6-10, 11-20, 20+

3.2 Ranking cities

Using the volcano location co-ordinates as the centroids we created 10, 30, and 100-km radial buffers around each volcano, as these are commonly used to assess volcanic exposure based on typical maximum distances of primary volcanic hazards (Ewert, 2007; Brown et al., 2017; Biass et al., 2024). From here, these will be referred to as *volcano buffers*.

We clipped the *city polygons* by each of the three 10, 30, and 100-km radial *volcano buffers* and merged these together to create a map of the city classified by distance to a volcano. This means that parts of the city, or specific proportions, fall into one of the distance categories: <10 km, 10–30 km, 30–100 km, or >100 km from a volcano. We extracted the population using the method shown in 3.1 and where the volcano buffer partially covers a population raster pixel, this function extracts the population number based on the proportion of pixel covered. We then merged and pivoted the dataset so that it resulted in the population in each *volcano buffer* for each city (Table 1). For each *volcano buffer* we ranked the cities by the total populations exposed.

We also ranked cities by how many volcanoes each city's population is exposed to. We overlaid the 100-km *volcano buffers* and calculated the number of buffers that were in contact with each *city polygon*. By intersecting the overlaid buffers by the *city polygons*, we created a map where the areas within the city are classified by the number of volcanoes it is exposed to. From this map, we then extracted the population, so that, for each city, the numbers of people exposed to numbers of volcanoes is known (Table 1). This was repeated for the 30-km and 10-km *volcano buffers*. In separate columns we entered the maximum number of volcanoes that the city is exposed to (within 100 km) and ranked the cities by this amount. This means that the maximum number of volcanoes the city is exposed to relates to the total number of 100-km *volcano buffers* in contact with the *city polygon*.

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Finally, we calculated a composite ranking for each city, summing the three rankings of distance to nearest volcano, population <100 km, and number of volcanoes <100 km, and dividing by three to create a final ranking of cities. This assumes the same weighting for each ranking.

3.3 Ranking volcanoes

In a separate dataset shown in Table 2, for each volcano, we recorded the volcano name, name, vent co-ordinates, and country from the Global Volcanism Program (2023) Holocene Volcano List. We also calculated the distance of the vent location to the nearest *city polygon*. For each *volcano buffer* of each volcano, we calculated the total populations located within each *volcano buffer* and *city polygons* using the extraction method detailed in 3.1. We then ranked the volcanoes by the total city populations within 100 km of the volcano. We also calculated the total number of *city polygons* within each *volcano buffer* for each volcano and ranked the volcanoes by the total number of cities within 100 km of the volcano. Finally, we calculated a composite ranking for each volcano, summing the three rankings of total population <100 km, number of cities <100 km, and distance to nearest city, and dividing by three to create a final ranking of volcanoes. This assumes the same weighting for each ranking.

Table 2: *The results collated in this study are set out in a dataset with the columns named as in this table. One row represents one city.*

Column Name		
Volcano	Volcano Name	
	Vent co-ordinates	Latitude, Longitude
	Country	
	Nearest city	
	Distance to nearest city (km)	
	Composite rank	
Results by city population	Rank (by <100 km)	
	City population by distance	<100 km, <30 km, <10 km, 100 – 30 km, 30 – 10 km
Results by number of cities	Rank (by max <100 km)	
	Number of cities	<100 km, <30 km, <10 km, 100 – 30 km, 30 – 10 km

4. Results

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We present our results in two parts, firstly we present the rankings for cities and volcanoes within each of the 10, 30, and 100-km *volcano buffers*, and secondly, we present regional trends in the city exposure. Cities were ranked based on: a) the total city population exposed to one or more volcanoes, b) the number of volcanoes the city is exposed to, and c) the distance to nearest volcano. Volcanoes were ranked based on: a) the total exposed city population, b) the number of cities exposed, and c) the distance to the nearest city. In the following section, we explore the quantification and ranking of these city populations and volcanoes, detailing spatial trends in city exposure. We also explore regional trends in city exposures. The results for all our exposure analyses are presented in Section 9.

4.1 Quantifying and ranking city exposure to volcanoes

Globally, 1,106 cities have some proportion of their populations living within 100 km of at least one volcano active in the Holocene (Table 3). Within these cities, ~430 million people are exposed within 100 km of volcanoes (Table 3), representing 50% of the total population exposed within 100 km (n= 852,989,097) and ~12% of the total population of cities globally (n=3,511,560,764). For each city, the exposed population varies from four people in Hamamatsu, Japan, to ~38.1 million people in Jakarta.

Table 3: *The total number of cities with some proportion of their area within the three volcano buffer distances of at least one volcano, and city populations exposed to volcanoes within each volcano buffer size used in our study.*

Distance from nearest volcano	Number of cities exposed	City populations exposed
10	99	13,756,890
30	381	128,065,560
100	1,106	429,145,006

The greatest number of cities and populations exposed are in Indonesia (see Fig. A3 in the Appendix). The top five cities with the most people living within 100 km from at least one volcano are Jakarta, Indonesia; Tokyo, Japan; Manila, Philippines; Mexico City, Mexico; and Seoul, South Korea (Fig. 4). For these cities, the entire populations are exposed to at least one volcano (Jakarta: Salak, Perbakti-Gagak; Manila: Laguna Caldera; Mexico City: Iztaccihuatl, Chichinautzin, Popocatepetl), except for Tokyo and Seoul where parts of the cities are not exposed to any volcanoes (see Fig. A3 in the Appendix). These top five cities represent ~28 % (~121 million) of the total exposed city populations

(~429 million), with over 677,000 people within 10 km from a volcano. For the other exposed cities, exposed populations decrease gradually as rank increases (Fig. 4; Fig. A2 in the Appendix). When combining rankings of number of people within 100 km, number of volcanoes within 100 km, and distance to nearest volcano, Bandung is the highest ranked city (Fig. 3).

As the spatial distribution of populations varies across cities, we found that some of the highly ranked cities have proportions of their populations located more than 100 km from volcanoes (e.g., Tokyo, Japan; Seoul, South Korea; Tehran, Iran), whilst others have high proportions of their populations located very close to volcanoes. Notably, for the 30 km *volcano buffer*, the entire populations of Bandung, Indonesia (n=8,443,660) and Quito, Ecuador (n=2,435,784) reside within 30 km of at least one volcano. The top five cities ranked by people living within 100 km of volcanoes have relatively low proportions of their populations within 30 km (~18 %), with most (~82 %) living between 30 and 100 km. As a result, for rankings at smaller *volcano buffer* distances, these cities drop down to lower rankings (Fig. 4). However, Jakarta and Bandung feature in the top ten ranked cities for exposed populations within all three *volcano buffer* distances and have the highest number of people exposed to at least one volcano within 100 km (n=38,050,484) and 30 km (n=8,443,660). The top two ranked cities for the 10-km *volcano buffer*: Naples, Italy, and Managua, Nicaragua, combined have a smaller total population than Jakarta; however, they have 40% and 66% of their city populations living within 10 km of volcanoes, respectively, compared to 1% of Jakarta (Fig. 4). Thus, cities may have low total populations but have high proportions of their populations living in close proximity of nearby volcanoes.

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City Rankings					Volcano Rankings				
Rank	City Name	Population exposed rank	Number of volcanoes rank	Distance to nearest volcano rank	Rank	Volcano Name	Population exposed rank	Number of cities exposed rank	Distance to nearest city
17	Bandung, Indonesia	8	31	11	8	Tangkuban Parahu, Indonesia	4	10	11
19	Jakarta, Indonesia	1	40	17	13	San Pablo V.F., Philippines	9	26	5
22	San Salvador, El Salvador	39	1	26	17	Tampomas, Indonesia	17	6	28
24	Quito, Ecuador	28	14	30	18	Guntur, Indonesia	20	6	27
27	Managua, Nicaragua	50	31	1	21	Talagabodas, Indonesia	24	5	34
35	Guatemala City, Guatemala	24	13	68	22	Ciremai, Indonesia	19	6	42
42	Tokyo, Japan	2	57	67	22	Ungaran, Indonesia	35	19	13
44	Tarogong, Indonesia	47	57	29	23	Patuha, Indonesia	11	42	16
46	Tasikmalaya, Indonesia	25	74	40	25	Laguna Caldera, Philippines	7	13	55
48	Surabaya, Indonesia	9	111	24	25	Penanggungan, Indonesia	28	19	29
49	Semarang, Indonesia	20	111	15	27	Galunggung, Indonesia	25	6	49
65	Kuningan, Indonesia	84	74	38	27	Sundoro, Indonesia	34	13	33
70	Bishoftu, Ethiopia	151	57	3	29	Kendang, Indonesia	23	26	39
72	Cipanas, Indonesia	94	74	49	30	Papandayan, Indonesia	26	30	35
76	Malang, Indonesia	34	111	84	32	Banahaw, Philippines	10	35	50

Fig. 3: *Top 20 composite rankings of city exposure to volcanic hazards and their score within the different ranks. For cities these are based on three different ranks: a) the total city population exposed to one or more volcanoes within 100 km of volcanoes, b) the number of volcanoes the city is exposed to, c) the distance to nearest volcano. For volcanoes, these rankings are based on three different ranks: a) the total exposed city population within 100 km, b) the number of cities exposed, c) the distance of the volcano to the nearest city. The cities and volcanoes are ordered by the average of three rankings (composite rank shown in the Rank column rounded to the nearest integer). V.F. stands for Volcanic Field and V.C. stands for Volcanic Complex.*

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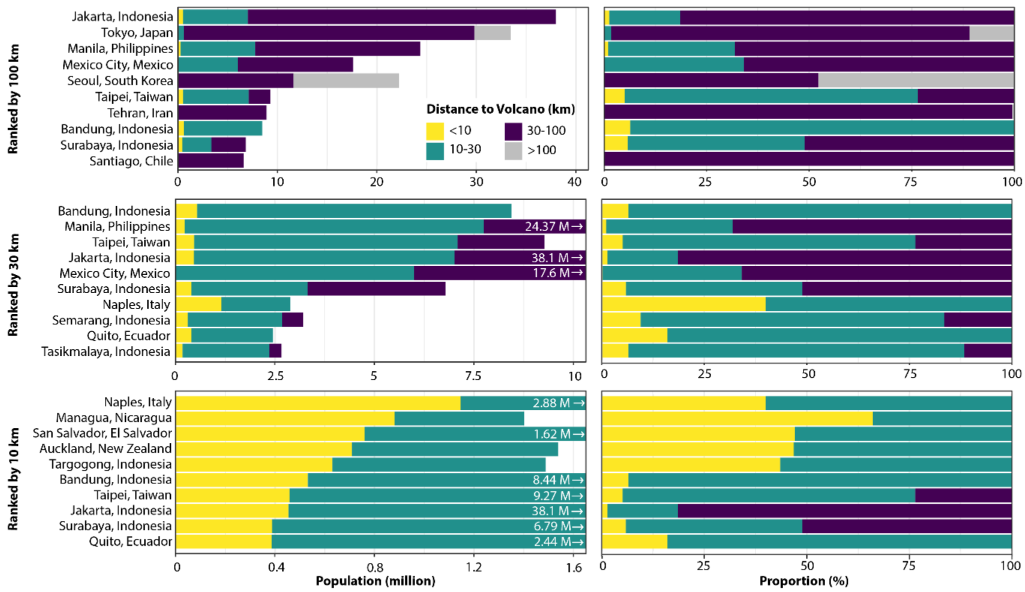

Fig. 4: *Horizontal stacked bar charts of city population (left) and proportion (right) of each city classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. Each bar represents a city exposed to volcanoes, and the x axis limits (left) reflect the population range for that volcano buffer.*

Fig. 4 shows city rankings of populations by distances to their *nearest* volcanoes, with 99 cities having their city margins within 10 km from a volcano. However, ~63 % of cities with populations within 100 km of volcanoes (n=698) are exposed to more than one volcano. Fig. 5 presents the top 20 ranking of cities by exposed populations, classified by the number of volcanoes the city is exposed to. The Fig. shows that portions of the populations of Tokyo, Japan; Seoul, South Korea; and Nagoya, Japan, are not exposed to any volcanoes, but these cities still rank within the top 20 exposed cities (Fig. 5). Interestingly, not all the largest exposed populations are exposed to multiple volcanoes, such as Seoul, South Korea; Tehran, Iran; Barcelona, Spain; Antananarivo, Madagascar; and Athens, Greece, which have populations exposed to only one volcano. The top four cities with exposed populations have much larger populations compared to the others, with millions more residents. In contrast, the differences in exposed populations among the remaining cities exhibit a more gradual increase, illustrated in Fig. 5 and for mid-sized cities (populations under 1 million) in the Appendix (Fig. A4).

Most of the cities exposed to multiple volcanoes are in Central America, with populations in Quezaltepeque is exposed to the highest number of volcanoes (n=23), and San Salvador is the city with >1 million people exposed to the highest number of volcanoes (n=22) (Fig. 6). Although San Salvador is ranked 39th by population within 100 km, it is third in the composite ranking behind Bandung and Jakarta, due to its high ranking of the number of volcanoes (Fig. 3). Despite this proximity of cities to multiple volcanoes, there is the same ranking of the top 10 cities when ranked by the people exposed to the nearest volcano, and those exposed to at least one volcano. Bandung ranks highly for both maximum number of volcanoes to which the city is exposed, and the number of people exposed, with exposed populations within 100 km of between 9 and 12 volcanoes, with the most, ~4 million, exposed to 10 volcanoes (Fig. 6).

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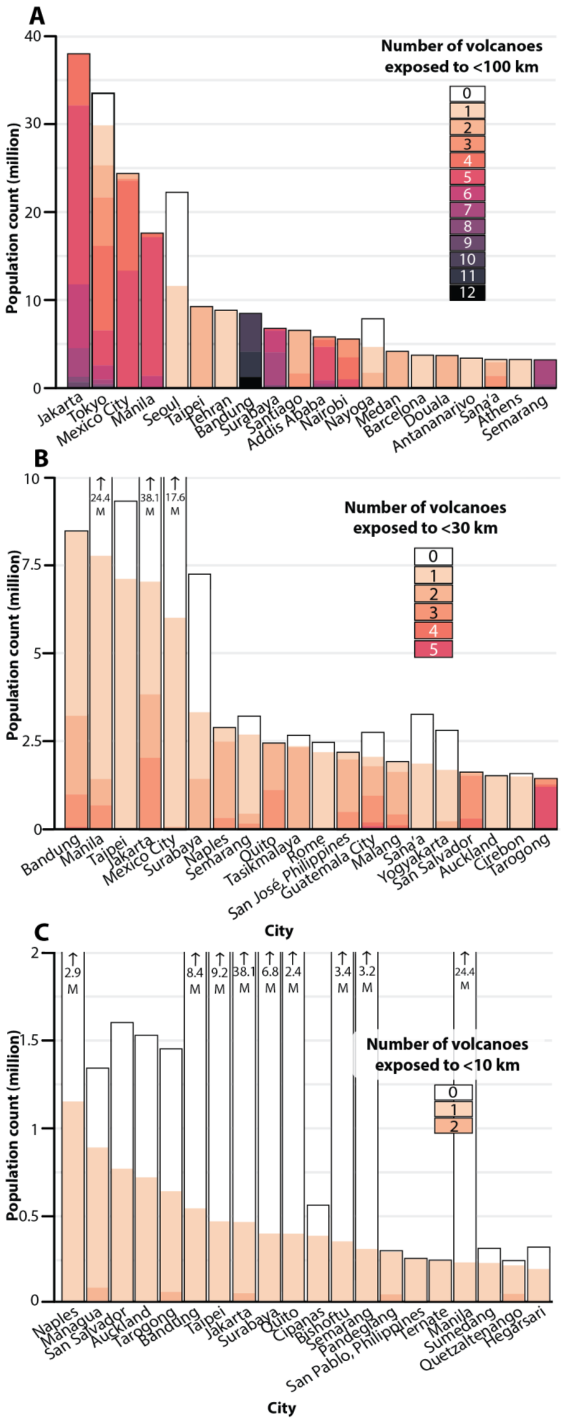

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Fig. 5: *Stacked bar charts of city population exposure for the top 20 cities coloured by the number of volcanoes the populations are exposed to, within A) 100-km, B) 30-km, and C) 10-km volcano buffers.*

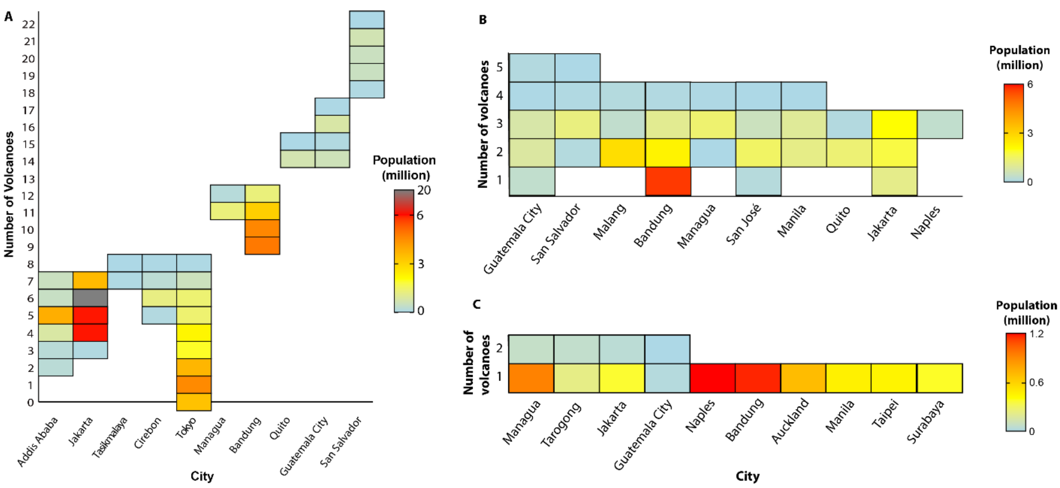

Fig. 6: *Heatmap for the top 10 cities with total populations of over 1 million ranked by exposure to number of volcanoes, showing the city population exposed to increasing numbers of volcanoes for A) 100-km, B) 30-km, and C) 10-km volcano buffers.*

4.2 Ranking volcanoes by city exposure

Almost 47% of Holocene volcanoes (n=596) have city populations located within 100 km of their assumed vents. Indonesia dominates the rankings for city populations within 100 km of volcanoes. Five, seven, and three of the top 10 volcanoes within the 100-km, 30-km and 10-km buffers, respectively, are in Indonesia. Among the 596 volcanoes close to city populations, Gede-Pangrango, Salak, and Pebakti-Gagak volcanoes, all located in Indonesia, rank highest in terms of city population exposure within 100 km (Fig. 7), including the entire population of Jakarta for Salak and Gede-Pangrango, shown in the Appendix (Fig. A3). For the top 10 cities within 100 km, up to 35% of the population live within 30 km, with most living between 30 and 100 km (Fig. 7). Notably, Gede-Pangrango volcano has the most city populations living within 100 km and Guntur volcano hosts the largest population within a 10-km distance in Indonesia, reaching populations in Bandung and Jakarta. Outside of Indonesia, volcanoes Nejapa-Miraflores, Nicaragua, and the Auckland Volcanic Field have almost 50 % of city populations nearby living within 10 km of the volcanoes. In fact, Auckland

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Volcanic Field and San Salvador have the entire city population exposure within 30 km of the volcanoes and the entire country of El Salvador is within 30 km of a volcano (Fig. 9).

In addition to distances, it is also important to consider the number of cities that are close to volcanoes. Ethiopia is noted for its high number (n=108) of cities close to volcanoes, and the greatest number of cities (n=23) have the Northern Lake Abaya Volcanic Field, Ethiopia, as their nearest volcano, as detailed in the Appendix (Fig. A1). Tangkuban Parahu volcano ranks highly across our rankings of the number of people within 100 km, the number of cities, and the distance to the nearest city (Fig. 3).

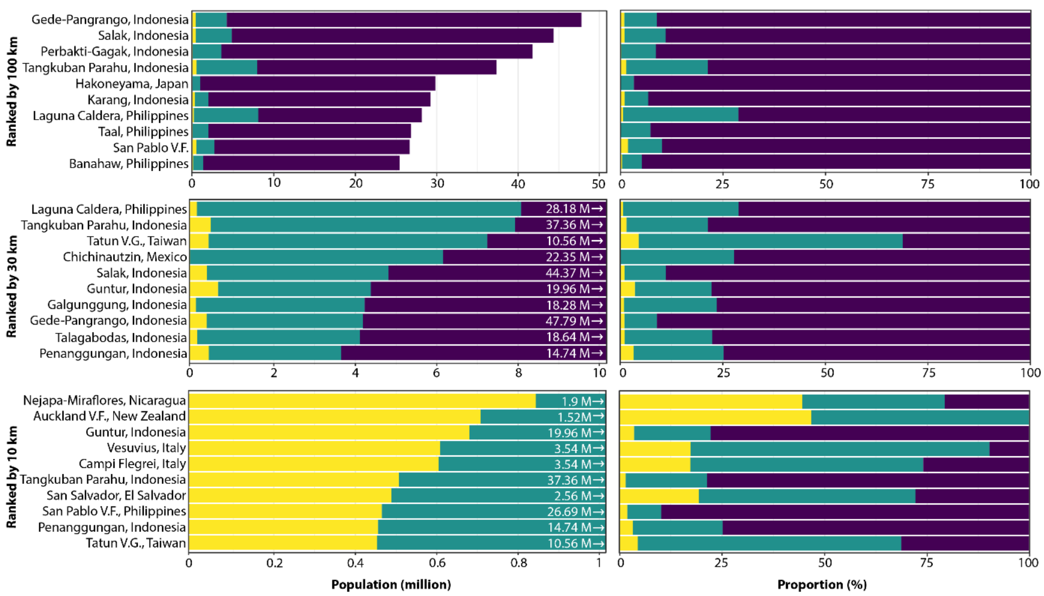

Fig. 7: Horizontal stacked bar charts of city population (left) and proportion (right) around each volcano, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. Each bar represents a volcano, and the x axis limits (left) reflect the population range for that volcano buffer.

4.4 Regional trends in city exposure to volcanoes

The largest amount of people living in cities exposed to at least one volcano are in South-East Asia, with 6,450,774; 62,503,491; and 162,357,787 people living within 10, 30, and 100 km of a volcano,

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respectively (Fig. 8A). However, the highest proportion of city populations exposed to volcanoes are in Central America (Fig. 8B) where approximately 66%, 31% and 4% of city populations are located within 100 km, 30 km, and 10 km, respectively, of at least one volcano. In Australia and New Zealand, and Europe, subregions there are the least number of people exposed, with 2,018,698 and 22,942,510, respectively, within 100 km. City populations in the subregions of Australia and New Zealand, and Europe, are also exposed to fewer volcanoes than the other continents, with more than 10% of the exposed populations exposed to one or two volcanoes (Fig. 8B). However, 4% of the total city population of Australia and New Zealand lies within 10 km of at least one volcano, the highest proportion of any subregion (Fig. 8).

Indonesia stands out globally for having the greatest number of cities and residents located in proximity to volcanoes, with the largest populations within 10, 30, and 100 km of at least one volcano (Fig. 9). Japan ranked second for the 100-km *volcano buffer* but ranks fifth and fourteenth for the 30-km and 10-km *volcano buffers* as a high proportion of the city population are living within 30 and 100 km of volcanoes. This is also the case for South Korea, Iran, and Chile, with high numbers of people living within 30 and 100 km of volcanoes compared to <30 km. Meanwhile, the Philippines, ranked third for the 100-km buffer, has a high proportion of its city populations residing within all three distances, meaning that it ranks highly for all three buffer sizes. For the 32% of city populations exposed in East Africa (Fig. 8), these are dominated by Ethiopia and Yemen (Fig. 9), where the cities are not reflected in the top city rankings of Fig. 4 as the city populations are split across multiple smaller cities. Ethiopia has almost 100 cities exposed, and Yemen has ~60 cities exposed to volcanoes (see Fig. A1 in the Appendix). Remarkably, El Salvador presents a unique case for the top 10 ranked cities, where the entirety of its population lives within 30 km of at least one volcano. Both Nicaragua and El Salvador have over 40% of their city populations living within 10 km of at least one volcano.

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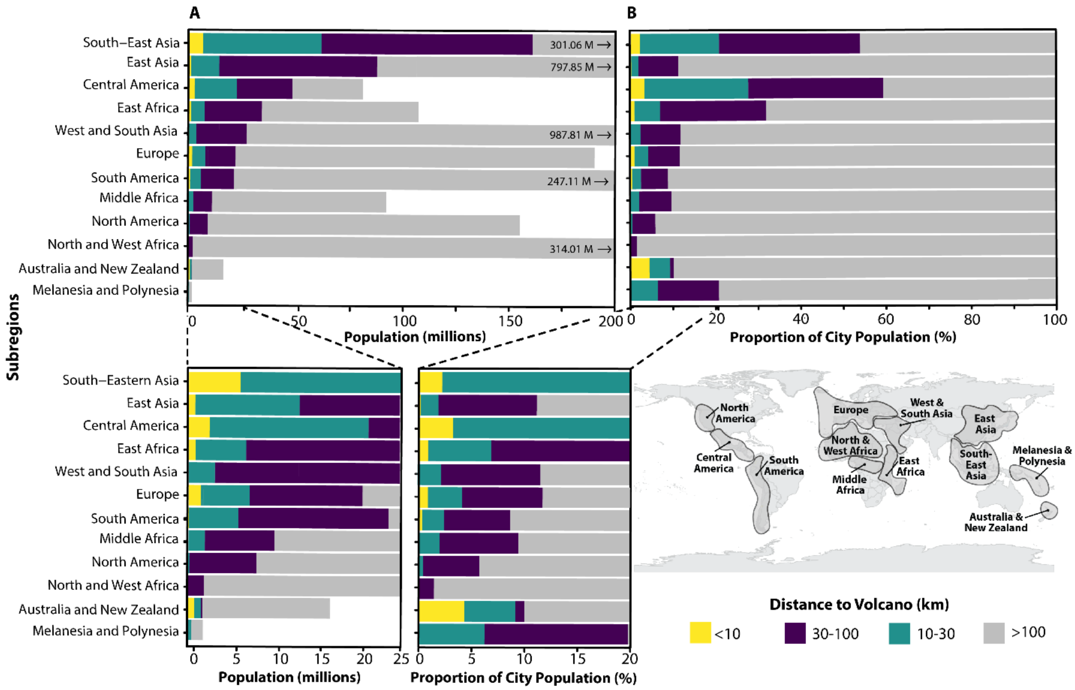

Fig. 8: *The exposed city population (A) and proportion of total city population (B) split by subregion and classified by the distance of the population to nearest volcano. The subregions are highlighted on the bottom right schematic map showing an approximate location of where the cities are located. Note that cities in French Polynesia are included in Melanesia and Polynesia, and Réunion, Martinique, and Mayotte Islands, and Kamchatka, are included in Europe.*

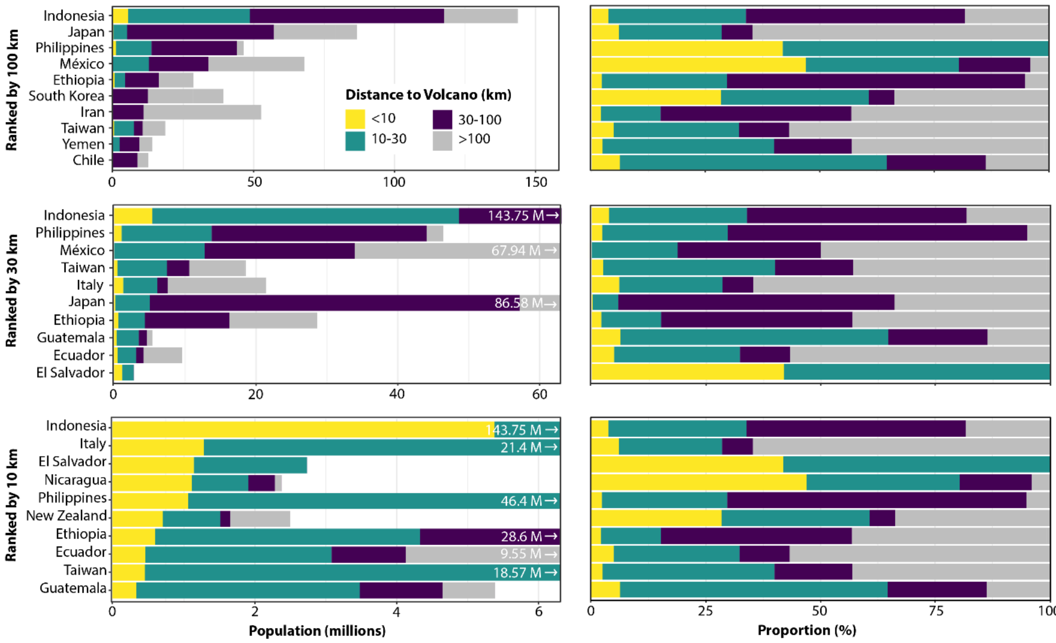

Fig. 9: *Horizontal stacked bar charts of city population (left) and proportion (right) around each volcano, grouped by country, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. Each bar represents a country, and the x axis limits (left) reflect the population range for that volcano buffer .*

4 Discussion

4.1 City Rankings

Our methodology offers a ranking of cities and revised population metrics and distance to the nearest volcano, advancing the polar charts of past studies showing the distance, direction, and population of example cities (Auker et al., 2013; Chester et al., 2000). We updated city populations: for instance, while Chester et al., (2000) reported Manila had a population of 7.94 million and Tokyo had a population of 25 million, our 2020 CE data was ~ 16 million and ~ 5 million higher, respectively. In this study, 557 cities exposed to volcanoes have populations greater than 100,000 people, a substantial increase from the 67 cities documented by Heiken (2013). We identify Jakarta, Tokyo, and Manila, as having the highest exposure within 100 km of volcanoes. These large cities have high proportions of

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people living between 30 and 100 km from the nearest volcano and population spread across the three *volcano buffers* (Fig. 4; Table 4), highlighting the potential for variable impacts. Jenkins et al., (2018) also identified these three cities as having the greatest tephra fall hazard and risk in Asia, when wind conditions, eruption characteristics, and tephra transport were accounted for. Jakarta is highlighted as the largest city exposed to volcanoes in Pelling (2012) and Blaikie (1994). However, Heiken (2013) identifies Tokyo, Manila, and Mexico City as the only megacities exposed to volcanoes. Jakarta is not selected as an example by Heiken (2013), Auker et al. (2013), or Chester et al. (2000). This may be due to potential differences in criteria used in assessing exposure.

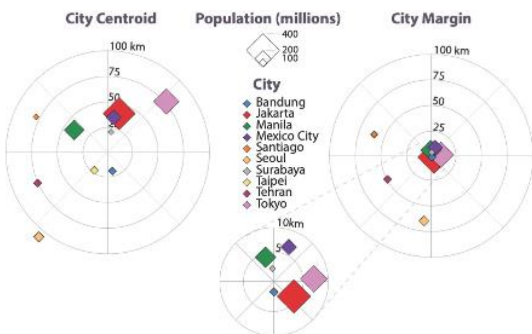

Fig. 10: *Polar chart to show the top 10 cities with the most exposed city populations within 100 km of the nearest volcano. The city centroids (left) and nearest city margin to the volcano (right) are plotted as diamonds relative to the nearest volcano (centre of the plots), and the diamond size refers to the size of the population exposed. The centroid of Seoul is located outside of the 100-km radial buffer, but the population within the 100 km is high enough to rank the city into the top 10 exposed.*

Identifying an exposed city by its centroid alone is not an ideal representation of city exposure as it does not capture the spatial extent (sprawl) of a city, or changes in population density across the city. City margins are closer to volcanoes than the centroids (Fig. 10). Some cities have higher population densities closer to volcanoes despite having greater areas of the city farther away (Table 4), suggesting that cities can have higher population densities in the city peripheries away from the city centre. For example, the city centroid of Seoul is located more than 100 km from Mount Baekdu (Changbaishan), however approximately half of Seoul's city population (n=11,705,767), and some of the most densely populated parts of the city (~11,119 people per km^2) are located within the 100-km *volcano buffer* (Fig. 10), with the closest margin of the city 64 km from the volcano. This is likely due to residential zones

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being situated farther from the city centre, in areas where population density may increase as cities expand. These close city margins place dense populations very close to potential volcanic hazards. Therefore, our approach better captures the spatial sprawl and variation in population across the cities, which are overlooked by the centroid approach.

Table 4: *Cities with populations across three different buffer distances of volcanoes: 10, 10 – 30, and 30 – 100 km, with city population exposed, area of city polygon, and the averaged population density within each buffer distance. The population, area, and densities in bold font are those higher than the other two buffer distances. The cities are in order of population density <10 km of volcanoes. Numbers are rounded to the nearest integer*

City	Population			Area (km^2)			Population Density (/km^2)		
Name	**10 km**	**10 - 30 km**	**30 - 100 km**	**10 km**	**10 - 30 km**	**30 - 100 km**	**10 km**	**30 - 100 km**	**30 - 100 km**
Taipei, Taiwan	457807	5987736	**11607299**	64	**512**	374	7112	**12964**	5833
Manila, Philippines	220952	**2020662**	694688	48	669	**1773**	4635	**11251**	9376
Semarang, Indonesia	298695	7525192	**16627938**	66	**330**	205	4543	**7205**	2559
Surabaya, Indonesia	387688	**2160308**	279119	102	**769**	429	3803	3807	**8088**
Guatemala City, Guatemala	23943	**2182277**	306364	6	**326**	120	3702	**6193**	5777
Jakarta, Indonesia	453914	**2927379**	3471151	110	1123	**3258**	4142	5841	**9525**
Rome, Italy	16698	**6633853**	2181179	5	**399**	63	3205	**5417**	4429
Tasikmalaya, Indonesia	167908	6559219	**31037351**	70	**403**	49	2392	5418	**6247**
Mexico City, Mexico	2373	**2376679**	525538	2	733	**1391**	1052	8173	**8344**
Tokyo, Japan	21	558703	**29275558**	<1	170	**4229**	296	3282	**6922**

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In this research we focussed on identifying cities with high populations exposed to volcanic hazards. However, we emphasise the importance of assessing both the total numbers of exposure as well as the proportions of the city (Fig. 4B), as less populated and smaller cities may have their entire population exposed. While these cities may not rank highly in terms of total population, smaller cities may be more susceptible to complete destruction (Pelling, 2012), whereas an eruption affecting part of a larger city may allow for greater capacity to recover. Limited resources and less infrastructure in smaller cities may also magnify the impacts of eruptions. Thus, eruptions affecting an entire city potentially cause challenges in ters of evacuation, continuity, and recovery. An eruption that affects multiple neighbouring cities can compound this effect. If the eruption affects multiple small cities instead of one large city, it may result in a high total number of exposed individuals dispersed across multiple cities. This scenario can strain emergency response efforts and limit the options for evacuation and recovery. We accounted for this in our composite ranking by including ranks by the number of nearby cities (Fig. 3).

Conversely, an eruption affecting part of a large populous city can have implications for the entire city, neighbouring cities, the country and potentially globally. In large urban areas, the interdependence of infrastructure systems, such as transportation and utilities, means that even minor damage can lead to widespread functional disruptions, affecting populations beyond the immediate impacted area (Pelling, 2012; Heiken, 2013; Weir et al., 2024). For example, lahars triggered following the 1991 Pinatubo eruption in the Philippines (VEI 5) damaged highways to the North of Metro Manila, resulting in cascading impacts that disrupted access to the city (Solway, 1994; Pelling, 2012). These indirect impacts can extend beyond infrastructure disruption, affecting supply chains, labour markets, and public health systems, with potential for the effects of an eruption to impact regionally or globally, particularly for those cities that are central to financial systems (Pelling, 2012). Thus, these large cities that have a small proportion exposed may be ranked low in our analysis in terms of exposure, but this could mask potential widespread indirect impacts across the broader city (Mossler, 1996; Pelling, 2012). Understanding these wider effects is crucial for assessing the full scope of urban vulnerability to volcanic hazards. Further localised assessments and systematic risk evaluations are recommended to capture a more complete range of potential impacts (Mossler, 1996; Pelling, 2012).

4.2 Volcano Rankings

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We highlight key volcanoes such as Salak, Gede-Pangrango, and Perbakti-Gagak with the most people exposed within cities nearby, as well as Tangkuban Parahu and Tampomas, Indonesia, and San Pablo Volcanic Field, Philippines, that rank highly in our composite ranking. Other studies highlight volcanoes in Indonesia as having high levels of exposure. For example, in our study, Gede-Pangrango was ranked second and seventh for populations living within 100 km and 30 km of volcanoes, respectively. Gede-Pangrango was also ranked by Small and Naumann (2001) as the most populous volcano globally and by Jenkins et al. (2022), as the fifth highest volcano for exposure in Indonesia and the Philippines when considering both populations and physical assets threatened by VEI 3-5 eruptions. Jenkins et al. (2022) also identified Guntur volcano as a volcano in need of further study due to its resulting exposure and the lack of localised hazard or exposure assessments. Our findings support this, as Guntur volcano ranks highest in Indonesia for city populations within 10 km of the volcano and ranks fourth in the composite ranking. Our findings highlight key hotspot volcanoes for further localised exposure and hazard assessments.

Large city populations within 10 km of volcanoes, a distance reached by destructive proximal hazards, can be affected by a smaller or moderate eruption at one of these volcanoes, which may have greater direct impacts than a larger eruption where populations are located farther away. A large proportion of these close populations are residing near volcanoes in Central and South America (Fig. 9). Escobar et al. (2007) found that a high proportion of city populations in Central America are living close to the most dangerous volcanoes in the region, something supported by our study (Fig. 7). Ewert and Harpel (2004) highlight Central America as having potentially significant exposure to volcanic hazards, with 2.7 million people (data from 2004 CE) within 10 km of volcanoes living in both urban and rural areas. In our study, using 2020 CE city population data for the same buffer distance, we find that a similar number (2.6 million) of people now live just within the urban (city) areas. The high proportions of urban populations close to volcanoes in Central and South America (Fig. 9) is perhaps linked to the colonial past of the region, whereby investments into agriculture in the early to mid-20th Century resulted in a growth of agricultural settlements through time (Swyngedouw, 2006). Nejapa-Miraflores volcano is one example of where almost 1 million people, or 60 % of the exposed population, are located within 10 km of the volcano. These populations are distributed over multiple cities, adding complexity to potential eruption impacts and response strategies.

4.4 Future Research Directions

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In this study, we define cities as those areas classified in the GHS-UCDB dataset as *urban centres*, which excludes suburbs and regions of lower population densities. For example, the remaining ~25% (n=336) of volcanoes that do not have city populations within 100 km, may still be situated near suburban or rural populations, or have tourists, not assessed in this study. Through time, these urban centres may merge together and densify. Therefore, total city populations may slightly differ when using other datasets. Our approach could be expanded or used to explore more than just cities, by assessing changing land-use patterns, transient populations, or other population densities around volcanoes. We can also explore past trends in city population exposure through time, and future projections, to quantify rates of exposure change. Mapping the urban sprawl of these cities allows us to identify key areas around volcanoes to focus on future mitigation efforts and land-use planning.

Additionally, our 2020 CE dataset includes 137 cities exposed to volcanoes located in other countries, underscoring the need for research in cross-border cooperation and planning to mitigate the impacts of eruptions with transboundary effects (Donovan & Oppenheimer, 2019).

We used a comparative approach to quantify the hazard by using the distance to the nearest volcano and the number of nearby volcanoes, which could be explored further. For example, the volcano buffers used in this study relate to the average maximum distances of primary hazards. However, our use of a 100-km radial buffer does not account for far-reaching volcanic flows or tephra falls that may reach beyond 100 km (Biass et al., 2024) or cascading hazards that may extend beyond this distance, such as tsunamis. Future studies could explore these cascading and widespread impacts, in the key cities identified in this study, to capture potential losses.

The selection of the location of the volcanic crater as point co-ordinates provided by the Global Volcanism Program (2023), does not account for the uncertainty in next eruption site, for example at volcanic fields or rift zones. Future work could classify volcanoes by last eruption, VEI range, or tectonic setting, to better understand the specific types of potential hazard they pose to nearby cities. Additionally, research could explore alternative methods to the traditional volcano buffers, considering approaches that account for the spatial variability of volcanic fields and shield volcanoes. There is also necessity in localised exposure and risk assessment (Biass et al., 2024; Jenkins et al., 2022; Diefenbach et al., 2015). Future research can incorporate local topography, seasonal weather patterns, eruption frequencies, and hazard probabilities as well as exposures beyond population, and the vulnerability of these to the hazards to understand the specific risks faced by individual cities.

5 Conclusions

Cities close to volcanoes are at high risk of volcanic hazards. In our study, we present a framework to quantify and rank city population exposure to volcanoes by extracting and calculating 2020 CE population counts from *city polygons*. We evaluated the exposure of 1,106 cities within 100 km of 596 Holocene volcanoes, measuring exposure within 10, 30, and 100-km radial buffers, reflecting maximum distances for various eruption VEIs. Although topography and weather can affect hazard footprints (Biass et al., 2024), our method conservatively estimates and compares city exposure. These buffer sizes may overestimate exposure, but we preferred this approach to avoid underestimating it. The rankings can provide a foundation to identify areas for future detailed and localised exposure or risk assessments, especially for cities with limited past hazard or exposure data. Ranking cities by exposure also helps identify key locations for future research and land-use planning. Our results are provided at Section 9 and as a web application for visualisation of all city exposures (https://nteng.shinyapps.io/ExposureOfCities/).

Using this framework, we ranked cities by exposed population, number of nearby volcanoes, and distance to the nearest volcano. We highlight Jakarta, Bandung, and San Salvador as scoring highly across these rankings. Jakarta, Bandung, and Naples have the largest city populations within 100, 30, and 10 km, respectively, of at least one volcano. San Salvador, Guatemala City, and Managua are cities of over 1 million people that have the largest number of people exposed to the largest number of volcanoes within 100, 30 and 10 km respectively with 22, 5, and 2 volcanoes, respectively. We also ranked volcanoes in three ways: by number of exposed city populations, by the number of nearby cities, and the distance of the nearest city. We highlight Tangkuban Parahu, San Pablo Volcanic Field, and Tampomas as scoring highly across these rankings. Gede-Pangrango, Laguna Caldera, and Nejapa-Miraflores volcanoes have the largest number of city populations within 100, 30, and 10 km respectively. These rankings reveal hotspot cities with high populations exposed to multiple volcanoes; for example, ~8.5 million people in Bandung are exposed within 100 km to 12 volcanoes.

Globally, 50% of people exposed to volcanoes (within 100 km) live in cities. The size, number, and distance of cities near volcanoes, or spread of population density across cities, create different

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challenges regarding exposure to volcanoes. For example, Jakarta has high population density between 30 – 100 km of volcanoes, while 23 smaller cities in Ethiopia are exposed to a single volcano: Northern Lake Abaya Volcanic Field. Other cities, such as Auckland, are located on volcanic fields. Some countries are highly exposed to volcanic hazards. For example, all cities in El Salvador are located within 30 km of a volcano and in the Philippines, 90% of cities have some part of the city located within 100 km of a volcano. Understanding these diverse exposures is crucial for developing effective risk management strategies tailored to the specific needs of each country.

This research highlights key exposed cities at risk of volcanic hazards ranked in different ways. These findings can inform decision-making and further research around volcanoes. This work prompts more localised studies that overlay these exposures with probabilistic hazard maps which can enhance our understanding of the dynamic risks surrounding volcanoes.

8 Appendix A

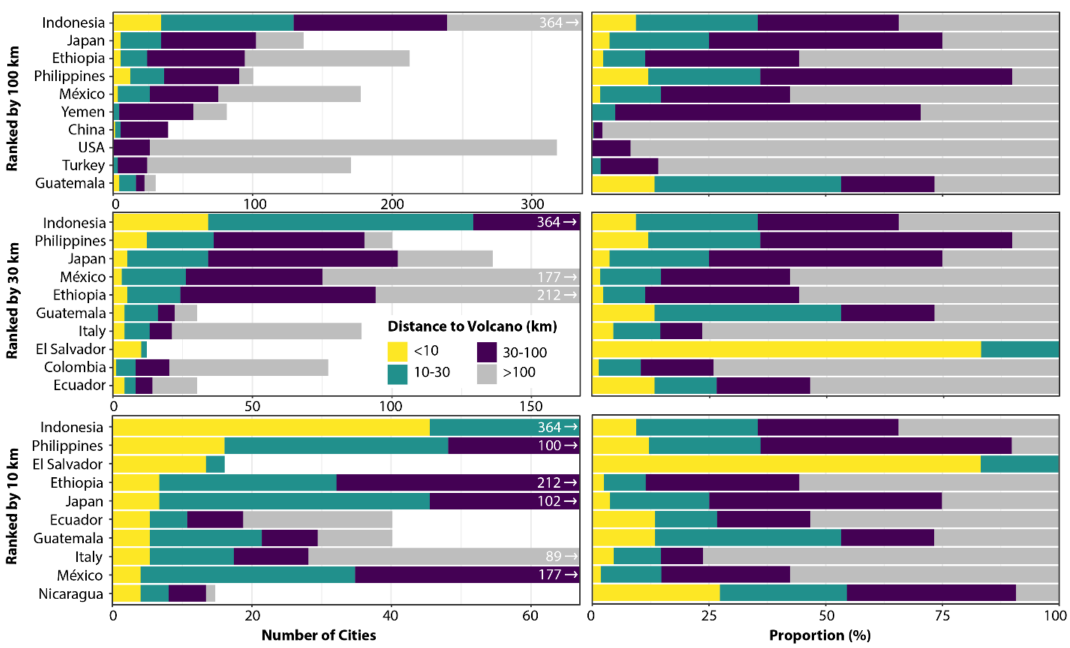

Fig. A1: Horizontal stacked bar charts of number of cities with populations within each buffer distance (left) and proportion (right) around each volcano, grouped by country, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. If the city is spread across multiple buffers, the closest to the volcano is selected. Each bar represents a country, and the x axis limits (left) reflect the population range for that volcano buffer.

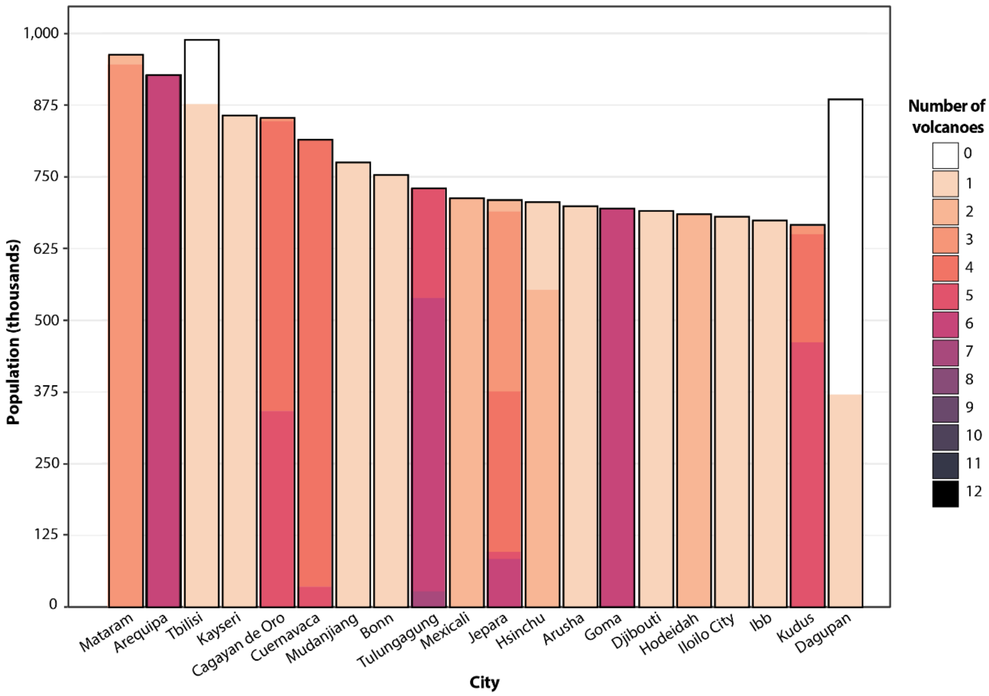

Fig. A2: Top 20 cities with less than one million exposed city populations, coloured by the number of volcanoes the population is exposed by.

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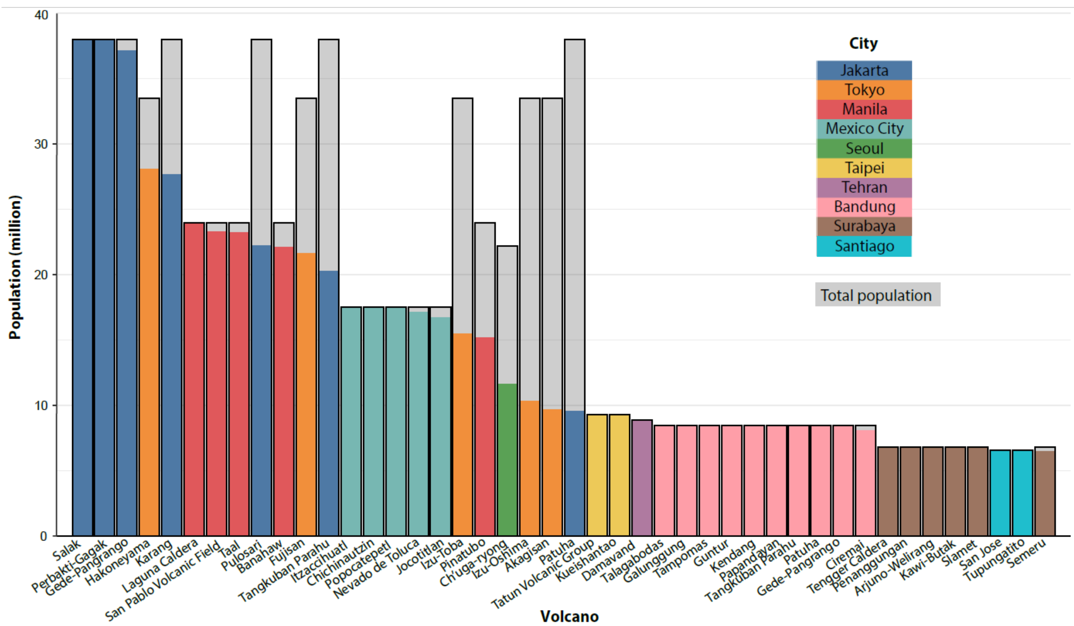

Fig. A3: City populations exposed to individual volcanoes within 100 km, ranked by the dominant city. Bars are coloured by the dominant city exposed population.

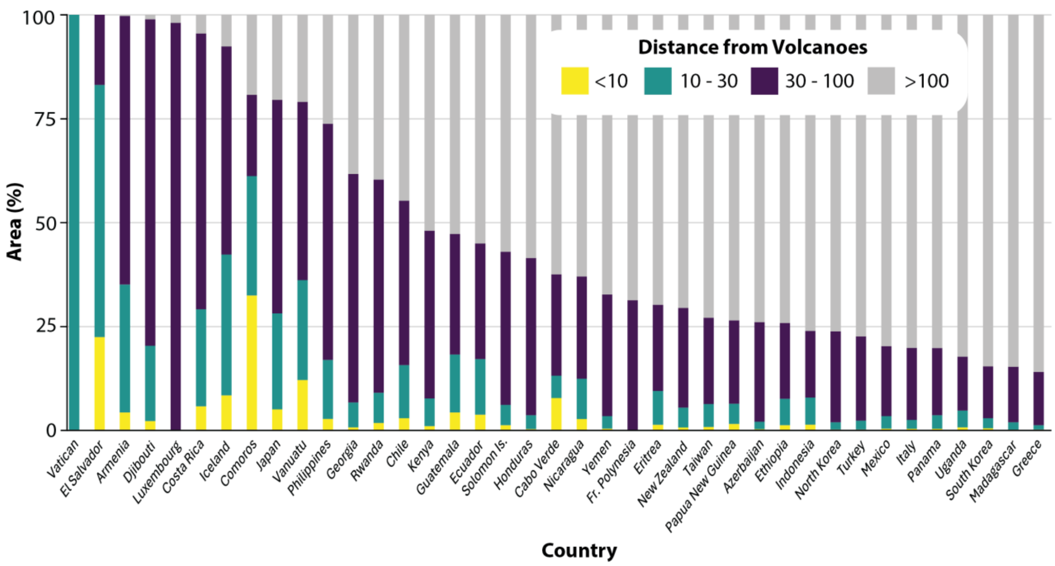

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Fig. A4: Top forty countries ranked in order of their total land area exposed to volcanic hazards, and coloured by the percentage of area. Is stands for islands and Fr stands for French.

8 Code Availability

The R code used in this manuscript is available at: https://github.com/vharg/VolcCities

9 Data Availability

The web application presenting results for all cities is available at https://nteng.shinyapps.io/ExposureOfCities/

Ranking results of city exposure to volcanic hazards and volcanoes by exposed populations is available at https://researchdata.ntu.edu.sg/privateurl.xhtml?token=65c3712c-461b-4d95-b499-f2eebb5ab30d

10 Author Contribution

The project was conceptualised by ESM, RXNT, SJF and SB. The methodology was developed by ESM and RXNT with support from SFJ, JLH, and SB. Visualisations were made by ESM and the web app was developed by RXNT. The original draft was written by ESM. All authors contributed to editing and reviewing the manuscript.

11 Competing Interests

The authors declare that they have no conflict of interest.

12 Acknowledgements

This research was partly supported by the Ministry of Education, Singapore, under its MOE Academic Research Fund Tier 3 InVEST project (Award MOE-MOET32021-0002). This work comprises EOS contribution number 631. SFJ acknowledges financial support from the AXA Joint Research Initiative. We acknowledge support for this work from the Centre for Disaster Resilience, ITC Faculty, University of Twente.

13 References

Alberico, I., Petrosino, P., & Lirer, L. (2011). Volcanic hazard and risk assessment in a multi-source volcanic area: The example of Napoli city (Southern Italy). Nat. Hazards Earth Syst. Sci., 11(4), 1057–1070. https://doi.org/10.5194/nhess-11-1057-2011

Ariyanti, V., Gaafar, T., De La Sala, S., Edelenbos, J., & Scholten, P. (2020). Towards liveable volcanic cities: A look at the governance of lahars in Yogyakarta, Indonesia, and Latacunga, Ecuador. Cities, 107, 102893. https://doi.org/10.1016/j.cities.2020.102893

Aspinall, W., Auker, M., Hincks, T., Mahony, S., Nadim, F., Pooley, J., Sparks, R. S. J., & Syre, E. (2011). Volcano hazard and exposure in GFDRR priority countries and risk mitigation measures–GFDRR Volcano Risk Study.

Auker, M. R., Sparks, R. S. J., Siebert, L., Crosweller, H. S., & Ewert, J. (2013). A statistical analysis of the global historical volcanic fatalities record. J. Appl. Volcanol., 2(1), 2. https://doi.org/10.1186/2191-5040-2-2

Biass, S., Jenkins, S. F., Hayes, J. L., Williams, G. T., Meredith, E. S., Tennant, E., Yang, Q., Lerner, G. A., Burgos, V., Syarifuddin, M., & Verolino, A. (2024). How well do concentric radii approximate population exposure to volcanic hazards? Bull. Volcanol., 86(1). https://doi.org/10.1007/s00445-023-01686-5

Bilham, R. (2009). The seismic future of cities. Bull. Earthq. Eng., 7(4), 839–887. https://doi.org/10.1007/s10518-009-9147-0

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (2004). At risk: Natural hazards, people's vulnerability and disasters. Routledge.

Brecht, H., Deichmann, U., & Wang, H. G. (2013). A global urban risk index. [World Bank Working Paper]. http://econ.worldbank.org

Brown, S. K., Jenkins, S. F., Sparks, R. S. J., Odbert, H., & Auker, M. R. (2017). Volcanic fatalities database: Analysis of volcanic threat with distance and victim classification. J. Appl. Volcanol., 6(1), 2. https://doi.org/10.1186/s13617-017-0067-4

Chester, D. K., Degg, M., Duncan, A. M., & Guest, J. E. (2000). The increasing exposure of cities to the effects of volcanic eruptions: A global survey. Environ. Hazards, 2(3), 89–103. https://doi.org/10.3763/ehaz.2000.0214

Degg, M. (1992). Natural disasters: Recent trends and future prospects. Geography, 77(3), 198–209.

Del Negro, C., Cappello, A., Bilotta, G., Ganci, G., Hérault, A., & Zago, V. (2020). Living at the edge of an active volcano: Risk from lava flows on Mt. Etna. Bull. Geol. Soc. Am., 132(7–8), 1615–1625. https://doi.org/10.1130/B35290.1

Delgado Granados, H., & Jenkins, S. F. (2015). Extreme volcanic risks 1: Mexico City. In J. Shroder (Ed.), Volcanic hazards, risks and disasters (pp. 315–354). Elsevier.

Diefenbach, A. K., Wood, N. J., & Ewert, J. W. (2015). Variations in community exposure to lahar hazards from multiple volcanoes in Washington State (USA). J. Appl. Volcanol., 4(1), 4. https://doi.org/10.1186/s13617-015-0024-z

Donovan, A., & Oppenheimer, C. (2019). Volcanoes on borders: A scientific and (geo)political challenge. Bull. Volcanol., 81(5), 28. https://doi.org/10.1007/s00445-019-1291-z

Durand, M. (2001). Impacts of, and responses to ashfall in Kagoshima from Sakurajima volcano: Lessons for New Zealand. Inst. Geol. Nucl. Sci. Ltd., New Zealand.

Erfurt-Cooper, P. (2014). Volcanic tourist destinations. Springer. https://doi.org/10.1007/978-3-642-16191-0

https://doi.org/10.5194/nhess-2024-219
Preprint. Discussion started: 29 January 2025

Escobar, R., Alvarado, G., Soto, G., Navarro, M., Escobar, D., Pullinger, C., & Bonis, S. (2007). Volcanic activity, hazards, and monitoring. In Central America (pp. 837–880). Taylor & Francis. https://doi.org/10.1201/9780203947043.ch38

Ewert, J. W. (2007). System for ranking relative threats of US volcanoes. Nat. Hazards Rev., 8(4), 112–124.

Ewert, J. W., Diefenbach, A. K., & Ramsey, D. W. (2018). 2018 Update to the U.S. Geological Survey National Volcanic Threat Assessment. Sci. Invest. Rep., 2018-5140.

Ewert, J. W., & Harpel, C. J. (2004). In harm's way: Population and volcanic risk. Geotimes, 49(4), 14–17.

Freire, S., Florczyk, A. J., Pesaresi, M., & Sliuzas, R. (2019). An improved global analysis of population distribution in proximity to active volcanoes, 1975–2015. ISPRS Int. J. Geo-Inf., 8(8), 341. https://doi.org/10.3390/ijgi8080341

Global Volcanism Program. (2024). Volcanoes of the World (v. 5.2.0; 6 Jun 2024). Smithsonian Institution. https://doi.org/10.5479/si.GVP.VOTW5-2024.5.2

Godschalk, D. R. (2003). Urban hazard mitigation: Creating resilient cities. Nat. Hazards Rev., 4(3), 136–143. https://doi.org/10.1061/ASCE1527-698820034:3136

Gu, D. (2019). Population exposure and vulnerability to natural disasters for world's cities. United Nations Populations Division Working Paper. www.unpopulation.org.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., & Chateau, J. (2011). A global ranking of port cities with high exposure to climate extremes. Clim. Change, 104(1), 89–111. https://doi.org/10.1007/s10584-010-9977-4

Heiken, G. (2013). Dangerous neighbors: Volcanoes and cities. Cambridge Univ. Press.

Iglesias, V., Braswell, A. E., Rossi, M. W., Joseph, M. B., McShane, C., Cattau, M., Koontz, M. J., McGlinchy, J., Nagy, R. C., Balch, J., Leyk, S., & Travis, W. R. (2021). Risky development: Increasing exposure to natural hazards in the United States. Earth's Future, 9(7).

Jenkins, S. F., Biass, S., Williams, G. T., Hayes, J. L., Tennant, E., Yang, Q., Burgos, V., Meredith, E. S., Lerner, G. A., Syarifuddin, M., & Verolino, A. (2022). Evaluating and ranking Southeast Asia's exposure to explosive volcanic hazards. Nat. Hazards Earth Syst. Sci., 22(4), 1233–1265. https://doi.org/10.5194/nhess-22-1233-2022

Jenkins, S. F., Magill, C. R., & Blong, R. J. (2018). Evaluating relative tephra fall hazard and risk in the Asia-Pacific region. Geosphere, 14(2), 492–509. https://doi.org/10.1130/GES01549.1

Levine, D. J. (2022). exactextractr: Fast Extraction from Raster Datasets using Polygons (R package version 0.8.3). Available at: https://CRAN.R-project.org/package=exactextractr [Accessed: January 2024].

Loughlin, S. C., Sparks, S., Brown, S. K., Jenkins, S. F., & Vye-Brown, C. (2015). Global volcanic hazards and risk. Global Volcanic Hazards and Risk. Cambridge University Press. https://doi.org/10.1017/CBO9781316276273

Magill, C., & Blong, R. (2005). Volcanic risk ranking for Auckland, New Zealand. II: Hazard consequences and risk calculation. *Bull. Volcanol.*, *67*(4), 340–349. https://doi.org/10.1007/s00445-004-0375-5

Mani, L., Tzachor, A., & Cole, P. (2021). Global catastrophic risk from lower magnitude volcanic eruptions. *Nat. Commun.*, *12*(1). https://doi.org/10.1038/s41467-021-25021-8

Mangan, B. M., Ball, J., Wood, N., Jones, J. L., Peters, J., Abdollahian, N., Dinitz, L., Blankenheim, S., Fenton, J., & Pridmore, C. (2018). SIR 2018–5159 ver. 1.1: California's Exposure to Volcanic Hazards.

Marí Rivero, I., Melchiorri, M., Florio, P., Schiavina, M., Krasnodębska, K., Politis, P., Uhl, J., Pesaresi, M., Maffenini, L., Sulis, P., Crippa, M., Guizzardi, D., Pisoni, E., Belis, C., Oom, D., Branco, A., Mwaniki, D., Kochulem, E., Githira, D., Carioli, A., Ehrlich, D., Tommasi, P., Kemper, T., & Dijkstra, L. (2024). Joint Research Centre (JRC) [Dataset]. https://doi.org/10.2905/1A338BE6-7EAF-480C-9664-3A8ADE88CBCD

Mossler, M. (1996). Environmental hazard analysis and small island states: rethinking academic approaches. Geogr. Zeitsch., 1, 86–93.

Natural Earth. (2023). Admin 0 – Countries. 1:10m, 1:50m, and 1:110m scales. Available at: https://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-admin-0-countries/ [Accessed: January 2024].

Newhall, C., Self, S., & Robock, A. (2018). Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts. Geosphere, 14(2), 572–603. https://doi.org/10.1130/GES01513.1

Nieto-Torres, A., Guimarães, L. F., Bonadonna, C., & Frischknecht, C. (2021). A New Inclusive Volcanic Risk Ranking, Part 1: Methodology. Front. Earth Sci., 9. https://doi.org/10.3389/feart.2021.697451

Pelling, M. (2012). The Vulnerability of Cities: Natural Disasters and Social Resilience.

Pesaresi, M., Florczyk, A., Schiavina, M., Melchiorri, M., Maffenini, L. (2019). GHS settlement grid, updated and refined REGIO model 2014 in application to GHS-BUILT R2018A and GHS-POP R2019A, multitemporal (1975-1990-2000-2015), R2019A. European Commission, Joint Research Centre (JRC). DOI: 10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218 PID: http://data.europa.eu/89h/42e8be89-54ff-464e-be7b-bf9e64da5218

Sandri, L., Thouret, J. C., Constantinescu, R., Biass, S., & Tonini, R. (2014). Long-term multi-hazard assessment for El Misti volcano (Peru). Bull. Volcanol., 76(2), 1–26. https://doi.org/10.1007/s00445-013-0771-9

Schiavina, M., Melchiorri, M., & Freire, S. (2023a). GHS-DUC R2023A - GHS Degree of Urbanisation Classification: Application of the Degree of Urbanisation methodology (stage II) to GADM 4.1 layer, multitemporal (1975–2030) [Data set]. European Commission, Joint Research Centre (JRC). https://doi.org/10.2905/DC0EB21D-472C-4F5A-8846-823C50836305

Schiavina, M., Freire, S., Carioli, A., & MacManus, K. (2023b). GHS-POP R2023A - GHS population grid multitemporal (1975-2030). In European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE PID: http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe.

Schiavina, M., Melchiorri, M., & Freire, S. (2021). GHS-DUC R2019A - GHS Degree of Urbanisation Classification (2015, 2000, 1990, 1975), R2019A - OBSOLETE RELEASE. In European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/ED8E8E11-62C3-4895-

A7B9-5EF851F112ED PID: http://data.europa.eu/89h/ed8e8e11-62c3-4895-a7b9-5ef851f112ed.

Small, C., & Naumann, T. (2001). The global distribution of human population and recent volcanism. Environ. Hazards, 3. http://www.LDEO.columbia.edu/Bsmall/PopVol.html.

Solway, L. (1994). Urban developments and megacities: vulnerability to natural disasters. Disaster Manag.-Redhill, 6, 160.

Strader, S. M., Ashley, W., & Walker, J. (2015). Changes in volcanic hazard exposure in the Northwest USA from 1940 to 2100. Nat. Hazards, 77(2), 1365–1392. https://doi.org/10.1007/s11069-015-1658-1

Swyngedouw, E. (2006). Human Development Report 2006 Power, Water and Money: Exploring the Nexus United Nations Development Programme Background Paper Power, Water and Money: Exploring the Nexus.

Thouret, J.-C. (1999). Urban hazards and risks; consequences of earthquakes and volcanic eruptions: an introduction. GeoJournal, 49(2).

Thouret, J.-C., Finizola, A., Fornari, M., Legeley-Padovani, A., Suni, J., & Frechen, M. (2001). Geology of El Misti volcano near the city of Arequipa, Peru. Geology, 113(12). https://doi.org/10.1130/0016-7606(2001)1132.0.CO;2

UNDP. (2021). Urban Risk Management and Resilience Strategy. United Nations Development Programme. www.undp.org

Weir, A. M. (2024). Quantifying systemic vulnerability of interdependent critical infrastructure networks: A case study for volcanic hazards. https://orcid.org/0000-0001-7449-016X

Wood, N., & Soulard, C. (2009). Variations in population exposure and sensitivity to lahar hazards from Mount Rainier, Washington. J. Volcanol. Geotherm. Res., 188(4), 367–378. https://doi.org/10.1016/j.jvolgeores.2009.09.019

World Bank. (2023). Urban Development. Washington, DC: World Bank. Available at: https://data.worldbank.org/topic/urban-development [Accessed: November 21, 2024].