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

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18   1. Abstract

19   Cities near volcanoes expose dense concentrations of people, buildings, and infrastructure to

20   volcanic hazards. Identifying cities globally that are exposed to volcanic hazards helps guide local

21   risk assessment for better land-use planning and hazard mitigation. Previous city exposure

22   approaches have used the city centroid to represent an entire city, and to assess population exposure

23   and proximity to volcanoes. But cities can cover large areas and populations may not be equally

24   distributed within their bounds, meaning that a centroid may not accurately capture the true

25   exposure. In this study, we suggest a new framework to rank global city exposure to volcanic

26   hazards. We assessed global city exposure to volcanoes in the Global Volcanism Program database

27   that are active in the Holocene by analysing populations located within 10, 30, and 100 km of

28   volcanoes. These distances are commonly used in volcanic hazard exposure assessment. City

29   margins and populations were obtained from the Global Human Settlement (GHS) Model datasets.

30   We ranked 1,133 cities based on the number of people exposed at different distances from

31   volcanoes, the distance of the city margin from the nearest volcano, and by the number of nearby

32   volcanoes. Notably, 50 % of people living within 100 km of a volcano are in cities. We highlight

33   Jakarta, Bandung, and San Salvador, as scoring highly across these rankings. Bandung, Indonesia

34   ranks highest overall with over 8 million people exposed within 30 km of up to 12 volcanoes.

35   South-east Asia has the highest number of exposed city populations (~162 million). Jakarta (~38

36   million), Tokyo (~30 million), and Manila (~24 million) having the largest number of people

37   within 100 km. Central America has the highest proportion of its city population exposed, with

38   Quezaltepeque and San Salvador exposed to the most volcanoes (n=23). Additionally, we ranked

39   the 1,264 Holocene volcanoes by the city populations exposed within 10, 30, and 100 km, the

40   number of nearby cities, and distance to nearest city. Tangkuban Parahu, Tampomas, and San

41   Pablo Volcanic Field score highly across these rankings. Notably, Gede-Pangrango (~48 million),

42   Tangkuban Parahu (~8 million), and Nejapa-Miraflores (~0.8 million) volcanoes have the largest

43   city populations within 100, 30, and 10 km, respectively. We developed a web app to visualise all

44   the cities with over 100,000 people exposed. This study provides a global perspective on city

45   exposure to volcanic hazards, identifying critical areas for future research and mitigation efforts.

46   2. Introduction

47

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

60

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

75

76 In order to reduce the risks faced by cities situated close to volcanoes, we first must identify which
77 cities are most exposed to volcanic hazards. Some past studies have used a localised approach,
78 whereby they identify exposed urban areas close to case study volcanoes (e.g., Thouret et al., 2001;

79 Sandri et al., 2014; Strader et al., 2015; Magill & Blong, 2005; Alberico et al., 2011; Delgado

80 Granados & Jenkins, 2015; Torres et al., 2023). However, a more systematic regional or global

81 approach based on the location of all cities would reveal which cities are most exposed. For

82 example, taking a regional multi-volcano approach, Jenkins et al. (2018) evaluated the potential

83 impact of tephra fall on 16 major cities in the Asia-Pacific region, highlighting Tokyo, Japan;

84 Jakarta, Indonesia; and Manila, Philippines as being most exposed. Ranking cities or volcanoes by

85 city population exposure would allow us to identify global hotspots which may be missed by a

86 more localised approach.

87

88 Whilst global city analyses have been conducted for other hazards such as coastal flooding

89 (Hanson et al., 2011), earthquakes (Bilham, 2009), and multi-hazards (Degg, 1992; Brecht et al.,

90 2013; Gu, 2019), for volcanic hazards, reports or studies often focus on growth rates or total

91 population numbers of case study cities, based on the location of city centroids close to volcanoes.

92 For example, in 1989 CE, the UN estimated that of the top 50 fastest growing cities, only four

93 were exposed to volcanic hazards (United Nations, 1989). Three years later, it was estimated that

94 10 of the world's most populated cities were located within 30 km of an active volcano (Degg,

95 1992). Pelling (2012) and Blaikie (2004) highlight Jakarta as a major city at risk from volcanic

96 activity. Heiken (2013) identified 67 cities (with populations greater than 100,000), home to a total

97 of ~116 million people, located on or near active volcanoes. Other studies considered the city's

98 distance and direction from volcanoes. Donovan and Oppenheimer (2014) list 49 cities within 100

99 km of a volcano with recognised Quaternary activity and Erfurt-Cooper (2014) provided a list of

100 25 cities in close proximity to active volcanoes. Chester et al. (2000) and subsequently Auker et

101 al. (2013) plotted polar charts with examples of highly populated cities in relation to the distance

102 and direction of the city centroid from nearby volcanoes, within 200 km and 50 km of volcanoes,

103 respectively. Brown et al. (2015) identified seven capital cities globally within 10 km of volcanoes,

104 37 within 30 km, and 69 within 100 km. A systematic approach quantifying all global city

105 populations at specific distances from volcanoes would better capture the variable distribution of

106 populations across cities and exposure to volcanoes.

107

108 Key cities identified as exposed to volcanic hazards can then be targeted for more localised

109 research and mitigation efforts. For example, Jenkins et al. (2022) ranked volcanoes in South-East

110   Asia by population and physical exposure, and proposed that populations near Guntur volcano,

111   Indonesia, are highly exposed and thus require further study. For identified highly exposed cities,

112   combining high resolution exposure with hazard maps or footprints can identify key areas in a city

113   on which to focus future mitigation, such as structural adaptations (e.g., to tephra fall in

114   Kagoshima: Durand, 2001) and/or land-use planning efforts (e.g., Nieto-Torres et al., 2021;

115   Strader et al., 2015; Thouret et al., 2001).

116

117   In this study, we propose a new framework to quantify and rank global cities exposed to volcanoes

118   situated within varying proximity thresholds (10, 30, and 100 km), based on three variables:

119   population exposed; distance to nearest volcano; and the total count of volcanoes each city is

120   exposed to. Leveraging high-resolution updated population data allows for assessment of the

121   spatial variation of population exposure within each city. Instead of looking at the total population

122   of the city as presented in past studies, this approach more accurately identifies the proportion of

123   the city population within each distance threshold. Furthermore, our framework also ranks

124   volcanoes by city exposure based on their proximity to city populations, considering the total count

125   of cities and their respective populations within the specified distances from volcanoes.

126

127   2.1 Measuring population exposure around volcanoes

128

129   To quantify global population exposure around volcanoes, studies typically count the number of

130   people residing within concentric radial buffers of certain sizes around the volcanic vent (e.g.,

131   Small & Naumann, 2001; Ewert, 2007; Aspinall et al., 2011; Brown et al., 2017; Freire et al., 2019;

132   Nieto-Torres et al., 2021; Guimarães et al., 2021). For example, Freire et al. (2019) calculated total

133   populations living within 10, 30, 50, and 100-km radial buffers around active volcanoes between

134   1975 and 2015 CE. The concentric radial buffer size approach allows for a conservative estimate

135   of exposure at each volcano so that the cities can be compared and ranked, especially useful for

136   volcanoes without historical eruptions or high-resolution topography data (Biass et al., 2024). The

137   radius sizes of buffers around the volcanic vent used to calculate exposure are determined by the

138   maximum distances of primary volcanic hazards and the extents of potential Volcano Explosivity

139   Index (VEI) events. For instance, the emplacement of the majority of primary hazards in a VEI <4

140   eruption are within a 10-km radius around the volcano, including extents of ballistic projectiles

141   and most dome collapse pyroclastic density currents (PDCs) (Biass et al., 2024). A 30-km radius

142   generally represents the extent of the majority of VEI <5 eruption hazard extents, while a 100-km

143   radius signifies the extent of the majority of VEI <6 eruption hazard extents. However, larger

144   eruptions, secondary hazards, or eruptions occurring from fields or fissures beyond the vent might

145   extend beyond these maximum hazard distances. For example, shown by modelling of a VEI 5

146   scenario in Biass et al. (2024), tephra loads exceeding $1\,kg/m^2$ could extend as far as 600 km away.

147

148   These exposure counts can be assigned to specific indices for comparison across volcanoes. For

149   example, the Volcanic Population Index (VPI) estimates the number of people living within 5 and

150   10 km of volcanoes (Ewert & Harpel, 2004). Aspinall et al. (2011) developed this methodology to

151   assess populations within 10, 30, and 100 km of volcanoes. To calculate the Population Exposure

152   Index (PEI), the population counts are weighted according to evidence on historical distributions

153   of fatalities within a given distance from the vent and each volcano is assigned to one of seven PEI

154   indices (Brown et al., 2015). On a local or regional scale, past studies combined these population

155   counts with physical exposure (e.g., Etna volcano, Italy: Del Negro et al., 2022; Rainier volcano,

156   USA: Wood & Soulard, 2009) and/or hazard factors to understand localised volcanic threat (e.g.,

157   Ewert et al., 2018; Mangan et al., 2018; Nieto-Torres et al., 2021). Nieto-Torres et al. (2021)

158   developed a volcanic risk index considering 41 different factors related to hazards and exposure,

159   assessing population risks within distances of 5, 10, 30, and 100 km from volcanoes. Researchers

160   used various buffer sizes in ongoing efforts to accurately assess the risks that volcanic hazards

161   pose to total populations. No studies conducted exposure analysis based on population exposure

162   by urban type, such as city populations. In this study, we quantify and rank global cities exposed

163   to volcanoes situated within 10, 30, and 100 km of volcanoes.

164

165   3. Methods

166   We developed a framework designed to quantify, rank, and assess city exposure to volcanoes (see

167   Fig. 1 and Fig. 2). In this study, *exposed populations* refer to populations in cities within 100 km

168   (unless the distance is specified) from at least one volcano active in the Holocene, as explained in

169   Section 2.1. Below we detail how we prepared the city outlines, extracted populations, and ranked

170   the cities and volcanoes. The R code used to generate the results of this study is provided at:

171   https://github.com/vharg/VolcCities. The figures presented in this study focus on the top 10 cities

172 or volcanoes. We developed a web app to comprehensively present results of this study, including
173 the population exposure and maps of city polygons for all the cities with over 100,000 people
174 exposed, which is available at: https://vharg.github.io/shiny_VolcCities/.

175

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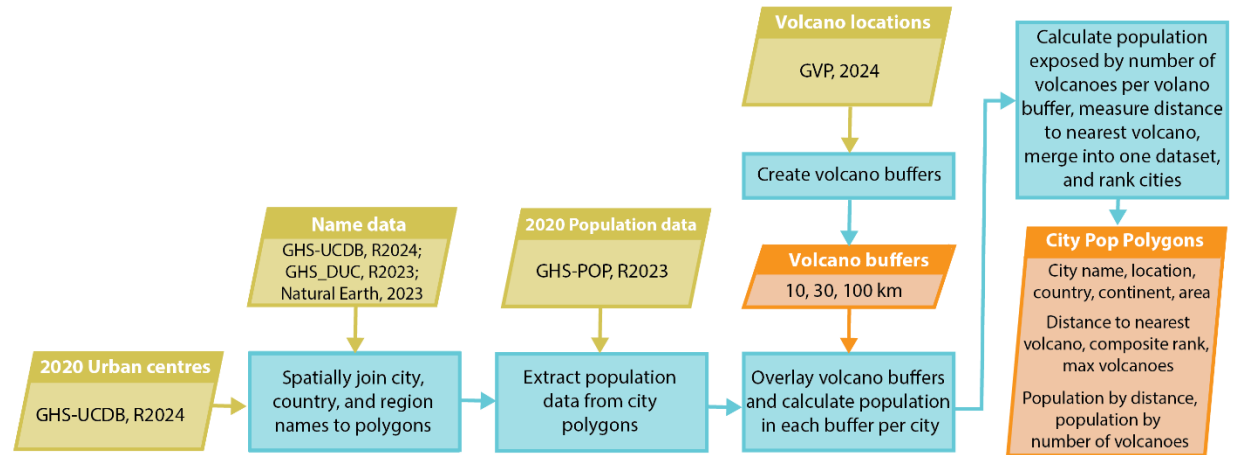
177

178 *Fig. 1: A flowchart of our framework to assess city exposure to volcanoes. Input datasets (yellow*
179 *rectangles) are fed into the GIS process (blue rectangles) to collate city polygons (left orange*
180 *rectangle) and attribute data, clipped by radial buffers (central orange rectangle), into the exposed*
181 *population polygon dataset (right orange rectangle). For the 2020 urban centres, the GHS-UCDB*
182 *(2024) dataset was used, and the spatially joined centroids of this dataset were used for names.*
183 *GHS_DUC (2023) Name_2 column was used for city names if they were not available. The cities*
184 *were ranked by the population size, the distance to nearest volcano, and the maximum number of*
185 *volcanoes exposed to, and the average of these was presented as the composite rank. The*
186 *volcanoes chosen are those active in the Holocene epoch. GVP stands for the Global Volcanism*
187 *Program and GHS stands for Global Human Settlement. The code used in this paper is provided*
188 *at: https://github.com/vharg/VolcCities*

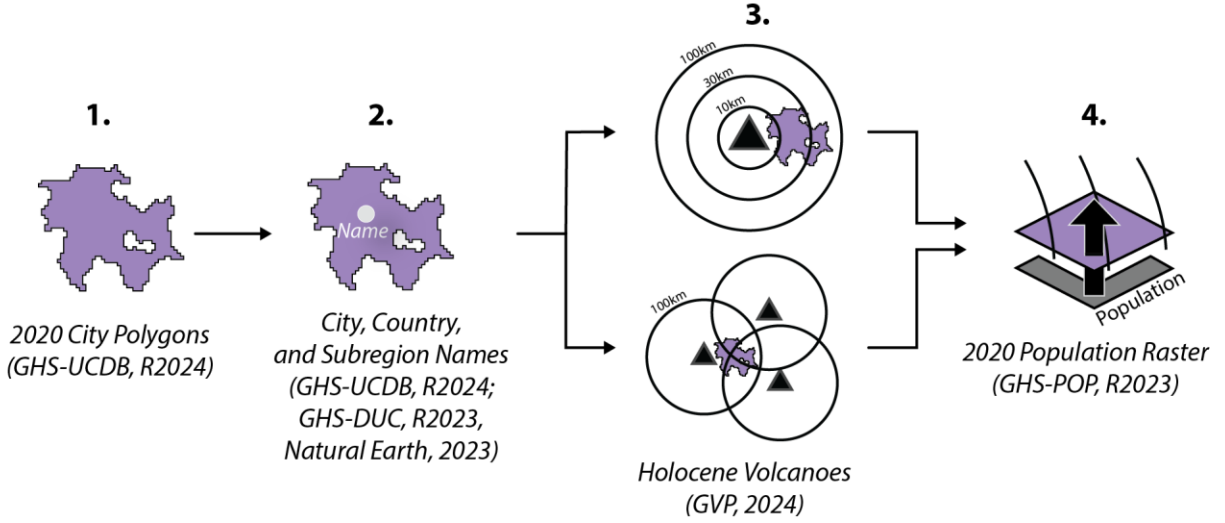



Fig. 2: *A schematic of our framework for assessing city exposure to volcanoes. The framework includes the following steps: 1) obtaining city polygons for 2020 from the GHS-UCDB (2024) urban centre polygons dataset, 2) joining city and country names from GHS-UCDB (2024) centroids, otherwise GHS_DUC polygons 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 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 coordinates and the areas of the *city polygons*.

211   We selected only those polygons that had all or part of their area within 100 km of a volcano

212   resulting in 1,154 polygons. Volcano locations in this study were based on coordinates from the

213   1,264 Holocene Volcano List from the Volcanoes of the World (VOTW) v 5.2.7 database (Global

214   Volcanism Program, 2024). Coordinates of the Holocene volcanoes in the database are positioned

215   either at the summit for volcanoes with a distinct primary edifice, or close to known vents. For

216   volcanic fields with multiple vents, the database presents the most prominent or active vent, most

217   recently erupting vent, or centre of the volcanic field, depending on information availability. Using

218   a single point to represent distributed volcanism introduces uncertainty, as the precise location of

219   future eruptions is unknown.

220

221   The *city polygons* generated from the raster lacked attribute data, therefore, we spatially joined

222   each polygon with the city and country names of the 2025 projected *city polygons* from the 2024

223   release of the Global Human Settlement Layer - Settlement Model, Urban Centre Database (GHS-

224   UCDB; Marí Rivero et al., 2024). The spatial join was based on the overlap of the centroids with

225   the *city polygons*. For the 30 cities that did not have city names (as they are not in the 2025 dataset),

226   we spatially joined the *city polygons* to the 2023 release of the GHS Degree of Urbanisation

227   Classification (GHS-DUC; Schiavina et al., 2023a) polygons dataset and selected the name from

228   the Name_2 column, and for one case, the Name_1 column as Name_2 was empty. For the 35

229   cities that did not have any country names, these were added from the spatially joined GHS_DUC

230   dataset. The spatial join was based on the location of the *city polygons'* centroids. For the

231   subregions, we spatially joined the *city polygons* to the Natural Earth (2023) country polygons and

232   selected the subregions, based on the location of the nearest polygon. This dataset was chosen as

233   there were more subregions included than the GHS-UCDB dataset. We then grouped the *city*

234   *polygons* by city name in each country, resulting in a dataset of 1,133 cities.

235

236   We made other calculations for the other columns in the dataset shown in Table 1, we included the

237   *city polygon* centroid coordinates based on the largest polygon, calculated the *city polygon* area

238   (km^2), and measured the shortest distance (km) of the *city polygon* margin that lies closest to the

239   nearest volcano. To calculate the total population of the city, we extracted the 2020 population

240   from Global Human Settlement Layer - Population (GHS-POP; Schiavina et al., 2023b) 100-m

241   population rasters within each of the *city polygons* using the *exactextract* function in R (Levine,

242 2022). This population dataset is in the World Mollweide (EPSG:54009) projection and we did

243 not reproject it.

244

245 ***Table 1:*** *The results collated in this study are set out in a dataset with the columns named as in*

246 *this table. One row represents one city.*

Column Name		
Total city polygon	Name	
	Centroid coordinates	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
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+

247

248

249 3.2 Ranking cities

250 Using the volcano location coordinates as the centroids we created 10, 30, and 100-km radial

251 buffers around each volcano, as these are commonly used to assess volcanic exposure based on

252 typical maximum distances of primary volcanic hazards (Ewert, 2007; Brown et al., 2017; Biass

253 et al., 2024). From here, these will be referred to as *volcano buffers*.

254

255   We clipped the *city polygons* by each of the three 10, 30, and 100-km radial *volcano buffers* and

256   merged these together to create a map of the city classified by distance to a volcano. This means

257   that parts of the city, or specific proportions, fall into one of the distance categories: <10 km, 10–

258   30 km, 30–100 km, or >100 km from a volcano. We extracted the population using the method

259   shown in 3.1 and where the volcano buffer partially covers a population raster pixel, this function

260   extracts the population number based on the proportion of pixel covered. We then merged and

261   pivoted the dataset so that it resulted in the population in each *volcano buffer* for each city (Table

262   1). For each *volcano buffer* we ranked the cities by the total populations exposed.

263

264   We also ranked cities by how many volcanoes each city's population is exposed to. We overlaid

265   the 100-km *volcano buffers* and calculated the number of buffers that were in contact with each

266   *city polygon*. By intersecting the overlaid buffers by the *city polygons*, we created a map where the

267   areas within the city are classified by the number of volcanoes it is exposed to. From this map, we

268   then extracted the population, so that, for each city, the numbers of people exposed to numbers of

269   volcanoes is known (Table 1). This was repeated for the 30-km and 10-km *volcano buffers*. In

270   separate columns we entered the maximum number of volcanoes that the city is exposed to (within

271   100 km) and ranked the cities by this amount. This means that the maximum number of volcanoes

272   the city is exposed to relates to the total number of 100-km *volcano buffers* in contact with the *city*

273   *polygon*.

274

275   Finally, we calculated a composite ranking for each city, summing the three rankings of distance

276   to nearest volcano, population <100 km, and number of volcanoes <100 km, and dividing by three

277   to create a final ranking of cities. This assumes the same weighting for each ranking.

278

279   3.3 Ranking volcanoes

280

281   In a separate dataset shown in Table 2, for each volcano, we recorded the volcano name, name,

282   vent coordinates, and country from the Global Volcanism Program (2023) Holocene Volcano List.

283   We also calculated the distance of the vent location to the nearest *city polygon*. For each *volcano*

284   *buffer* of each volcano, we calculated the total populations located within each *volcano buffer* and

285   *city polygons* using the extraction method detailed in 3.1. We then ranked the volcanoes by the

286   total city populations within 100 km of the volcano. We also calculated the total number of *city*

287   *polygons* within each *volcano buffer* for each volcano and ranked the volcanoes by the total number

288   of cities within 100 km of the volcano. Finally, we calculated a composite ranking for each

289   volcano, summing the three rankings of total population <100 km, number of cities <100 km, and

290   distance to nearest city, and dividing by three to create a final ranking of volcanoes. This assumes

291   the same weighting for each ranking.

292

293   ***Table 2:*** *The results collated in this study are set out in a dataset with the columns named as in*

294   *this table. One row represents one city.*

Column Name		
Volcano	Volcano Name	
	Vent coordinates	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

295

296   4. Results

297   We present our results in two parts, firstly we present the rankings for cities and volcanoes within

298   each of the 10, 30, and 100-km *volcano buffers*, and secondly, we present regional trends in the

299   city exposure. Cities were ranked based on: a) the total exposed city population to one or more

300   volcanoes, b) the number of volcanoes the city is exposed to, and c) the distance to nearest volcano.

301   Volcanoes were ranked based on: a) the total exposed city population, b) the number of cities

302   exposed, and c) the distance to the nearest city. Here, we define an exposed city population as the

303   population of cities located within 100 km of a volcano. In the following section, we explore the

304   quantification and ranking of these city populations and volcanoes, detailing spatial trends in city

305   exposure. We also explore regional trends in city exposures. The results for all our exposure

306   analyses are presented in Section 9.

307

4.1 Quantifying and ranking city exposure to volcanoes

Globally, 1,133 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, ~431 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 ~21 % of the total population of cities globally (n= 2,022,199,789). 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	94	13,182,876
30	381	118,852,034
100	1,133	430,696,763

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, almost the entire populations are exposed to at least one volcano (Jakarta: Salak, Perbakti-Gagak; Manila: San Pablo Volcanic Field, Taal; Mexico City: Iztaccihuatl, Chichinautzin Volcanic Field, Popocatepetl), except for Tokyo and Seoul where parts of the cities are not exposed to any volcanoes (farther than 100 km; see Fig. A3 in the Appendix). These top five cities represent ~28 % (~121 million) of the total exposed city populations (~431 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).

334

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 (~11 %), with most
(~78 %) 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=46,494,144)
and 30 km (n=15,456,793). 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 to nearby volcanoes.

City Rankings						Volcano Rankings					
Rank	City Name	Population exposed rank	Number of volcanoes rank	Distance to nearest volcano rank	Average of ranks	Rank	Volcano Name	Population exposed rank	Number of cities exposed rank	Distance to nearest city	Average of ranks
1	Bandung, Indonesia	8	30	11	16.33	1	Tangkuban Parahu, Indonesia	4	22	11	12.33
2	Jakarta, Indonesia	1	40	16	19	2	Tampomas, Indonesia	16	9	27	17.33
3	San Salvador, El Salvador	39	1	25	21.67	3	San Pablo V.F., Philippines	8	42	4	18
4	Quito, Ecuador	28	14	29	23.67	4	Guntur, Indonesia	19	11	26	18.67
5	Managua, Nicaragua	50	30	1	27	5	Talagabodas, Indonesia	23	6	34	21
6	Guatemala City, Guatemala	24	13	66	34.33	6	Ciremai, Indonesia	18	4	42	21.33
7	Tokyo, Japan	2	56	65	41	7	Penanggungan, Indonesia	27	9	28	21.33
8	Tarogong, Indonesia	47	56	28	43.67	8	Patuha, Indonesia	10	42	15	22.33
9	Surabaya, Indonesia	9	104	23	45.33	9	Sundoro, Indonesia	33	5	33	23.67
10	Tasikmalaya, Indonesia	25	75	39	46.33	10	Galunggung, Indonesia	24	11	49	28
11	Kuningan, Indonesia	85	75	37	65.67	11	Papandayan, Indonesia	25	27	35	29
12	Bishoftu, Ethiopia	154	56	3	71	12	Kendang, Indonesia	22	27	39	29.33
13	Malang, Indonesia	34	104	78	72	13	Arjuno-Welirang, Indonesia	29	11	52	30.67
14	Adama, Ethiopia	100	40	88	76	14	Bishoftu V.F., Ethiopia	50	51	3	34.67
15	Cirebon, Indonesia	40	75	129	81.33	15	Sumbing, Indonesia	30	11	65	35.33

351

352 ***Fig. 3:*** *Top 15 composite rankings of city exposure to volcanic hazards and their score within the*
353 *different ranks. For cities these are based on three different ranks: a) the total city population*
354 *exposed to one or more volcanoes within 100 km of volcanoes, b) the number of volcanoes the city*
355 *is exposed to, c) the distance to nearest volcano. For volcanoes, these rankings are based on three*
356 *different ranks: a) the total exposed city population within 100 km, b) the number of cities exposed,*
357 *c) the distance of the volcano to the nearest city. The cells are coloured by the ranking position*
358 *within the column, with darker red as a higher ranking. The cities and volcanoes are ordered by*
359 *the average of three rankings. V.F. stands for Volcanic Field.*

360

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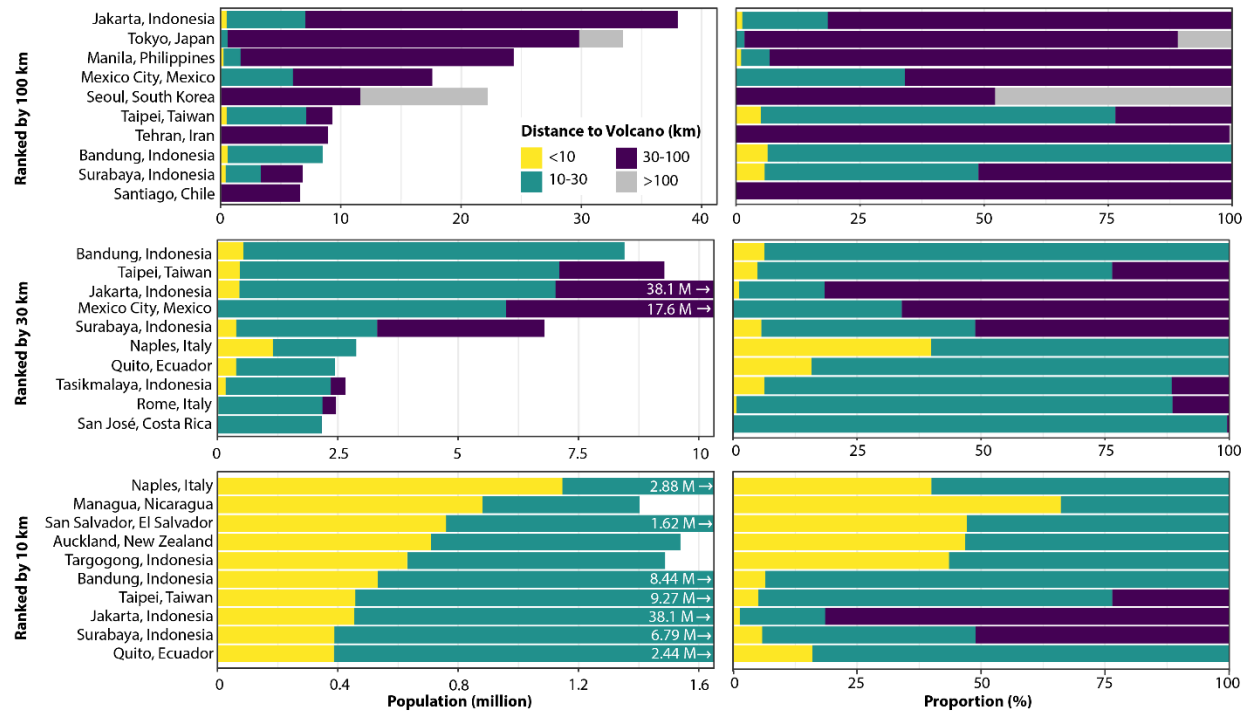
363 ***Fig. 4:*** *Horizontal stacked bar charts of city population (left) and proportion (right) of each city*
364 *classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-*
365 *km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers.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

368

369 Fig. 4 shows city rankings of populations by distances to their *nearest* volcanoes, with 94 cities
370 having their city margins within 10 km from a volcano. However, ~67 % of cities with populations

371 within 100 km of volcanoes (n=615) are exposed to more than one volcano. Fig. 5 presents the top

372 20 ranking of cities by exposed populations, classified by the number of volcanoes the city is

373 exposed to. The Fig. shows that portions of the populations of Tokyo, Japan; Seoul, South Korea;

374 and Nagoya, Japan, are not exposed to any volcanoes, but these cities still rank within the top 20

375 exposed cities (Fig. 5). Interestingly, not all the largest exposed populations are exposed to

376 multiple volcanoes, such as Seoul, South Korea; Tehran, Iran; Barcelona, Spain; Antananarivo,

377 Madagascar; and Athens, Greece, which have populations exposed to only one volcano. The top

378 four cities with exposed populations have much larger populations compared to the others, with

379 millions more residents. In contrast, the differences in exposed populations among the remaining

380 cities exhibit a more gradual increase, illustrated in Fig. 5 and for mid-sized cities (populations

381 under 1 million) in the Appendix (Fig. A4).

382

383 Most of the cities exposed to multiple volcanoes are in Central America, populations in

384 Quezaltepeque, El Salvador is exposed to the highest number of volcanoes (n=23), and San

385 Salvador, El Salvador is the city with >1 million people exposed to the highest number of

386 volcanoes (n=23) (Fig. 6). Although San Salvador is ranked 39th by population within 100 km, it

387 is third in the composite ranking behind Bandung and Jakarta, due to its high ranking of the number

388 of volcanoes (Fig. 3). Despite this proximity of cities to multiple volcanoes, there is the same

389 ranking of the top 10 cities when ranked by the people exposed to the nearest volcano, and those

390 exposed to at least one volcano. Bandung ranks highly for both the maximum number of volcanoes

391 to which the city is exposed, and the number of people exposed, with exposed populations within

392 100 km of between 9 and 12 volcanoes, with the most, ~4 million, exposed to 10 volcanoes (Fig.

393 6).

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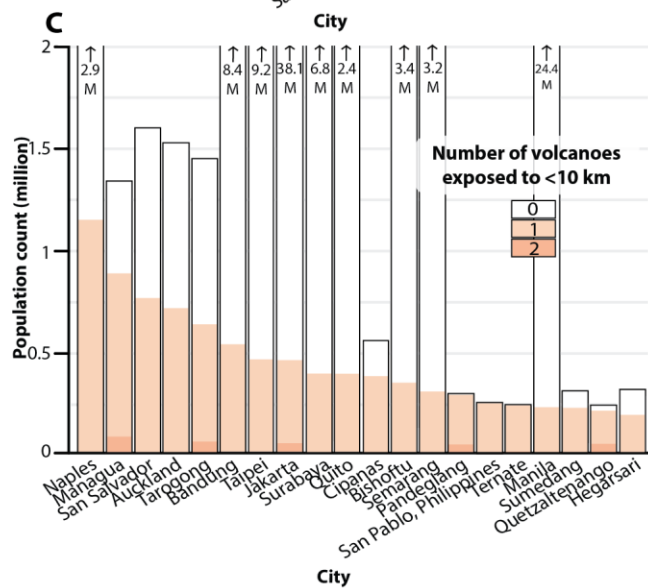
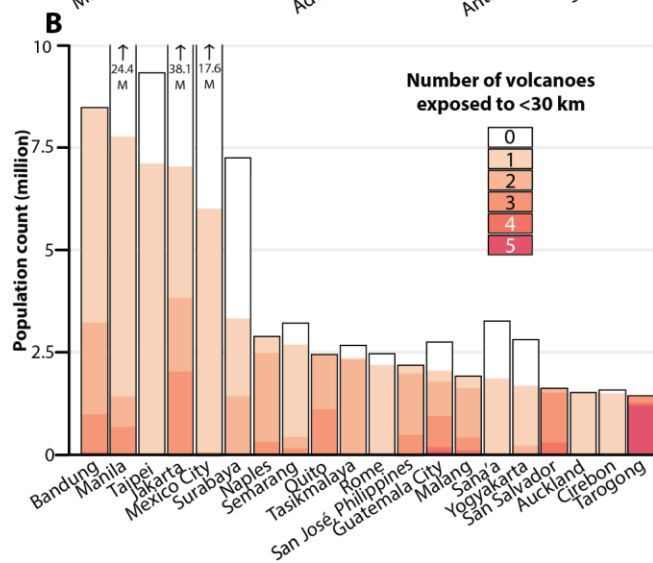
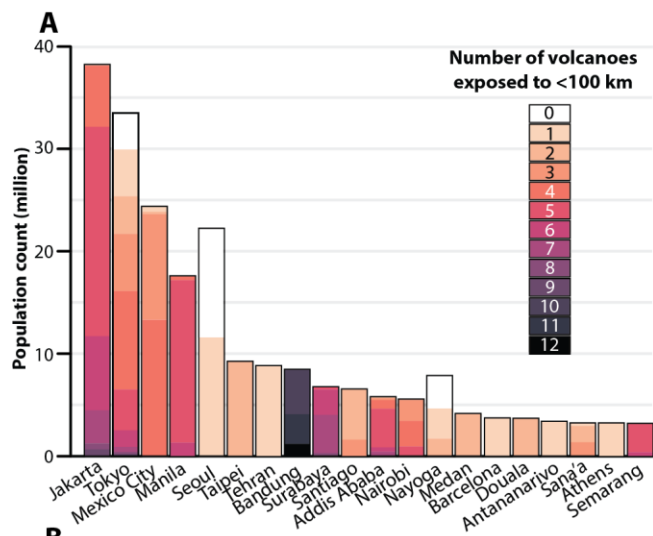


Fig. 5: Stacked bar charts of city population exposure for the top 20 cities coloured by the number of volcanoes the populations are exposed to, within A) 100-km, B) 30-km, and C) 10-km volcano buffers.

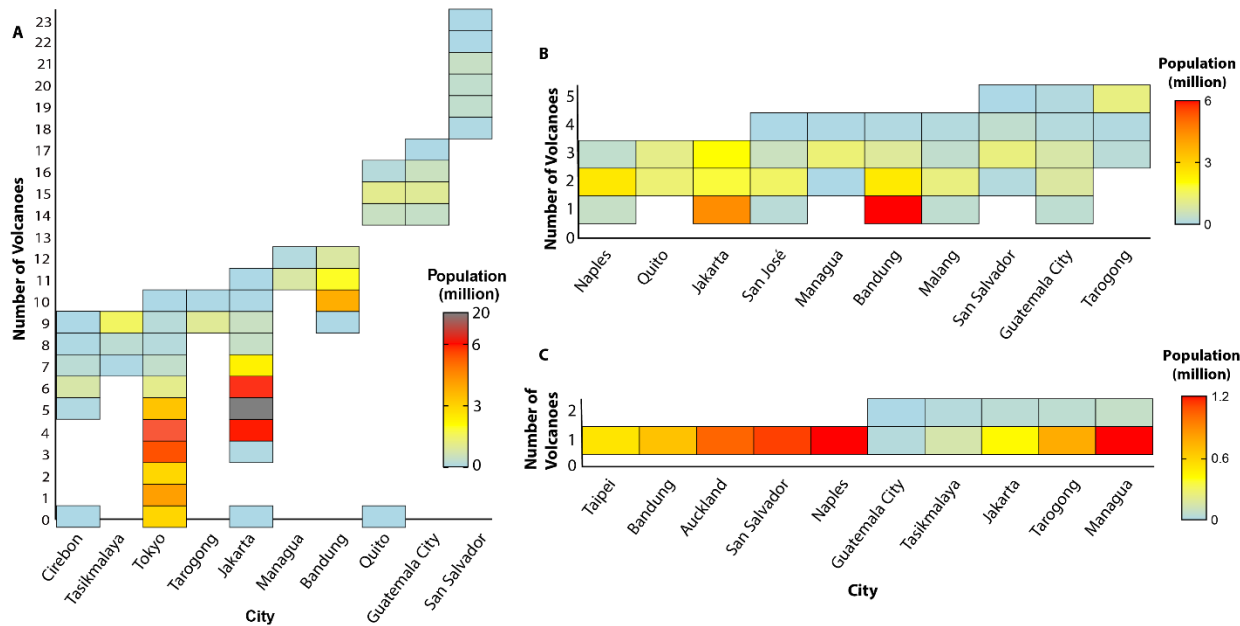



Fig. 6: Heatmap for the top 10 cities with total populations of over 1 million ranked by exposure to number of volcanoes, showing the city population exposed to increasing numbers of volcanoes for A) 100-km, B) 30-km, and C) 10-km volcano buffers.

4.2 Ranking volcanoes by city exposure

Almost 46 % of Holocene volcanoes (n=578) have city populations located within 100 km of their assumed vents. Indonesia dominates the rankings for city populations within 100 km of volcanoes. Six, eight, and three of the top 10 volcanoes within the 100-km, 30-km and 10-km buffers, respectively, are in Indonesia. Among the 578 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 volcanoes with cities within 100 km, up to 9 % 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 Volcanic Field and San Salvador have almost 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=96) of cities close to volcanoes, and the greatest number of cities within the country (n=18) have the Northern Lake Abaya Volcanic Field 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).

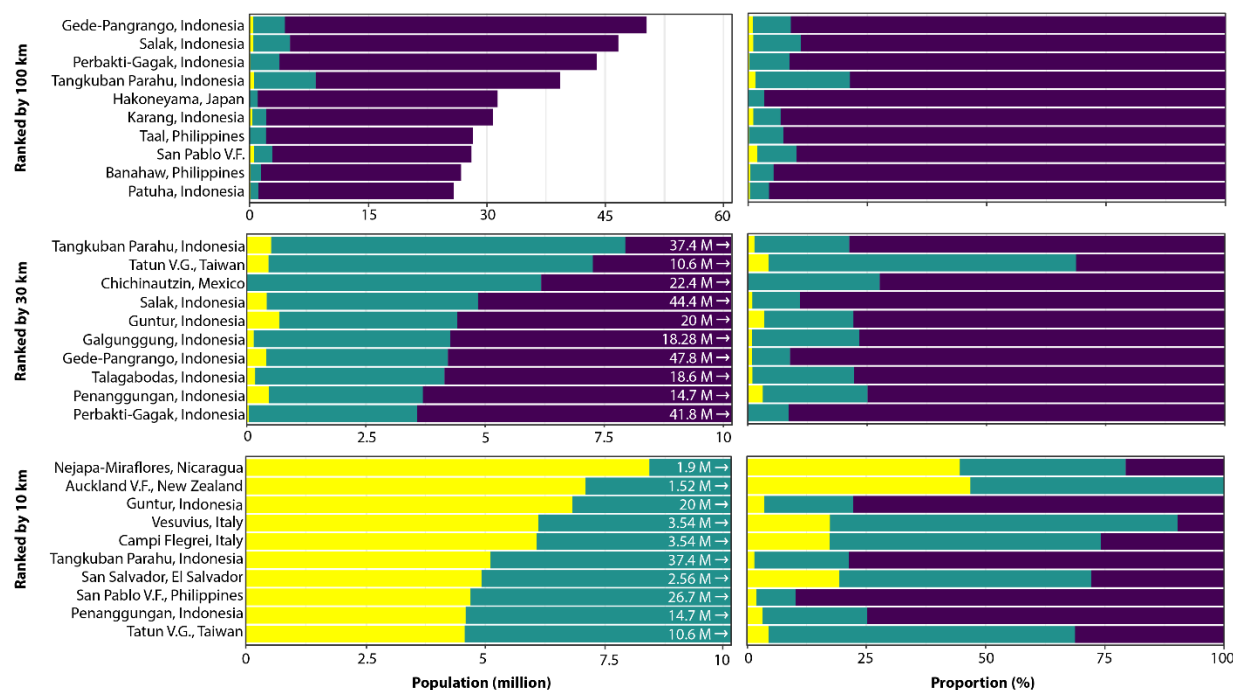



Fig. 7: *Horizontal stacked bar charts of city population (left) and proportion (right) around each volcano, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. Each*

434   *bar represents a volcano, and the x axis limits (left) reflect the population range for that volcano*

435   *buffer.*

436

437   4.4 Regional trends in city exposure to volcanoes

438

439   The largest amount of people living in cities exposed to at least one volcano are in South-East

440   Asia, with 5,847,751; 52,621,515; and 160,870,875 people living within 10, 30, and 100 km of a

441   volcano, respectively (Fig. 8A). However, the highest proportion of city populations exposed to

442   volcanoes are in Central America (Fig. 8B) where approximately 57 %, 27 % and 3 % of city

443   populations are located within 100 km, 30 km, and 10 km, respectively, of at least one volcano. In

444   Australia and New Zealand, and Europe, subregions there are the least number of people exposed,

445   with 1,660,474 and 22,077,280, respectively, within 100 km. City populations in the subregions

446   of Australia and New Zealand, and Europe, are also exposed to fewer volcanoes than the other

447   continents, with more than 10 % of the exposed populations exposed to one or two volcanoes (Fig.

448   8B). However, 4 % of the total city population of Australia and New Zealand lies within 10 km of

449   at least one volcano, the highest proportion of any subregion (Fig. 8).

450

451   Indonesia stands out globally for having the greatest number of cities and residents located in

452   proximity to volcanoes, with the largest populations within 10, 30, and 100 km of at least one

453   volcano (Fig. 9). Japan ranked second for the 100-km *volcano buffer* but ranks sixth and thirteenth

454   for the 30-km and 10-km *volcano buffers* as a high proportion of the city population are living

455   within 30 and 100 km of volcanoes. This is also the case for South Korea, Iran, and Chile, with

456   high numbers of people living within 30 and 100 km of volcanoes compared to <30 km.

457   Meanwhile, the Philippines, ranked third for the 100-km buffer, has a high proportion of its city

458   populations residing within all three distances, meaning that it ranks highly for all three buffer

459   sizes. For the 33 % of city populations exposed in East Africa (Fig. 8), these are dominated by

460   Ethiopia and Yemen (Fig. 9), where the cities are not reflected in the top city rankings of Fig. 4 as

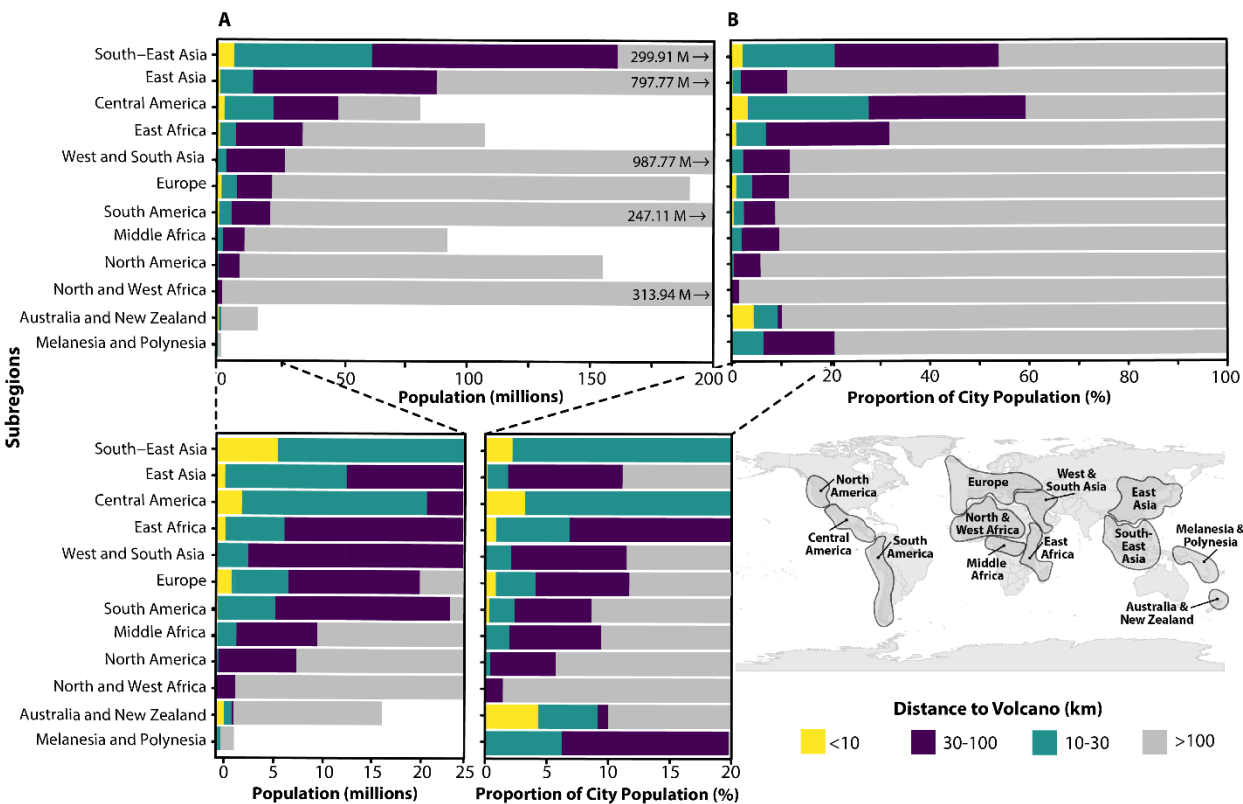
461   the city populations are split across multiple smaller cities. Ethiopia has almost 100 cities exposed,

462   and Yemen has almost 60 cities exposed to volcanoes (see Fig. A1 in the Appendix). Remarkably,

463   El Salvador presents a unique case for the top 10 ranked cities, where the entirety of its population

464 lives within 30 km of at least one volcano. Both Nicaragua and El Salvador have over 40 % of

465 their city populations living within 10 km of at least one volcano.

466

467 *Fig. 8: The exposed city population (A) and proportion of total city population (B) split by*

468 *subregion and classified by the distance of the population to nearest volcano. The subregions are*

469 *highlighted on the bottom right schematic map showing an approximate location of where the*

470 *cities are located. Note that cities in French Polynesia are included in Melanesia and Polynesia,*

471 *and Réunion, Martinique, and Mayotte Islands, and Kamchatka, are included in Europe.*

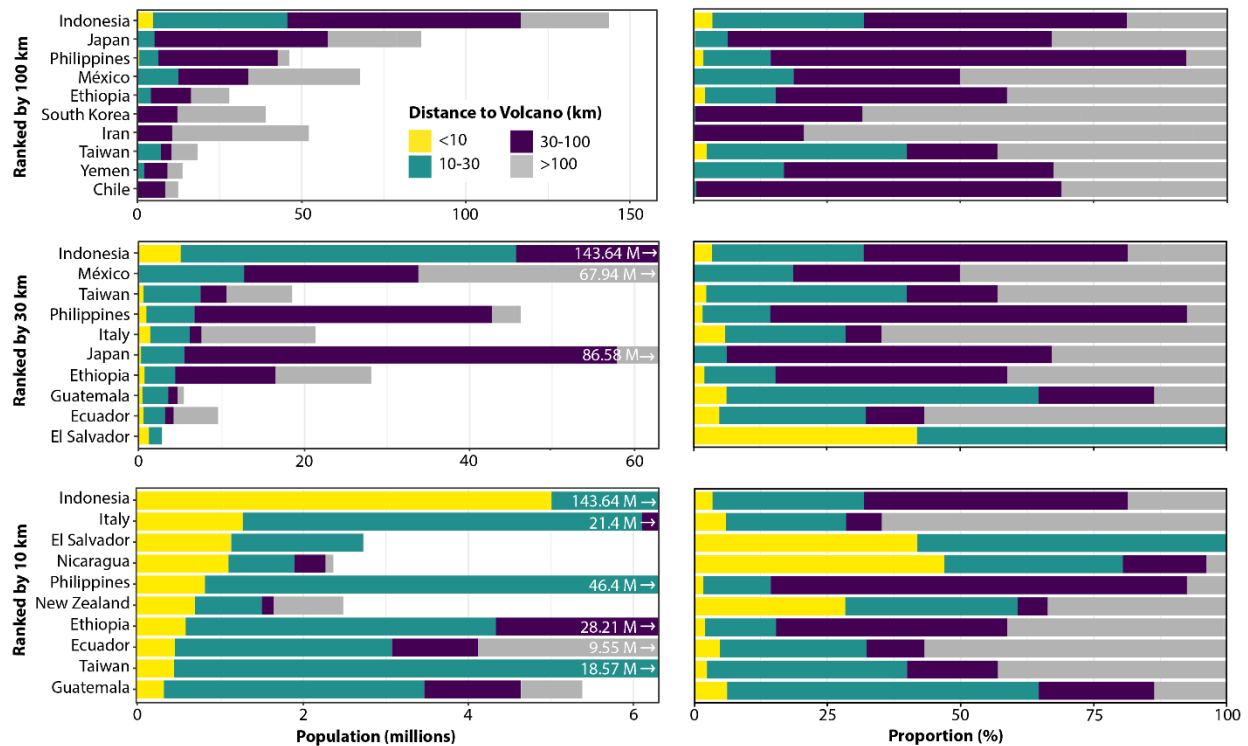



Fig. 9: *Horizontal stacked bar charts of city population (left) and proportion (right) around each volcano, grouped by country, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. 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 data was ~ 16 million and ~ 5 million higher, respectively. In this study, 575 cities exposed to volcanoes have populations greater than 100,000 people, a substantial increase from the 67 cities documented by Heiken (2013). We

490   identify Jakarta, Tokyo, and Manila, as having the highest exposure within 100 km of volcanoes.

491   These large cities have high proportions of people living between 30 and 100 km from the nearest

492   volcano and population spread across the three *volcano buffers* (Fig. 4; Table 4), highlighting the

493   potential for variable impacts. Jenkins et al. (2018) also identified these three cities as having the

494   greatest tephra fall hazard and risk in Asia, when wind conditions, eruption characteristics, and

495   tephra transport were accounted for. Jakarta is highlighted as the largest city exposed to volcanoes

496   in Pelling (2012) and Blaikie (1994). However, Heiken (2013) identifies Tokyo, Manila, and

497   Mexico City as the only megacities exposed to volcanoes. Jakarta is not selected as an example by

498   Heiken (2013), Auker et al. (2013), or Chester et al. (2000). This may be due to potential

499   differences in criteria used in assessing exposure.

500

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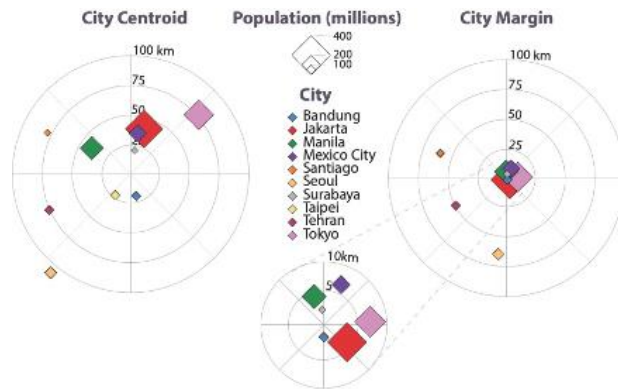
502   ***Fig. 10:*** *Polar chart to show the top 10 cities with the most exposed city populations within 100*

503   *km of the nearest volcano. The city centroids (left) and nearest city margin to the volcano (right)*

504   *are plotted as diamonds relative to the nearest volcano (centre of the plots), and the diamond size*

505   *refers to the size of the population exposed. The centroid of Seoul is located outside of the 100-km*

506   *radial buffer, but the population within the 100 km is high enough to rank the city in the top 10*

507   *exposed.*

508

509   Identifying an exposed city by its centroid alone is not an ideal representation of city exposure as

510   it does not capture the spatial extent (sprawl) of a city, or changes in population density across the

511   city. City margins are closer to volcanoes than the centroids (Fig. 10). Some cities have higher

512   population densities closer to volcanoes despite having greater areas of the city farther away (Table

513   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=11,607,675),
and some of the most densely populated parts of the city (~11,362 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 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	457,807	**6,633,853**	2,181,179	64	512	374	7,116	**12,965**	5,836
Jakarta, Indonesia	453,914	6,559,219	**31,037,351**	110	1,123	**3,258**	4,142	5,838	**9,520**
Surabaya, Indonesia	387,688	2,927,379	**3,471,151**	102	**769**	429	3,805	3,806	**8,088**
Manila, Philippines	220,952	1,399,747	**22,753,383**	48	215	**2,227**	4,636	**6,499**	629
Tasikmalaya, Indonesia	167,908	**2,182,277**	306,365	70	**403**	49	2,393	5,420	**6,246**
Guatemala City, Guatemala	23,943	**2,020,662**	694,688	6	**326**	120	3,705	**6,192**	5,776

Rome, Italy	16,698	**2,160,308**	279,120	5	**399**	63	3,206	**5,418**	4,430
Mexico City, Mexico	2,373	5,987,736	**11,607,299**	2	733	**1,391**	1,052	8,170	**8,348**
Tokyo, Japan	21	558,703	**29,275,558**	<1	170	**4,229**	290	3,284	**6,924**

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 terms 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

556 ranked low in our analysis in terms of exposure, but this could mask potential widespread indirect
557 impacts across the broader city (Mossler, 1996; Pelling, 2012). Understanding these wider effects
558 is crucial for assessing the full scope of urban vulnerability to volcanic hazards. Further localised
559 assessments and systematic risk evaluations are recommended to capture a more complete range
560 of potential impacts (Mossler, 1996; Pelling, 2012).

561

562 4.2   Volcano Rankings

563

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

577

578 Large city populations within 10 km of volcanoes, a distance reached by destructive proximal
579 hazards, can be affected by a smaller or moderate eruption at one of these volcanoes, which may
580 have greater direct impacts than a larger eruption where populations are located farther away. A
581 large proportion of these close populations are residing near volcanoes in Central and South
582 America, such as Managua, Nicaragua, San Salvador, El Salvador, and Quito, Ecuador (Fig. 4;
583 Fig. 9). Escobar et al. (2007) found that a high proportion of city populations in Central America
584 are living close to the most dangerous volcanoes in the region, something supported by our study
585 (Fig. 7). Ewert and Harpel (2004) highlight Central America as having potentially significant
586 exposure to volcanic hazards, with 2.7 million people (data from 2004 CE) within 10 km of

587   volcanoes living in both urban and rural areas. In our study, using 2020 city population data for
588   the same buffer distance, we find that a similar number (2.6 million) of people now live just within
589   urban (city) areas. The high proportions of urban populations close to volcanoes in Central and
590   South America (Fig. 9) is perhaps linked to the colonial past of the region, whereby investments
591   into agriculture in the early to mid-20th Century resulted in a growth of agricultural settlements
592   through time (Swyngedouw, 2006). Nejapa-Miraflores volcano, Nicaragua is one example of
593   where almost 1 million people, or 45 % of the exposed population, are located within 10 km of the
594   volcano. These populations are distributed over multiple cities, adding complexity to potential
595   eruption impacts and response strategies.

596

597   4.4 Future Research Directions

598

599   In this study, we define cities as those areas classified in the GHS-UCDB dataset as *urban centres,*
600   which excludes suburbs and regions of lower population densities. For example, the remaining
601   ~46 % (n=686) of volcanoes that do not have city populations within 100 km, may still be situated
602   near suburban or rural populations, or have tourists, not assessed in this study. The delineation
603   between urban, peri-urban, and rural areas is not always clear (Chen et al., 2018; Sorensen and
604   Labbé, 2020). Urban centres can sprawl into surrounding peri-urban and rural regions, and through
605   time, urban centres may merge together and densify. Therefore, total city populations may slightly
606   differ when using other datasets. If suburban and rural populations were also considered, the
607   ranking of volcanoes would likely change, as these areas may have higher exposure to volcanic
608   hazards. Past volcanic eruptions such as 1982 El Chichon eruption, Mexico, have primarily
609   affected rural communities rather than city centres. Our approach could be expanded or used to
610   explore more than just cities, by assessing changing land-use patterns, transient populations using
611   different population datasets (e.g., LandScan ambient population dataset: Lebakula et al., 2024),
612   or gradations of population density around volcanoes using different buffer distances. We can also
613   explore past trends in city population exposure through time, and future projections, to quantify
614   rates of exposure change. Mapping the urban sprawl of these cities allows us to identify key areas
615   around volcanoes to focus on future mitigation efforts and land-use planning. Further research is
616   needed to understand how the interconnectedness of cities and suburbs, influences impact.

617

618   Additionally, our 2020 dataset includes 137 cities exposed to volcanoes located in other countries,

619   underscoring the need for research in cross-border cooperation and planning to mitigate the

620   impacts of eruptions with transboundary effects (Donovan & Oppenheimer, 2019).

621

622   We used a comparative approach to quantify the hazard by using the distance to the nearest volcano

623   and the number of nearby volcanoes, which could be explored further. For example, the volcano

624   buffers used in this study relate to the average maximum distances of primary hazards. However,

625   our use of a 100-km radial buffer does not account for far-reaching volcanic flows or tephra falls

626   that may reach beyond 100 km (Biass et al., 2024) or cascading hazards that may extend beyond

627   this distance, such as tsunamis. Future studies could explore these cascading and widespread

628   impacts, in the key cities identified in this study, to capture potential losses.

629

630   The selection of the location of the volcanic crater as point coordinates provided by the Global

631   Volcanism Program (2023), does not account for the uncertainty in the next eruption site, for

632   example within volcanic fields or rift zones. Additionally, research could explore alternative

633   methods to the traditional volcano buffers, considering approaches that account for the spatial

634   variability of distributed volcanism, such as those used in Nieto-Torres et al. (2021), and of shield

635   volcanoes. Future work could classify volcanoes by probability of eruption, last eruption, VEI

636   range, or tectonic setting, to better understand the specific types of potential hazard they pose to

637   nearby cities. For example, the presence of multiple volcanoes within 100 km, as in San Salvador,

638   does not directly equate to higher hazard, as eruption probabilities vary. While our approach

639   identifies cities with high volcanic exposure, localised hazard assessments are essential for a more

640   precise evaluation of the threat (Biass et al., 2024; Jenkins et al., 2022; Diefenbach et al., 2015).

641   Future research can incorporate local topography, seasonal weather patterns, eruption frequencies,

642   and hazard probabilities as well as exposures beyond population, and the vulnerability of these to

643   the hazards to understand the specific risks faced by individual cities.

644   5 Conclusions

645   Cities close to volcanoes are at high risk of volcanic hazards. We present a framework to quantify

646   and rank global city population exposure. Although topography and weather can affect hazard

647   footprints, our method using concentric radial buffers conservatively estimates and compares city

648 exposure. Our results are provided at Section 9 and as a web application for visualisation of all

649 city exposures (https://vharg.github.io/shiny_VolcCities/). The rankings of 1,133 cities within 100

650 km of 578 Holocene volcanoes provide a foundation to identify areas for future detailed and

651 localised exposure or risk assessments, especially for cities with limited past hazard or exposure

652 data. Ranking cities by exposure also helps identify key locations for future research and land-use

653 planning.

654 We highlight Jakarta, Bandung, and San Salvador as scoring highly across these rankings. Jakarta,

655 Bandung, and Naples have the largest city populations within 100, 30, and 10 km, respectively, of

656 at least one volcano. San Salvador, Guatemala City, and Managua are cities of over 1 million

657 people that have the largest number of people exposed to the largest number of volcanoes within

658 100, 30 and 10 km respectively with 23, 6, and 2 volcanoes, respectively. We also ranked

659 volcanoes in three ways: by number of exposed city populations, by the number of nearby cities,

660 and the distance of the nearest city. We highlight Tangkuban Parahu, Tampomas, and San Pablo

661 Volcanic Field as scoring highly across these rankings. Gede-Pangrango, Tangkuban Parahu, and

662 Nejapa-Miraflores volcanoes have the largest number of city populations within 100, 30, and 10

663 km respectively. These rankings reveal hotspot cities with high populations exposed to multiple

664 volcanoes; for example, ~8.5 million people in Bandung are exposed within 100 km to 12

665 volcanoes.

666

667 Globally, 50 % of people exposed to volcanoes (within 100 km) live in cities. The size, number,

668 and distance of cities near volcanoes, or spread of population density across cities, create different

669 challenges regarding exposure to volcanoes. For example, Jakarta has high population density

670 between 30 – 100 km of volcanoes, while 39 smaller cities in Ethiopia are exposed to a single

671 volcano: Northern Lake Abaya Volcanic Field. Other cities, such as Auckland, are located on

672 volcanic fields. Some countries are highly exposed to volcanic hazards. For example, all cities in

673 El Salvador are located within 30 km of a volcano and in the Philippines, ~80 % of cities have

674 some part of the city located within 100 km of a volcano. Understanding these diverse exposures

675 is crucial for developing effective risk management strategies tailored to the specific needs of each

676 country.

677 These findings can inform decision-making and further research around volcanoes. This work
678 prompts more localised studies that overlay these exposures with probabilistic hazard maps which
679 can enhance our understanding of the dynamic risks surrounding volcanoes.

680 8 Appendix A

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682
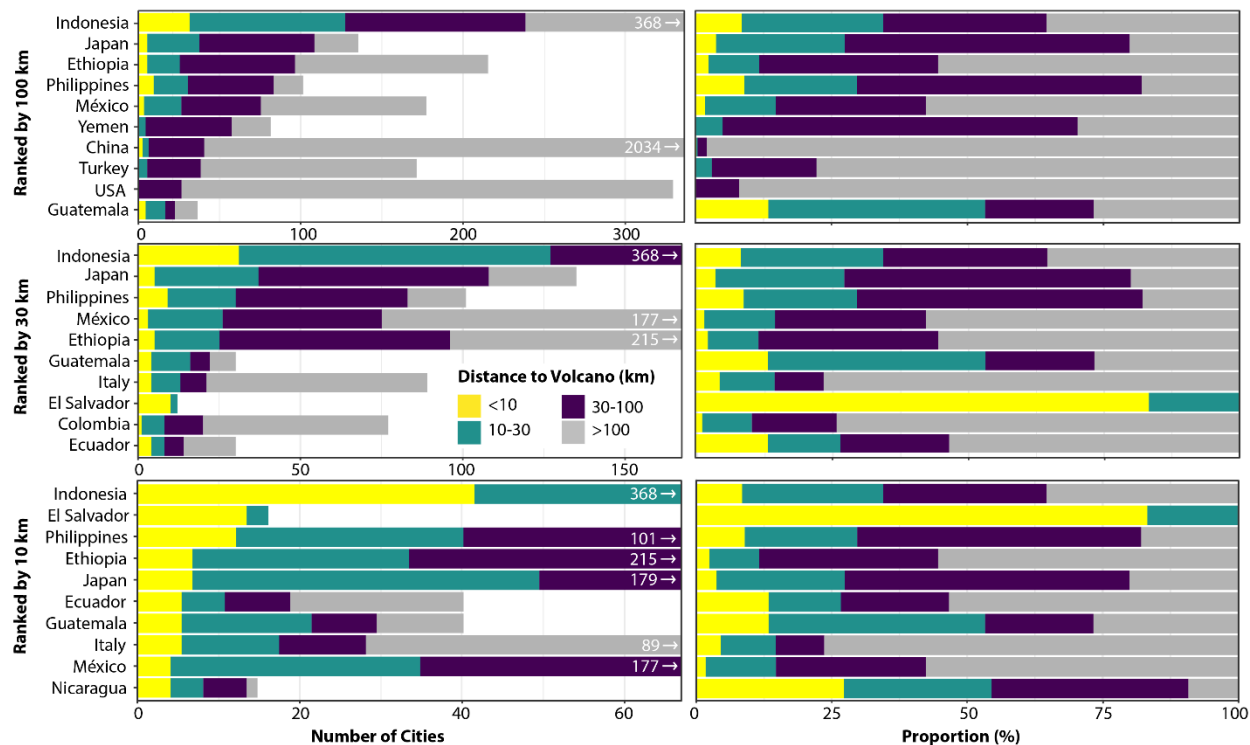
Fig. A1: Horizontal stacked bar charts of number of cities with populations within each buffer
distance (left) and proportion (right) around each volcano, grouped by country, classified by
distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances
from volcanoes), 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.

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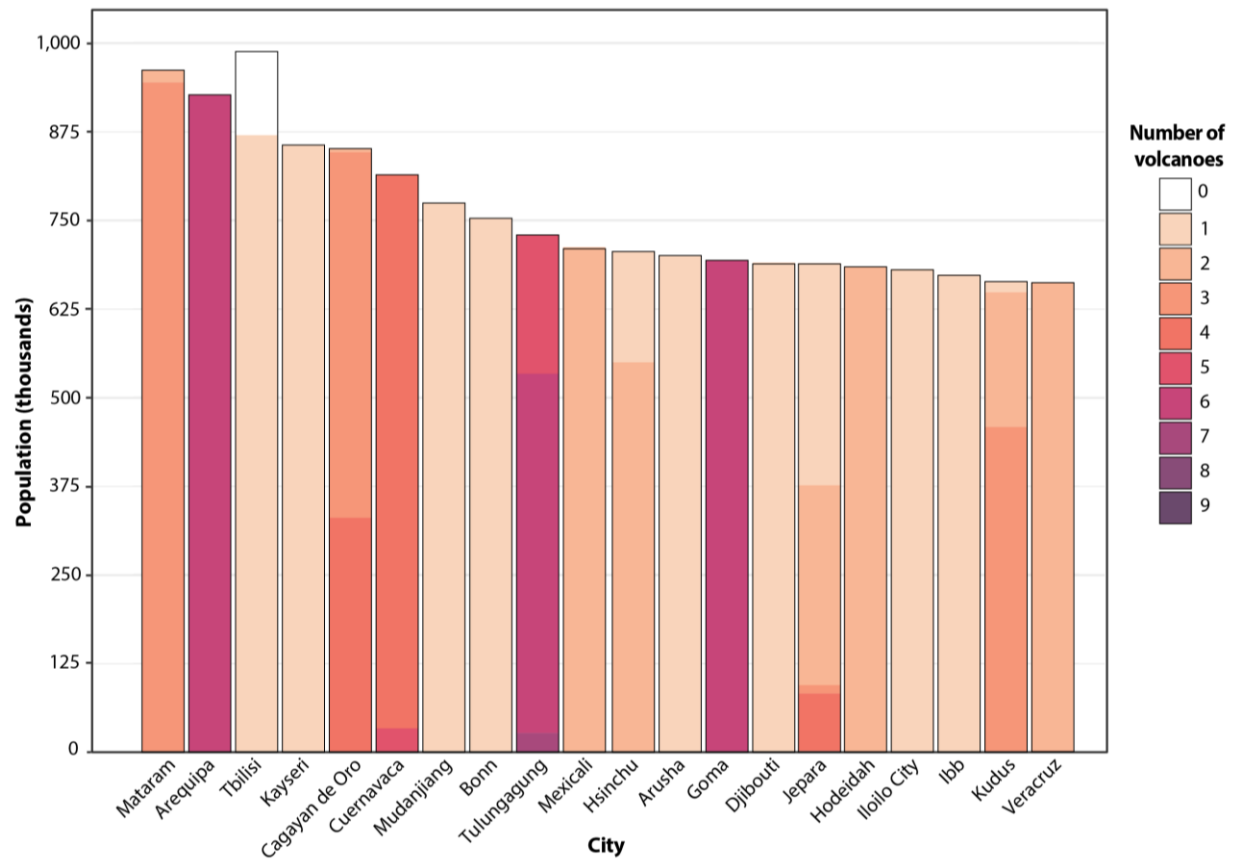
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692 *Fig. A2: Top 20 cities with exposed populations below one million, coloured by the number of*

693 *volcanoes for which the city lies within a 100 km radius.*

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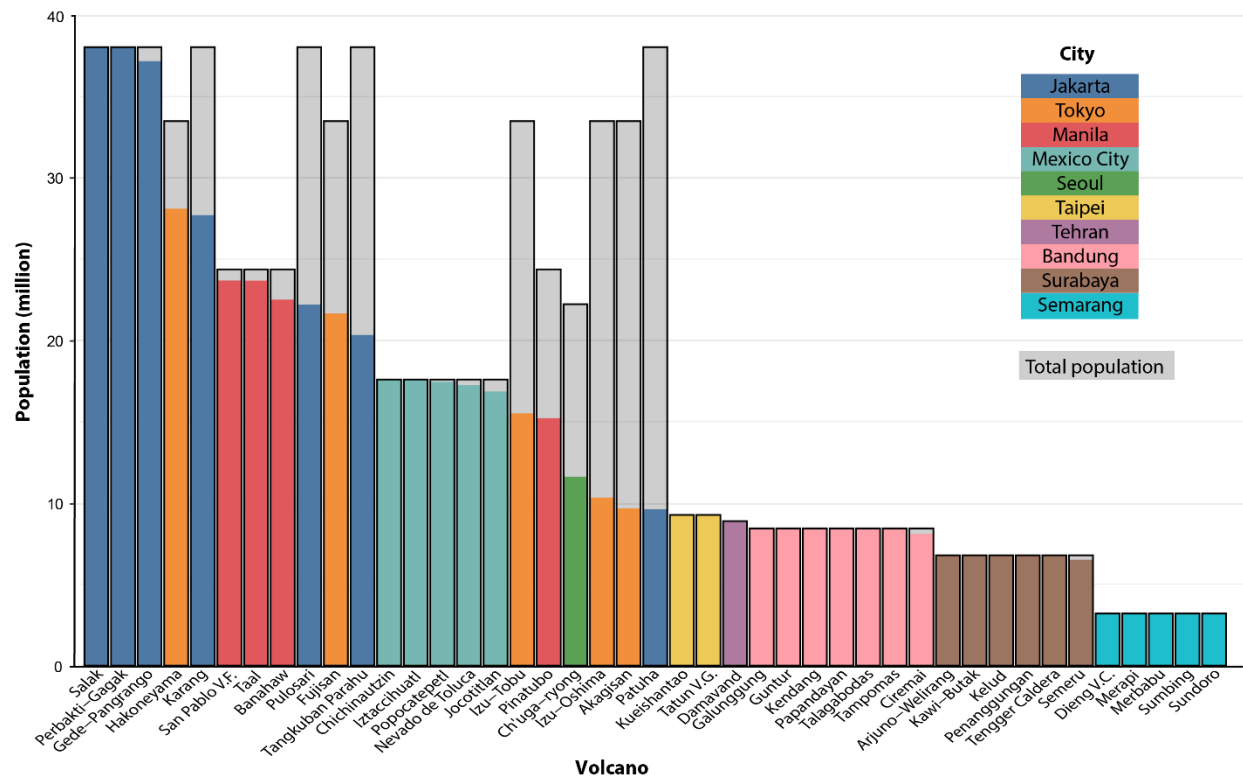
Fig. A3: City populations exposed to individual volcanoes within 100 km, ranked by the dominant city. Bars are coloured by the dominant city exposed population. V.F. stands for Volcanic Field, V.G. stands for Volcanic Group, and V.C. stands for Volcanic Complex.

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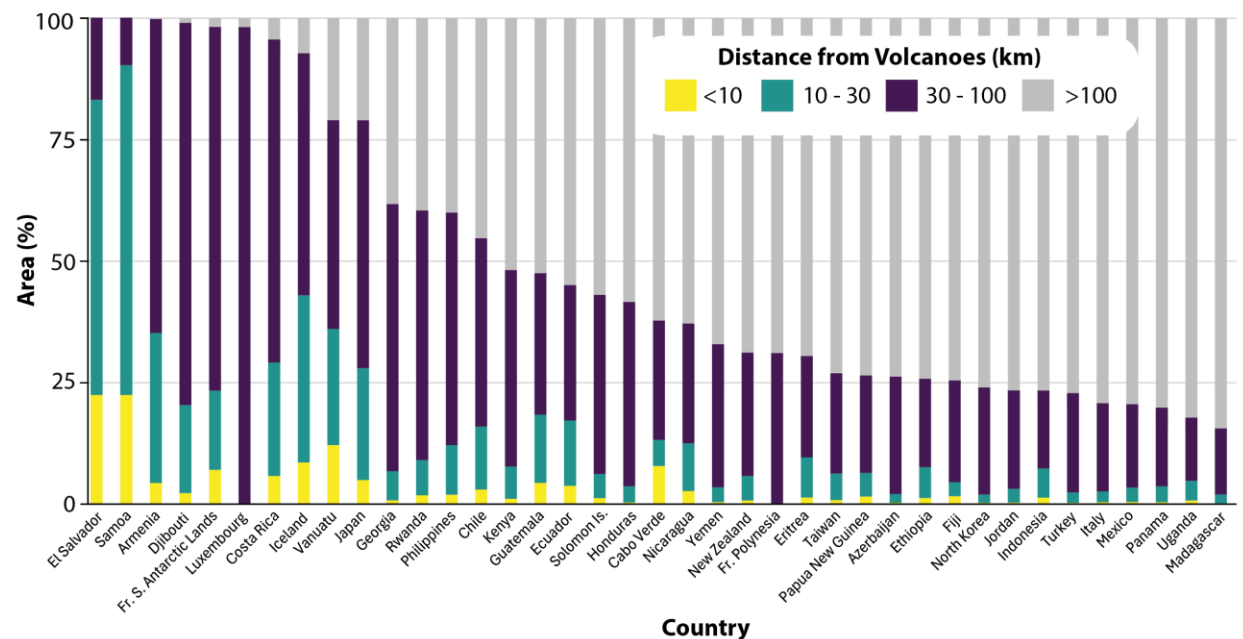
701 *Fig. A4: Top forty countries with a total area of >2,000 km² ranked in order of their total land*

702 *area exposed to volcanic hazards, and coloured by the percentage of area. Is stands for islands*

703 *and Fr stands for French. Land area from Natural Earth (2023)*

704 8 Code Availability

705 The R code used in this manuscript is available at: https://github.com/vharg/VolcCities
706

707 9 Data Availability

708 The web application presenting results for all cities is available

709 at https://vharg.github.io/shiny_VolcCities/

710 Ranking results of city exposure to volcanic hazards and volcanoes by exposed populations is

711 available at https://researchdata.ntu.edu.sg/privateurl.xhtml?token=65c3712c-461b-4d95-b499-

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714 10 Author Contribution

715 The project was conceptualised by ESM, RXNT, SJF and SB. The methodology was developed

716 by ESM and RXNT with support from SFJ, JLH, and SB. Visualisations were made by ESM and

717 the web app was developed by RXNT. The original draft was written by ESM. All authors

718 contributed to editing and reviewing the manuscript.

719 11 Competing Interests

720 The authors declare that they have no conflict of interest.
721

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730

731 13 References

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