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

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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 1,133 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 1,264 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, Tampomas, and San Pablo Volcanic Field score highly across these rankings. Notably, Gede-Pangrango (~48 million), Tangkuban Parahu (~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

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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,

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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., 20222023). 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 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 (UNUnited Nations, 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 (19942004) 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 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

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

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

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

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

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

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

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

147 scenario in Biass et al. (2024), tephra loads exceeding 1 km̶kg/m^2 could extend as far as 600 km

148 away.

149

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

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

152 10 km of volcanoes (Ewert & Harpel, 2004). Aspinall et al. (2011) developed this methodology to

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

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

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

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

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

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

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

160 developed a volcanic risk index for Central America considering 41 different factors related to

161 hazards and exposure, assessing population risks within distances of 5, 10, 30, and 100 km from

162 volcanoes. Researchers used various buffer sizes in ongoing efforts to accurately assess the risks

163 that volcanic hazards pose to total populations. No studies conducted exposure analysis based on

164 population exposure by urban type, such as city populations. In this study, we quantify and rank

165 global cities exposed to volcanoes situated within 10, 30, and 100 km of volcanoes.

166

167   3. Methods

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

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

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

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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~~figures 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~~vharg.github.io/~~ExposureOfCities~~shiny_VolcCities/.
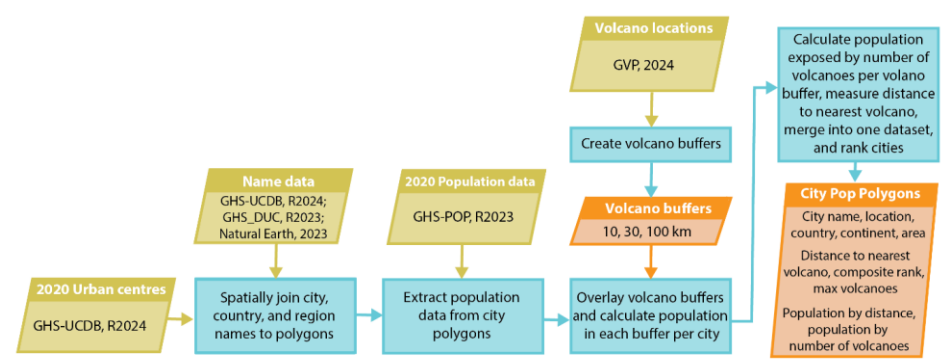
Fig. 1: A flowchart of our framework to assess city exposure to volcanoes. Input datasets (yellow rectangles) are fed into the GIS process (blue rectangles) to collate city polygons (left orange rectangle) and attribute data, clipped by radial buffers (central orange rectangle), into the exposed population 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
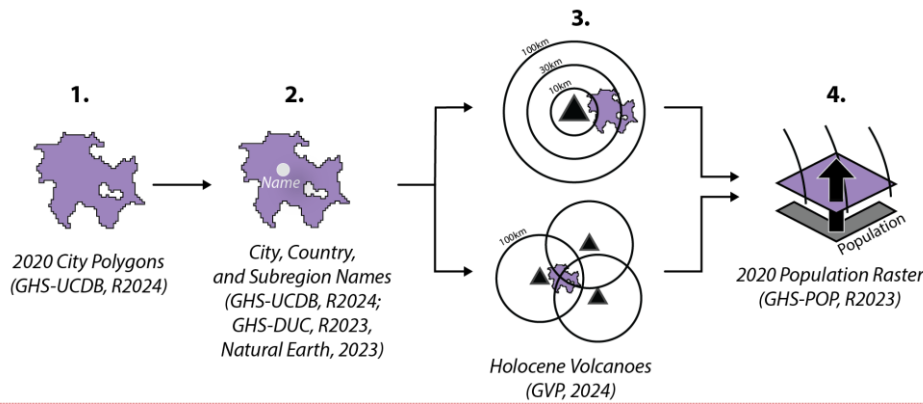
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Fig. 2: *A schematic of our framework for assessing city exposure to volcanoes. The framework includes the following steps: 1) obtaining city polygons for 2020 CE from the GHS-UCDB (2024) urban centre polygons dataset, 2) joining city and country names 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 $\geq$ 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 coordinates and the areas of the *city polygons*.

214

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

216 resulting in 1,~~158 *city*~~154 polygons. Volcano locations in this study were based on coordinates from

217 the 1,~~283~~264 Holocene Volcano List from the Volcanoes of the World (VOTW) ~~v4.11.1~~v 5.2.7

218 database (Global Volcanism Program, 2024). ~~Co-ordinates~~Coordinates of the Holocene volcanoes

219 in the database are positioned either at the summit for volcanoes with a distinct primary edifice, or

220 close to known vents. For volcanic fields with multiple vents, the database presents the most

221 prominent or active vent, most recently erupting vent, or centre of the volcanic field, depending

222 on information availability. ~~Only the 958 volcanoes that are located within 100 km of a *city polygon*~~

223 ~~are used within this study~~Using a single point to represent distributed volcanism introduces

224 uncertainty, as the precise location of future eruptions is unknown.

225

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

227 each polygon with the city and country names of the 2025 ~~CE~~ projected *city polygons* from the

228 2024 ~~CE~~ release of the Global Human Settlement Layer - Settlement Model, Urban Centre

229 Database (GHS-UCDB; Marí Rivero et al., 2024). The spatial join was based on the overlap of the

230 centroids with the *city polygons*. For the 30 cities that did not have city names (as they are not in

231 the 2025 ~~CE~~ dataset), we spatially joined the *city polygons* to the 2023 ~~CE~~ release of the GHS

232 Degree of Urbanisation Classification (GHS-DUC; Schiavina et al., 2023a) polygons dataset and

233 selected the name from the Name_2 column, and for one case, the Name_1 column as Name_2

234 was empty. For the 35 cities that did not have any country names, these were added from the

235 spatially joined GHS_DUC dataset. The spatial join was based on the location of the *city polygons'*

236 centroids. For the subregions, we spatially joined the *city polygons* to the Natural Earth (2023)

237 country polygons and selected the subregions, based on the location of the nearest polygon. This

238 dataset was chosen as there were more subregions included than the GHS-UCDB dataset. We then

239 grouped the *city polygons* by city name in each country, resulting in a dataset of 1,~~106~~133 cities.

240

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

242 *city polygon* centroid ~~co-ordinates~~coordinates based on the largest polygon, calculated the *city*

243 *polygon* area (km^2), and measured the shortest distance (km) of the *city polygon* margin that lies

244 closest to the nearest volcano. To calculate the total population of the city, we extracted the 2020

9

245 CE population from Global Human Settlement Layer - Population (GHS-POP; Schiavina et al.,

246 2023b) 100-m population rasters within each of the *city polygons* using the *exactextract* function

247 in R (Levine, 2022). This population dataset is in the World Mollweide (EPSG:54009) projection

248 and we did not reproject it.

249

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

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

Column Name		
Total city polygon	Name	
	Centroid co-ordinates 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+

252

253

254 3.2 Ranking cities

255 Using the volcano location co-ordinates coordinates as the centroids we created 10, 30, and 100-

256 km radial buffers around each volcano, as these are commonly used to assess volcanic exposure

257 based on typical maximum distances of primary volcanic hazards (Ewert, 2007; Brown et al., 2017;

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

10

259

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

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

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

263   30 km, 30–100 km, or >100 km from a volcano. We extracted the population using the method

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

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

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

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

268

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

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

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

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

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

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

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

276   100 km) and ranked the cities by this amount. This means that the maximum number of volcanoes

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

278   *polygon*.

279

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

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

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

283

284   3.3 Ranking volcanoes

285

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

287   vent ~~co-ordinates~~coordinates, and country from the Global Volcanism Program (2023) Holocene

288   Volcano List. We also calculated the distance of the vent location to the nearest *city polygon*. For

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

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290 *volcano buffer* and *city polygons* using the extraction method detailed in 3.1. We then ranked the

291 volcanoes by the total city populations within 100 km of the volcano. We also calculated the total

292 number of *city polygons* within each *volcano buffer* for each volcano and ranked the volcanoes by

293 the total number of cities within 100 km of the volcano. Finally, we calculated a composite ranking

294 for each volcano, summing the three rankings of total population <100 km, number of cities <100

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

296 assumes the same weighting for each ranking.

297

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

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

Column Name		
Volcano	Volcano Name	
	Vent ~~co-ordinates~~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

300

301   4. Results

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

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

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

305 more volcanoes, b) the number of volcanoes the city is exposed to, and c) the distance to nearest

306 volcano. Volcanoes were ranked based on: a) the total exposed city population, b) the number of

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

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

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

12

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

311 analyses are presented in Section 9.

312

313 4.1 Quantifying and ranking city exposure to volcanoes

314

315 Globally, 1,~~106~~133 cities have some proportion of their populations living within 100 km of at

316 least one volcano active in the Holocene (Table 3). Within these cities, ~~~430~~431 million people

317 are exposed within 100 km of volcanoes (Table 3), representing ~50 % of the total population

318 exposed within 100 km (n= 852,989,097) and ~~~12~~21 % of the total population of cities globally

319 (n=~~3,511,560,764~~ 2,022,199,789). For each city, the exposed population varies from four people in

320 Hamamatsu, Japan, to ~38.1 million people in Jakarta.

321

322 **Table 3:** *The total number of cities with some proportion of their area within the three volcano*

323 *buffer distances of at least one volcano, and city populations exposed to volcanoes within each*

324 *volcano buffer size used in our study.*

325

Distance from nearest volcano	Number of cities exposed	City populations exposed
10	~~99~~94	13,~~756,890~~182,876
30	381	~~128,065,560~~118,852,034
100	1,~~106~~133	~~429,145,006~~430,696,763

326

327 The greatest number of cities and populations exposed are in Indonesia (see Fig. A3 in the

328 Appendix). The top five cities with the most people living within 100 km from at least one volcano

329 are Jakarta, Indonesia; Tokyo, Japan; Manila, Philippines; Mexico City, Mexico; and Seoul, South

330 Korea (Fig. 4). For these cities, almost the entire populations are exposed to at least one volcano

331 (Jakarta: Salak, Perbakti-Gagak; Manila: ~~Laguna Caldera~~San Pablo Volcanic Field, Taal; Mexico

332 City: Iztaccihuatl, Chichinautzin Volcanic Field, Popocatepetl), except for Tokyo and Seoul where

333 parts of the cities are not exposed to any volcanoes (farther than 100 km; see Fig. A3 in the

334 Appendix). These top five cities represent ~28 % (~121 million) of the total exposed city

335 populations (~~~429~~431 million), with over 677,000 people within 10 km from a volcano. For the

336 other exposed cities, exposed populations decrease gradually as rank increases (Fig. 4; Fig. A2 in

337 the Appendix). When combining rankings of number of people within 100 km, number of
338 volcanoes within 100 km, and distance to nearest volcano, Bandung is the highest ranked city (Fig.
339 3).
340
341 As the spatial distribution of populations varies across cities, we found that some of the highly
342 ranked cities have proportions of their populations located more than 100 km from volcanoes (e.g.,
343 Tokyo, Japan; Seoul, South Korea; Tehran, Iran), whilst others have high proportions of their
344 populations located very close to volcanoes. Notably, for the 30 km *volcano buffer*, the entire
345 populations of Bandung, Indonesia (n=8,443,660) and Quito, Ecuador (n=2,435,784) reside within
346 30 km of at least one volcano. The top five cities ranked by people living within 100 km of
347 volcanoes have relatively low proportions of their populations within 30 km (~1811 %), with most
348 (~8278 %) living between 30 and 100 km. As a result, for rankings at smaller *volcano buffer*
349 distances, these cities drop down to lower rankings (Fig. 4). However, Jakarta and Bandung feature
350 in the top ten ranked cities for exposed populations within all three *volcano buffer* distances and
351 have the highest number of people exposed to at least one volcano within 100 km
352 (n=38,050,48446,494,144) and 30 km (n=8,443,66015,456,793). The top two ranked cities for the
353 10-km *volcano buffer*: Naples, Italy, and Managua, Nicaragua, combined have a smaller total
354 population than Jakarta; however, they have 40 % and 66 % of their city populations living within
355 10 km of volcanoes, respectively, compared to 1 % of Jakarta (Fig. 4). Thus, cities may have low
356 total populations but have high proportions of their populations living in close proximity ofto
357 nearby volcanoes.
358

14

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

Fig. 3: Top 20 15 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 cells are coloured by the ranking position within the column, with darker red as a higher ranking. 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.
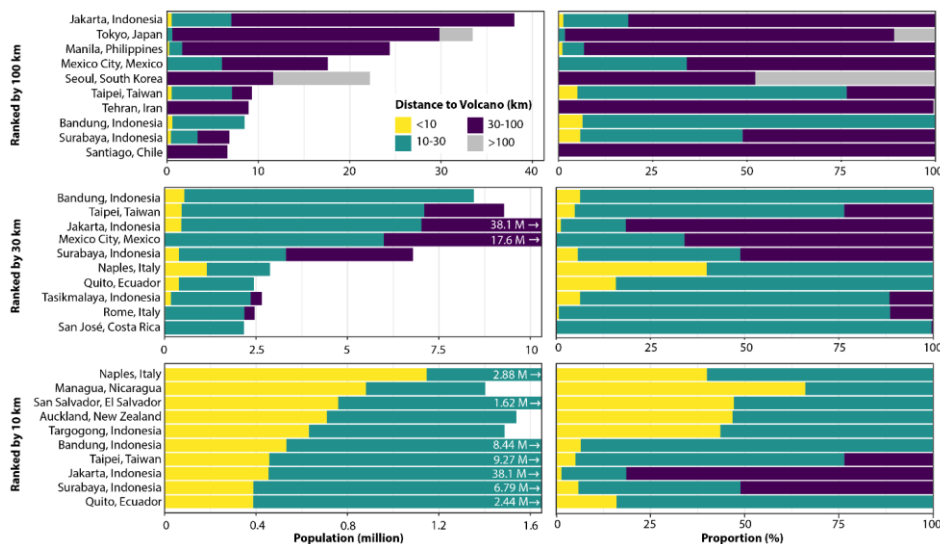
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Fig. 4: Horizontal stacked bar charts of city population (left) and proportion (right) of each city classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 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 9994 cities having their city margins within 10 km from a volcano. However, ~6367 % of cities with populations within 100 km of volcanoes (n=698615) 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

390 cities exhibit a more gradual increase, illustrated in Fig. 5 and for mid-sized cities (populations
391 under 1 million) in the Appendix (Fig. A4).
392
393 Most of the cities exposed to multiple volcanoes are in Central America, with populations in
394 Quezaltepeque, El Salvador, is exposed to the highest number of volcanoes (n=23), and San
395 Salvador, El Salvador, is the city with >1 million people exposed to the highest number of
396 volcanoes (n=2223) (Fig. 6). Although San Salvador is ranked 39th by population within 100 km,
397 it is third in the composite ranking behind Bandung and Jakarta, due to its high ranking of the
398 number of volcanoes (Fig. 3). Despite this proximity of cities to multiple volcanoes, there is the
399 same ranking of the top 10 cities when ranked by the people exposed to the nearest volcano, and
400 those exposed to at least one volcano. Bandung ranks highly for both the maximum number of
401 volcanoes to which the city is exposed, and the number of people exposed, with exposed
402 populations within 100 km of between 9 and 12 volcanoes, with the most, ~4 million, exposed to
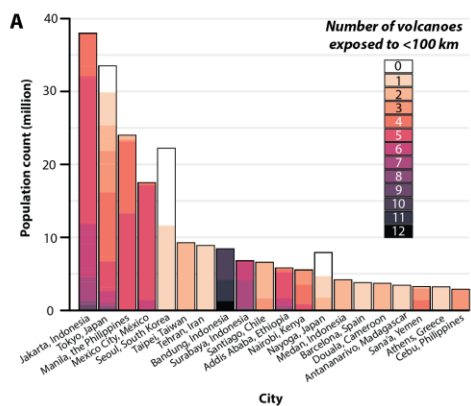403 10 volcanoes (Fig. 6).
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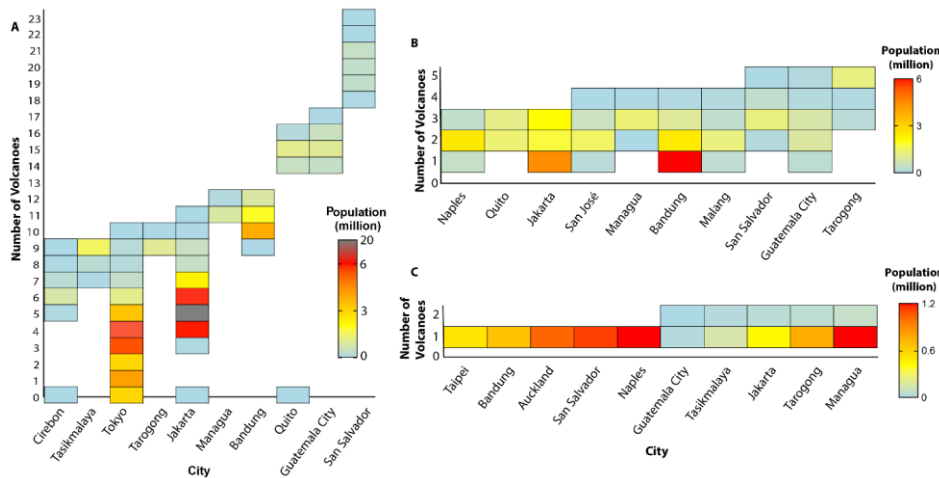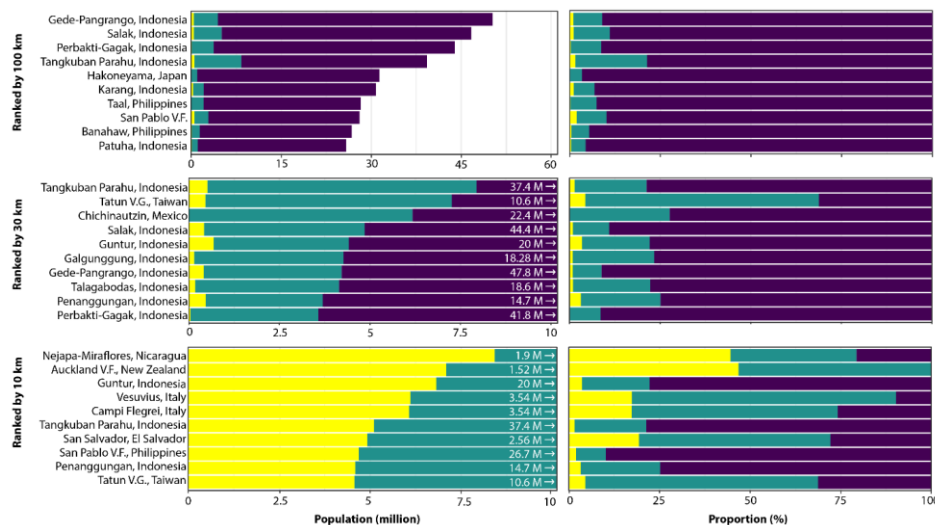
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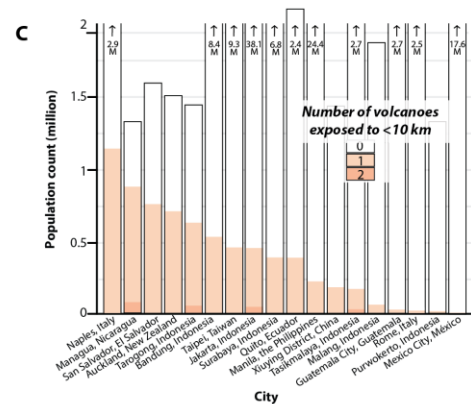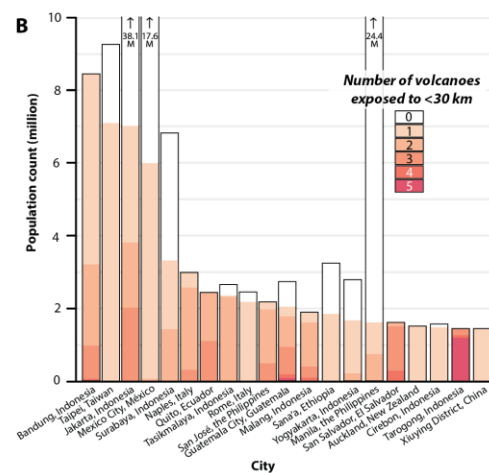
Fig. 5: Stacked bar charts of city population exposure for the top 20 cities coloured by the number of volcanoes the populations are exposed to, within A) 100-km, B) 30-km, and C) 10-km volcano buffers.

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 4746 % of Holocene volcanoes (n=596578) have city populations located within 100 km of their assumed vents. Indonesia dominates the rankings for city populations within 100 km of volcanoes. Five, sevenSix, eight, and three of the top 10 volcanoes within the 100-km, 30-km and 10-km buffers, respectively, are in Indonesia. Among the 596578 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 359 % 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=10896) of cities close to volcanoes, and the greatest number of cities within the country (n=2318) 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~~5,847,751; 52,621,515; and ~~162,357,787~~160,870,875 people living within 10, 30, and 100 km of a volcano, respectively (Fig. 8A). However, the highest proportion of city populations exposed to volcanoes are in Central America (Fig. 8B) where approximately ~~66%, 31~~57 %, 27 % and ~~4~~3 % 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~~1,660,474 and 22,~~942,510~~077,280, 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~~sixth and ~~fourteenth~~thirteenth 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~~33 % 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 ~~~~almost 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

477 the entirety of its population lives within 30 km of at least one volcano. Both Nicaragua and El
478 Salvador have over 40 % of their city populations living within 10 km of at least one volcano.

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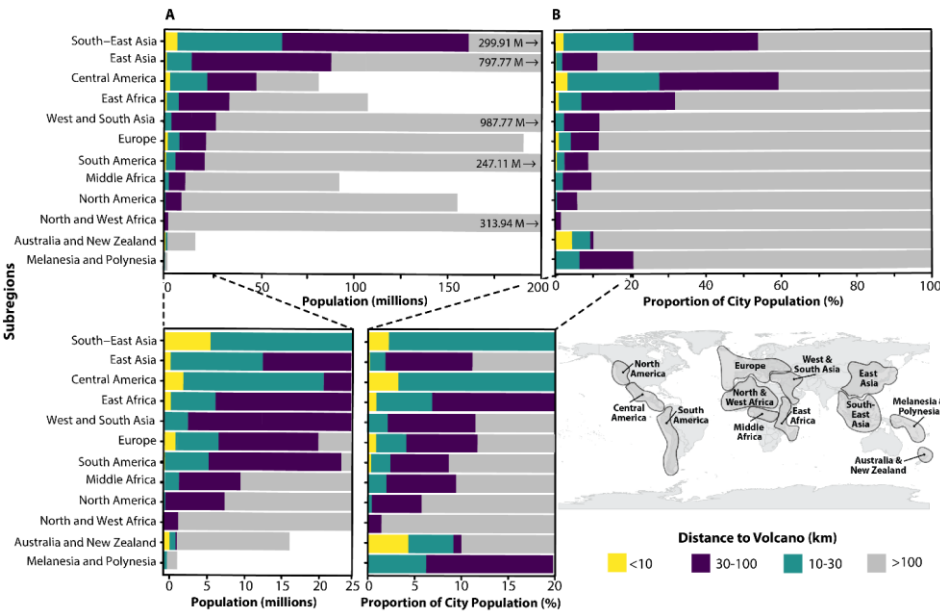
480 *Fig. 8: The exposed city population (A) and proportion of total city population (B) split by*
481 *subregion and classified by the distance of the population to nearest volcano. The subregions are*
482 *highlighted on the bottom right schematic map showing an approximate location of where the*
483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

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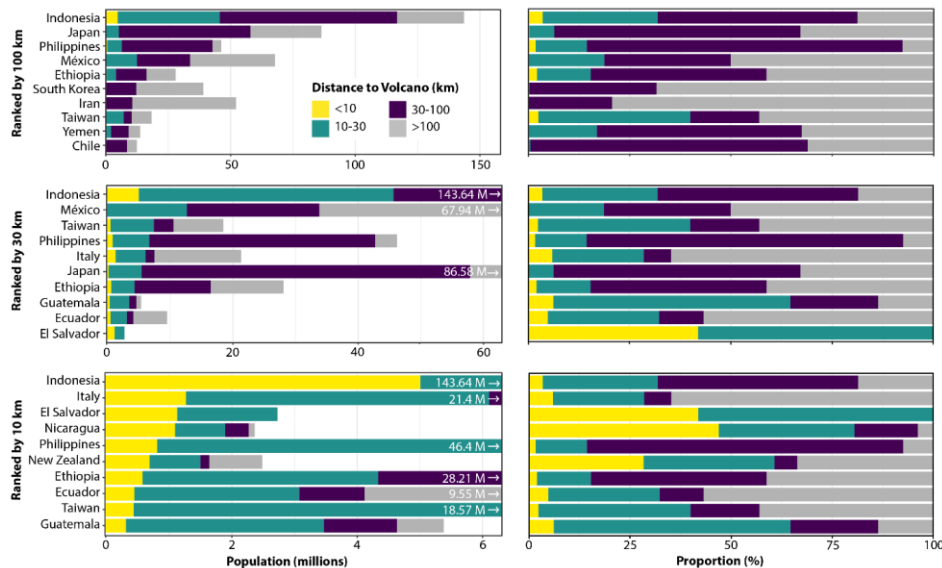
Fig. 9: Horizontal stacked bar charts of city population (left) and proportion (right) around each volcano, grouped by country, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), and ranked by 100, 30, and 10-km radial buffers. 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, 557575 cities exposed to volcanoes have populations greater than 100,000 people, a substantial increase from the 67 cities documented by Heiken

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(2013). We identify Jakarta, Tokyo, and Manila, as having the highest exposure within 100 km of volcanoes. These large cities have high proportions of 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.
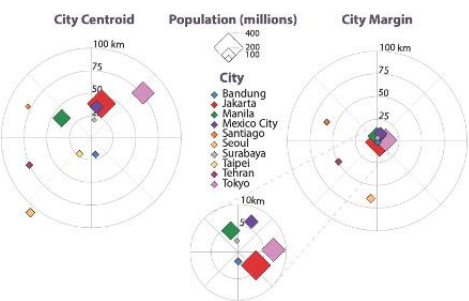
Fig. 10: Polar chart to show the top 10 cities with the most exposed city populations within 100 km of the nearest volcano. The city centroids (left) and nearest city margin to the volcano (right) are plotted as diamonds relative to the nearest volcano (centre of the plots), and the diamond size refers 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 in 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

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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~~607,675), and some of the most densely populated parts of the city (~11,~~119~~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

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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

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 secondfirst 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., such as Managua, Nicaragua, San Salvador, El Salvador, and Quito, Ecuador (Fig. 4; 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

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601 volcanoes living in both urban and rural areas. In our study, using 2020 ~~CE~~ city population data
602 for the same buffer distance, we find that a similar number (2.6 million) of people now live just
603 within ~~the~~ urban (city) areas. The high proportions of urban populations close to volcanoes in
604 Central and South America (Fig. 9) is perhaps linked to the colonial past of the region, whereby
605 investments into agriculture in the early to mid-20th Century resulted in a growth of agricultural
606 settlements through time (Swyngedouw, 2006). Nejapa-Miraflores volcano, Nicaragua is one
607 example of where almost 1 million people, or ~~60~~45 % of the exposed population, are located within
608 10 km of the volcano. These populations are distributed over multiple cities, adding complexity to
609 potential eruption impacts and response strategies.
610
611 4.4 Future Research Directions
612
613 In this study, we define cities as those areas classified in the GHS-UCDB dataset as *urban centres,*
614 which excludes suburbs and regions of lower population densities. For example, the remaining
615 ~~~25~~46 % (n=~~336~~686) of volcanoes that do not have city populations within 100 km, may still be
616 situated near suburban or rural populations, or have tourists, not assessed in this study. ~~Through~~
617 ~~time, these~~The delineation between urban, peri-urban, and rural areas is not always clear (Chen et
618 al., 2018; Sorensen and Labbé, 2020). Urban centres can sprawl into surrounding peri-urban and
619 rural regions, and through time, urban centres may merge together and densify. Therefore, total
620 city populations may slightly differ when using other datasets. If suburban and rural populations
621 were also considered, the ranking of volcanoes would likely change, as these areas may have
622 higher exposure to volcanic hazards. Past volcanic eruptions such as 1982 El Chichon eruption,
623 Mexico, have primarily affected rural communities rather than city centres. Our approach could
624 be expanded or used to explore more than just cities, by assessing changing land-use patterns,
625 transient populations, ~~or other~~ using different population ~~densities~~datasets (e.g., LandScan ambient
626 population dataset: Lebakula et al., 2024), or gradations of population density around volcanoes
627 using different buffer distances. We can also explore past trends in city population exposure
628 through time, and future projections, to quantify rates of exposure change. Mapping the urban
629 sprawl of these cities allows us to identify key areas around volcanoes to focus on future mitigation
630 efforts and land-use planning. Further research is needed to understand how the interconnectedness
631 of cities and suburbs, influences impact.

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~~coordinates provided by the Global Volcanism Program (2023), does not account for the uncertainty in the next eruption site, for example ~~at~~within 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~~distributed volcanism, such as those used in Nieto-Torres et al. (2021), and of shield volcanoes. Future work could classify volcanoes by probability of eruption, last eruption, VEI range, or tectonic setting, to better understand the specific types of potential hazard they pose to nearby cities. For example, the presence of multiple volcanoes within 100 km, as in San Salvador, does not directly equate to higher hazard, as eruption probabilities vary. While our approach identifies cities with high volcanic exposure, localised hazard assessments are essential for a more precise evaluation of the threat (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~~We present a framework to quantify and rank global 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 using concentric radial buffers conservatively estimates and compares city exposure. ~~These buffer sizes may overestimate exposure, but we preferred this approach to avoid underestimating it.~~ Our results are provided at Section 9 and as a web application for visualisation of all city exposures (https://vharg.github.io/shiny_VolcCities/). The rankings ~~can~~of 1,133 cities within 100 km of 578 Holocene volcanoes 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~~23, 6, 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, Tampomas, and San Pablo Volcanic Field~~, and Tampomas~~ as scoring highly across these rankings. Gede-Pangrango, ~~Laguna Caldera~~Tangkuban Parahu, 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 challenges regarding exposure to volcanoes. For example, Jakarta has high population density between 30 – 100 km of volcanoes, while 2339 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, 90~80 % 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
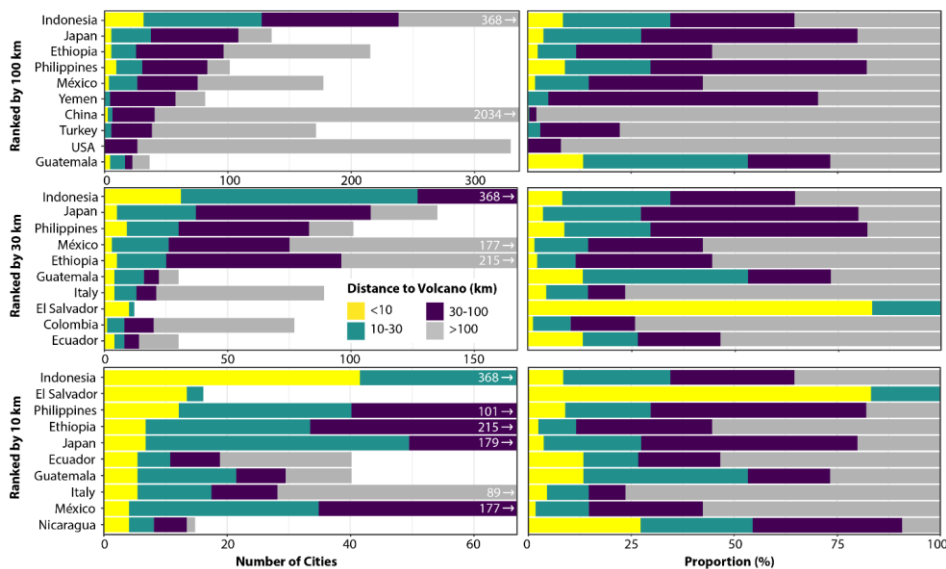
Fig. A1: Horizontal stacked bar charts of number of cities with populations within each buffer distance (left) and proportion (right) around each volcano, grouped by country, classified by distance of the city margin to the nearest volcano (within <10, 10 - 30, and 30 - 100-km distances from volcanoes), 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.
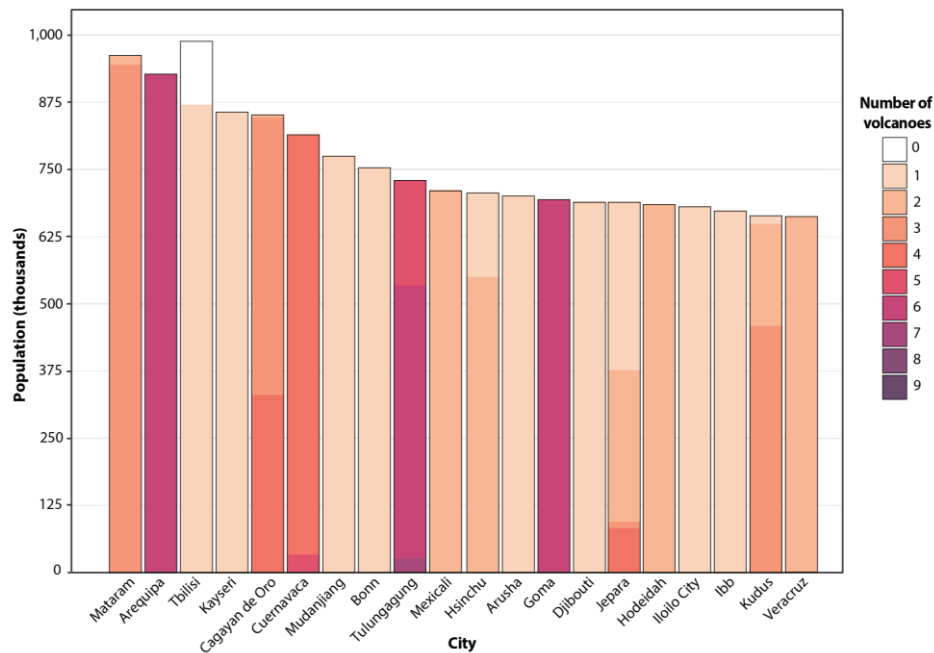
Fig. A2: Top 20 cities with ~~less than one million~~ *exposed* ~~city~~ *populations below one million, coloured by the number of volcanoes for which the* ~~population is exposed by~~*city lies within a 100 km radius.*
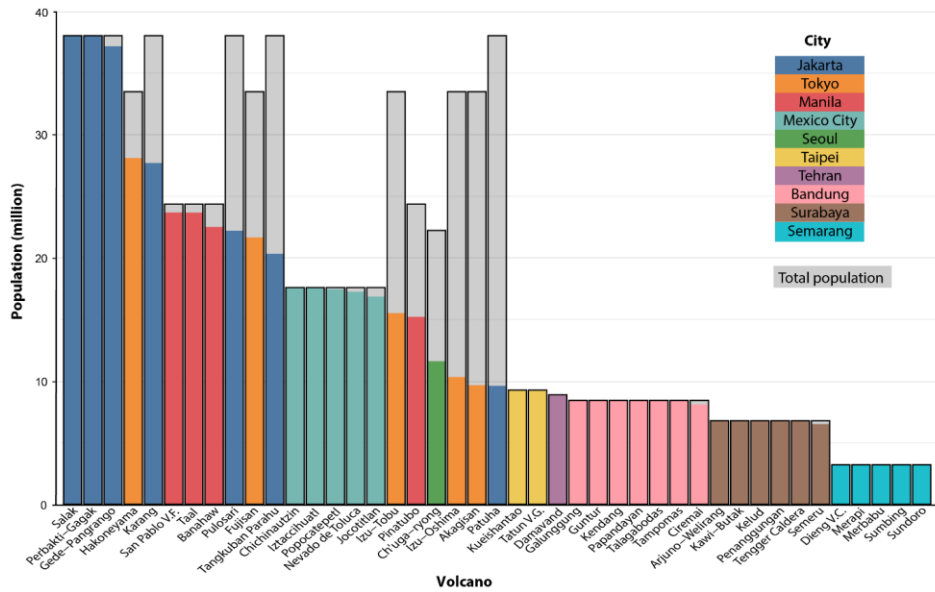
Fig. A3: City populations exposed to individual volcanoes within 100 km, ranked by the dominant city. Bars are coloured by the dominant city exposed population. V.F. stands for Volcanic Field, V.G. stands for Volcanic Group, and V.C. stands for Volcanic Complex.
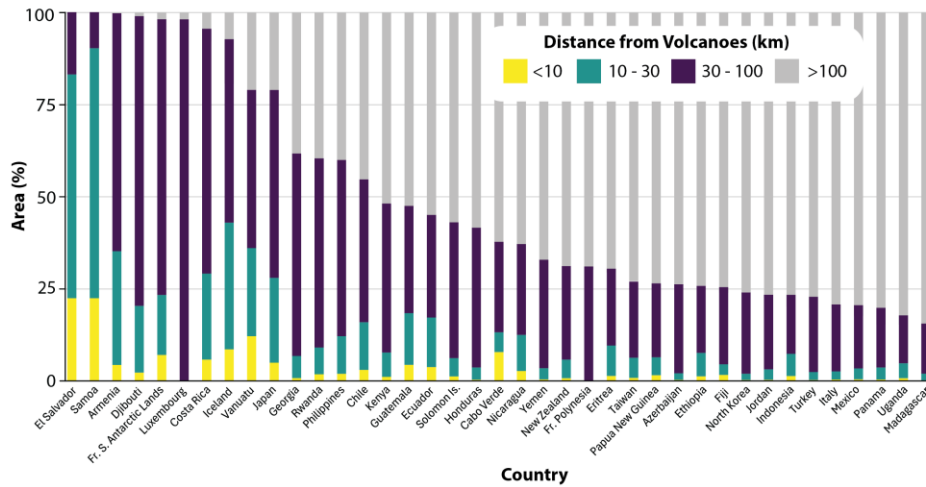
Fig. A4: Top forty countries with a total area of >2,000 km^2 ranked in order of their total land area exposed to volcanic hazards, and coloured by the percentage of area. Is stands for islands and Fr stands for French. Land area from Natural Earth (2023).

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/~~ https://vharg.github.io/shiny_VolcCities/

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.

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