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Environmental and economic impact of the potential eruptions of Imbabura (VEI = 2) and Cuicocha (VEI = 6) volcanoes in north-central Ecuador

Fabián Rodríguez-Espinosa*; Department of Earth Sciences and Constrution, Universidad de las Fuerzas Armadas – ESPE, Ave. General Rumiñahui w/n, and Ambato St.; Sangolquí, Ecuador; ffrodriguez3@espe.edu.ec; OrcidID: 0000-0002-2754-1347

Cristina Cabrera-Paladines, MASRED Master Program, Universidad Internacional de Valencia, Pintor Sorolla St. # 21, Valencia, Spain. cristinacp27@outlook.com.

Juan Calderón-Tupiza, Private consultant, Quito, Ecuador. jdcaldernt@espe.edu.ec.

Theofilos Toulkeridis*, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece; ttoulke@geo.auth.gr; OrcidID: 0000-0003-1903-7914.

* Correspondence: ffrodriguez3@espe.edu.ec;

Abstract: The present study aims to determine the physical and economic impact on Otavalo canton in north-central Ecuador out of the potential eruptive phase of the Imbabura (VEI = 2) and Cuicocha (VEI = 6) volcanoes. The current situation of Otavalo was identified in relation to the potential volcanic hazards of these two volcanoes through previous studies and field work. With geographic information on the given infrastructure of the area and the use of geospatial tools, maps of the Otavalo canton were prepared related to a variety of volcanic hazards but predominantly ash falls and pyroclastic flows from the two evaluated volcanoes in order to determine the physical impact. Furthermore, we determined the economic impact by using geographic information, volcanic hazard maps and economic cost analysis, with which the total economic losses were estimated. Contradictorily to the grade of the VEI, a total economic loss of only 235,524,287.89 USD has been yield in the canton of Otavalo in the case of an eventual eruption of the Cuicocha volcano and some 300,917,625.51 USD in the case of an eventual eruption of the Imbabura volcano. Subsequently, we developed the basis for a novel proposal of preventive measures in order to reduce the physical and economic impact in the studied area.

Keywords: Eruption, pyroclastic flow, ash fall, physical impact and damage, economic loss, Ecuador.

1. Introduction

The spatial range and reach of volcanic eruptions and corresponding hazards have been studied for centuries because of their potential destructive effects on social-economic activities, society and infrastructure [Ramírez et al., 2022; Sword-Daniels et al., 2022; Goujon et al., 2021; Medeiros et al., 2021; Nagamura, 2021; Fiantis et al., 2019; Cunningham, 2018; Zuccaro et al., 2013; Bedon, 2014; Wilson, et al., 2012). Besides the Santorini eruption of the 16th century BC, the very first documented catastrophic volcanic activity dates back to 79 A.C. in Italy with more than 25 thousands of fatalities and a destruction of cities and towns such as Pompeii and Herculaneum close to the Vesuvian volcano (Friedrich et al., 2006; Manning et al., 2014; Carolis et al., 2003; Soncin et al., 2021; Baxter et al., 1986; Sigurdsson et al., 1982). Regularly, human life losses are the result of people population living within 100 km of the vicinity of an active volcano (Doocy et al., 2013; Wilson et al., 2012; Brown et al., 2017; Self et al; 1984), especially in highly populated areas. In Indonesia, for example, Tambora volcano activity in 1815 caused more than 92 thousand deaths fatalities due to a wide range of volcanic hazards (Oppenheimer, 2003; Noji, 1997). Similarly, the Krakatoa eruption in 1883 caused approximately 36 thousand deaths (Gueugneau et al., 2020). Most of the deaths fatalities of eruptive events have been as the result of pyroclastic flows and surges, sector collapses, lahars and ballistic blocks, but these effects are not the only ones. In 1902, the volcano Montagne Pelée in Martinique within the Caribbean erupted killing almost 30,000 people due to pyroclastic density currents (Freeth, S. J. 1993). Furthermore, in Cameroon in 1986 some 1250 people lost their lives because of toxic gases as a result of a limnic eruption at Lake Nyos, as well as besides the loss of at least thirty-five thousand livestock (Zhang, 1996; Tanyileke et al., 2019; Bretón, 2018).

Due to the geodynamic constellation situated along an active continental rim, western Latin American countries are particularly susceptible to the effects of volcano eruptions (Harmon & Rapela, 1991). In fact, all countries around the entire Pacific coast is are located in what is known as the "ring of fire" which is a path along characterized by active volcanoes and frequent earthquakes (Decker and Decker, 1991; Naismith et al., 2019). A relatively recent eruption of Fuego volcano in Guatemala caused 114 deaths and 197 missing people (Romano, 2019). However, volcano ashes affected 1.7 million people, especially in Guatemalan rural areas (Voight, 1990). In the same region, one of the deadliest volcano eruptions occurred in Armero, Colombia. Hereby, Armero was decimated in 1985 by Nevado del Ruiz volcano and 25 thousand people died below debris of a highly voluminous volcanic lahar (Barberi et al., 1995). Classically, the Cotopaxi volcano in Ecuador has had a variety of deadly eruptive phases with hundreds of victims and economic disasters which would in a future potential event surpass 17 billion USD and potentially killing various dozens of thousands people living close by (Toulkeridis et al., 2015; Rodriguez et al., 2017; Echegaray-Aveiga et al., 2020; Mazzocchi et al., 2010).

Regarding economic cost amounts, Zuccaro et al. (2013) developed a model to estimate direct and indirect cost associated to a future, very likely Strombolian type of eruption of the Vesuvian volcano. These authors determined an estimate of 89 billion of euros (US$ 118 billions). This model included the normalization phase, meaning most of infrastructure and buildings rebuilt and functioning. In a further study by Oxford Economics (2010), which concentrated in aviation sector losses, found a loss in GDP was determined of being about US$4.7 billion. This estimated value included loss of revenues from airlines, damage of

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equipment, airport business operations, loss of government taxes, foregone spending on hotels, restaurants, taxis, shopping, entertainment and other services related to the aviation sector. A similar study of (Pinatubo Volcano Observatory Team, 1991) concentrated was focused in the trade value of aircraft companies and they found €3.3 million economic losses in companies' trade value as a result of falling ash from volcano eruptions The Pinatubo eruption in the Philippines of 1991 was also a very lethal volcanic eruption, killing more than a thousand persons, and while the damage in infrastructure and business reached at least US$374 million (De Guzman, 2006; Leone & Gaillard. 1999). Pinatubo This eruption in 1991 caused a loss of 1.95% of Philippines the country´s GDP (Annen and Wagner, 2003; El Hadri et al., 2021). In the United States, two volcanoes caused huge economic losses, being the Mount St. Helens eruption in 1980 caused which has led to a destruction and income losses of US$860 million and the Redoubt volcano at Alaska in 1990 with an economic loss of 160 million (Santos et al., 2022). (Jiang et al., 2013) using an input-output model, estimated the economic losses of the Taal volcano eruption in the Philippines, which reached approximately US$48 million. (Toulkeridis et al., 2022) compared direct and indirect cost economic damage of three volcanoes eruptions together, being of Mt Fuji and Mt. Unzen in Japan, and Mt. St. Helen in the United States. The economic cost of volcanoes ashes reached hereby some US$7.7, US$1.6 and US$5.0 billion respectively in economic losses. A very recent, very extraordinary volcanic event, the Tonga–Hunga Ha'apai volcanic eruption in Tonga caused economic damage in the order of US$90.4 million, which it is around 18.5% of Tonga´s GDP (World Bank, GFDRR 2022; Toulkeridis et al., 2021).

In Latin America there are several studies that contemplates economic effects of volcano activities. (Alvarado et al., 2023) presented the economic impact of Costa Rica' volcanoes between 1953 and 2005. This study concentrated on the production sector with almost US$ 250 million of calculated damage. Based on the EM-DAT International Disaster Database shows indicates that the most recent volcanic eruptions in Chile caused US$ 704 million in destruction and income losses (Santos et al., 2022). Same database showed yielded that El Chichon volcano in México caused economic losses of about US$117 million. Nevado del Ruiz in Colombia eruption brought resulted as expensive as of about US$1 billion (Santos et al., 2022; Jiang et al., 2013; World Bank, GFDRR 2022; Toulkeridis et al., 2021; World Bank, GFDRR 2022).

In this respect, Ecuador has a long history of volcanic eruptions (Toulkeridis et al., 2021; Ridolfi et al., 2008; Ramírez et al., 2022; Jacome 2011; Von Hillebrandt 1989; Toulkeridis & Zak, 2008; Toulkeridis et al., 2025). According to Toulkeridis (2013) and Toulkeridis and Zach (2017) there are nineteen active volcanos which are able to cause direct and indirect effects on population, production activities and economic losses. For example, the Pichincha volcano eruptions between 1998-1999 affected directly to two thousand people, mostly farmers, and economic losses over US$ 222 million (World Bank, GFDRR 2022). Later, ash fall affected to some forty thousand hectares of pastures close to El Chaco and Reventador towns in Ecuador due to the Reventador volcano eruption in 2002. Unfortunately, there was not an estimation of economic losses (Ramírez et al., 2022; Jacome 2011). The Tungurahua volcano produced economic losses of about US$ 150 million in 2006 (Santos et al., 2022; Jiang et al 2013; Toulkeridis et al., 2022; World Bank, GFDRR 2022; Toulkeridis et al., 2021; Ridolfi et al., 2008; Ramirez et al., 2022; Jacome, 2011; Von Hillebrandt, 1989). This volcano affected four thousands of hectares of agriculture and livestock sector, while forty-nine thousand families lost their homes (Von Hillebrandt, 1989).

In regard to the volcanoes Imbabura and Cuicocha, which are the objects of the current study, there is evidence of five thousand hectares affected by an ash layer and pumice stone in the nearby Otavalo Canton of Otavalo (Jacome 2011). Hereby, it has been mentioned that the last eruption happened occurred some 2900 and 3100 years ago, according to volcanic records of tephra. Additionally, Padròn et al. (2008) mentions extensive areas were affected by pyroclastic flows from the Cuicocha volcano. These authors sustain that the volcanic activity of Cuicocha has ever stopped (Padròn et al., 2008; Melián et al., 2021; Le Pennec et al., 2011). Closely, the Imbabura volcano has footprint of ash layers and pyroclastic flows over ten thousands of hectares. The last known eruption of Imbabura volcano was around 9 Ka ago (Pavón, 2017). Currently, several cities are place at the southern flank of the volcano and there is evidence of this volcano´s past eruptions with ash layers, lava domes and pyroclastic flows (Rodriguez et al., 2017).

The remains of the past eruptions of Imbabura and Cuicocha volcanos are evidence of the potential of a volcanic risk that Otavalo canton is facing (Guerrero, 2019). Furthermore, the communities' economic condition as well as lack of planning and little disaster preparedness from local government and population induce a low resilience for these types of hazards and threats (Corominas & Martí, 2015; GAD-Otavalo, 2020). All these factors brought about the necessity to determine the physical and economic impact of potential volcanic eruptions on the Otavalo Canton and provide in-formation to local government in order to develop needed corresponding appropriate policies.

2 Methods/Materials

All geographic information from the Canton of Otavalo was obtained from public institutions and agencies such as the Military Geographic Institute (IGM), Ecuadorian Spatial Institute (IEE), National Information System (SNI) Municipal Decentralized Government of Otavalo (GAD-Otavalo) and Provincial Decentralized Government of Imbabura (GAD-Imbabura).

2.1 Study Area

The Canton of Otavalo is located in the Inter Andean valley, within the northern part of central Ecuador comprising an area of 579 Km^2, situated at an average height of some 2,565 meters above sea level (58). Otavalo canton is composed by eleven parishes, of which two are urban and nine are rural (Figure 1). The average temperature is 16-°C and the average precipitation of about 1897 mm per year. Based on the Ecuadorian Census from 2010, the population reaches some 39,354 people (58). The Canton of Otavalo is located in a highly risk area because is located very close to the influence area of both active volcanoes (Figure 1), Imbabura and Cuicocha, which are classified with a Volcanic Explosivity Index of 2 and 6, respectively (Pavón, 2017; Melián et al., 2021; Le Pennec et al., 2011; Jenkins et al., 2015). As a result, the potential damage of infrastructure, properties, loss of revenues, economic impact could be enormous for the local government.

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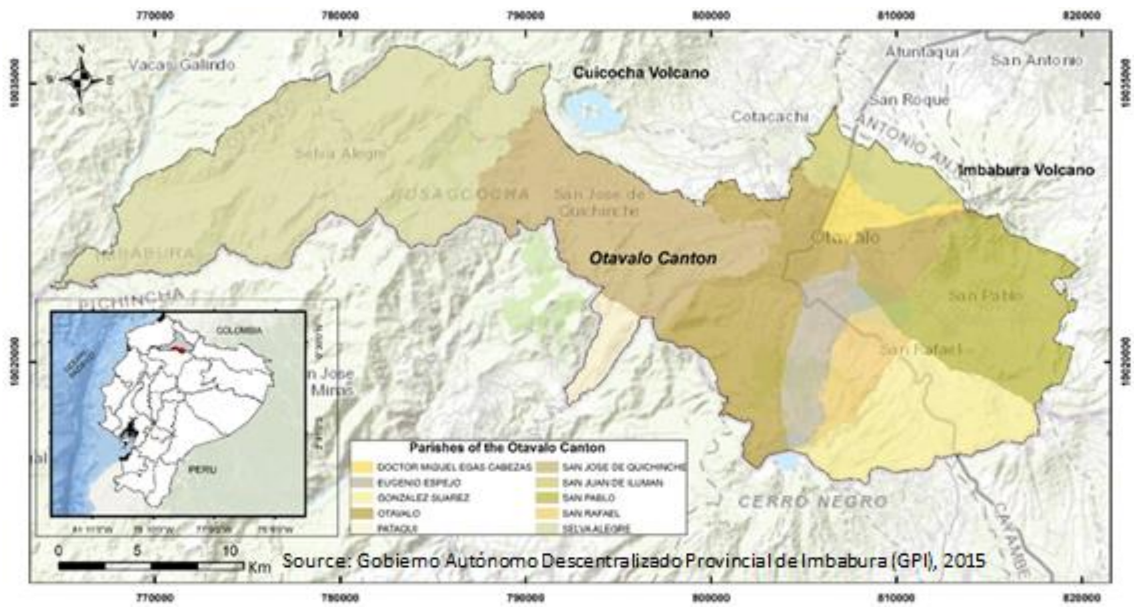

Figure 1. Area of Study of Canton Otavalo (División política oficial del cantón Otavalo, GPI, 2022)

2.2 Geospatial analysis of ash fall distribution

The volcanic ash hazard from Cuicocha and Imbabura volcanoes was determined from different sources and field visits. Geospatial information from the projected co-ordinate system and analysis and geoprocessing tools of the ArcGIS-ArcMap software were used. Heavier ash fragments fall closer to the crater of a volcano and lighter fragments disperse further from the source. Therefore, as a result of downwind, particular size distribution reduce with distance from the volcano and ash deposits accumulate in the direction of prevailing winds (62). Therefore, a volcanic ash transport and dispersion model was used to simulate Cuicocha and Imbabura cloud ash dispersion based on Plume-SPH developed by (63). This particular model uses a Lagrangian tracer particles with random variables.

$$R_i(t) = \left(x(t), y(t), z(t)\right)$$

Where i=1~M, which represents position vectors of particles from the origin of the ash source at the time t and M is the total number of Lagrangian tracer particles. Bonadonna and Houghton (2005) mentions that a sample of all ash particles is able to be represented as:

$$R_i(t + \Delta t) = R_i(t) + W(t)\Delta t + Z(t)\Delta t + S_i(t)\Delta t$$

Where, W accounts for local wind advection, Z is generated by Gaussian random numbers and accounts for turbulent dispersion, while S is the terminal gravitational fallout velocity or settling speed, which depends on a tracer's size.

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$$r(H) = r_{max} H / H_{max} R$$

where r(H) is the radius of the horizontal circle, within which all particles at the height of H are located. r_{max} is the horizontal spread. H is the height, and R is a uniformly distributed random number between 0 and 1.

In terms of Imbabura and Cuicocha volcanoes, the study used data from Global Forecast System / North American Model of the National Oceanic and Atmospheric Administration (NOAA) to estimate wind direction. The model was applied for Ecuadorian volcanos by Toulkeridis & Zach (2017) using 4,905 satellites images in 2017 in their analysis for five Ecuadorian volcanos and indicated the wind direction for these volcanoes. The data set has been actualized including now 15,723 satellites images for the period of September 1999 up to including October 2024 (Figure 2).

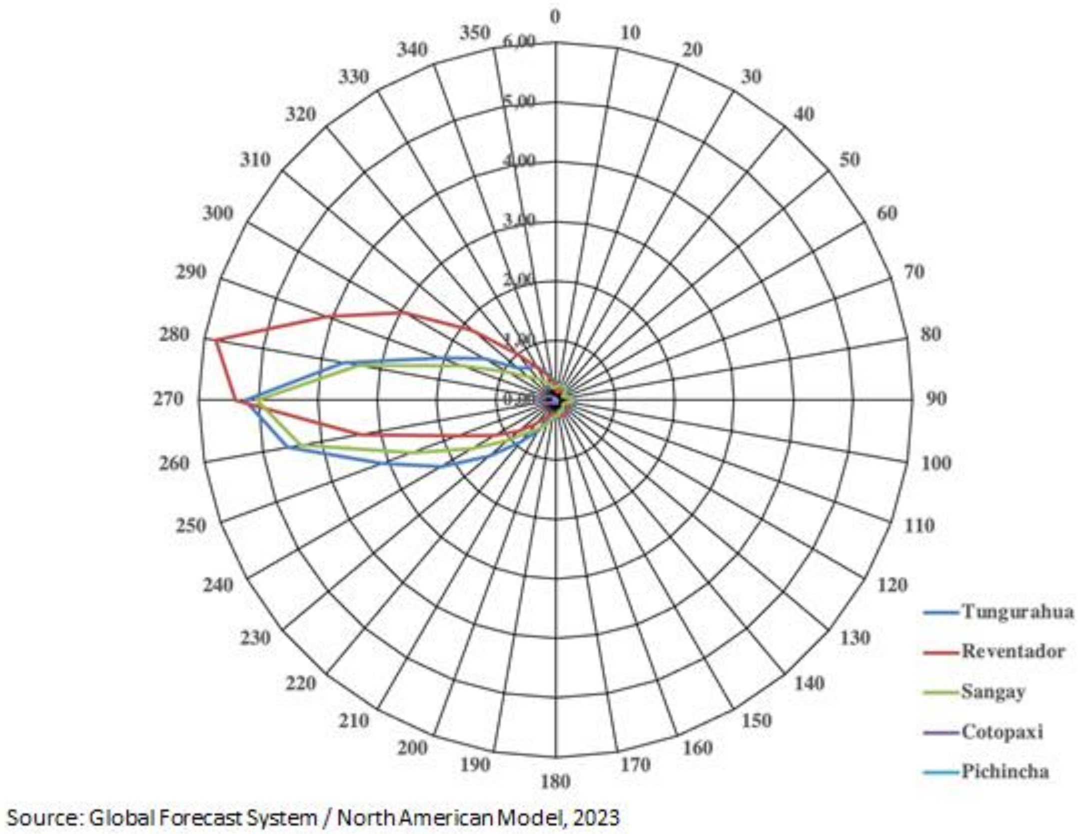

Figure 2. Wind directions of ash-containing clouds for the period September 1999 to October 2024.

In order to obtain a radial chart from ash fall for Imbabura and Cuicocha volcanoes, the studied wind directions for the period 1999-2024 was analyzed and digitalized. Ash layers' analysis were transformed to Aster format with ArcGIS-ArcMap

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and assigned a location throughout a georeferencing process within WGS 1984 UTM Zone 17S as it was described by Jenkins et al. (2015). Five control point were settled with center of Cuicocha crater and Imbabura crater as reference. This reference points were obtained from World Topographic base map for this region. The other four points of control were obtained from the radius length of the greater circumference in the rose diagram and the wind directions at 270°, 0°, 90° and 180°. Once the radios length was obtained, these distances were added and subtracted to Imbabura and Cuicocha to crater or caldera reference points, depending of intersection of wind ratios location at 270°, 0°, 90° and 180° and the greater circumference. The coordinates of the control points were based on other studies volcanoes tephra analysis with similar volcanic explosiveness index (Hill et al., 1998; Paladio-Melosantos et al., 1996; Ferreiro et al., 2020; Volentik et al., 2010; Bustos et al., 2015).

Finally, an ash direction model was obtained realized from radial chart raster of volcanoes ash fall with their radio length and ash thickness. Using ArcGIS-ArcMap, a predictive ash fall model was developed based on volcanoes ash thicknesses.

2.3 Geospatial analysis of pyroclastic flows

Within the geological map (Figure 3) from the study of (Padrón et al., 2008), pyroclastic flows were identified based on aerial photo interpretation and field records. Hereby, the geological map was transferred to a Raster format, which subsequently was georeferenced. As in an ash fall analysis, four points of reference were located for each volcano. In case of the Cuicocha volcano, reference points were located in the Theodor Wolf island, Mamarumi dome, Jacuapamba volcano and the north-eastern side of San Pablo lake. As in the case of Cuicocha ash fall, World Topographic map was used because is georeferenced and coincide with the geological map of Cuicocha (Figure 3). Once the four reference points were established, Cuicocha raster map was digitalized with a pyroclastic flow layer of Cuicocha volcano. This process has been suggested for several authors (Ferrari et al., 2018; Godoy et al., 2012; Aguilar & Alvarado, 2014).

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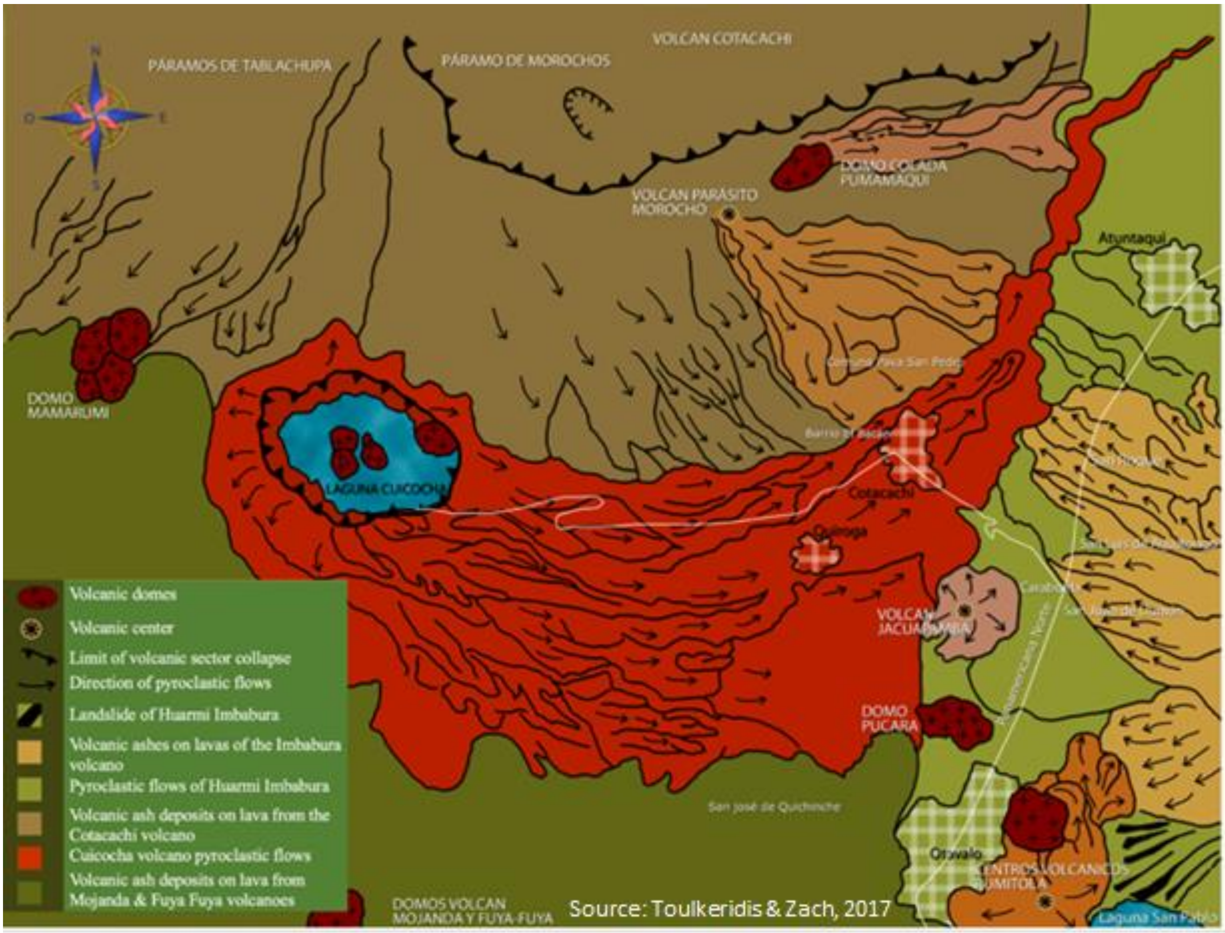

Figure 3. Geological map of Cuicocha volcano (Adapted and slightly modified from Toulkeridis & Zak, 2008)

Regarding Imbabura pyroclastic flows, a heuristic analysis was done using photointerpretation and field analysis. A World Topographic base map was used to identify and location of Imbabura volcano pyroclastic flow and its area of impact as well as other land and topographic characteristics that determine pyroclastic flow directions.

2.4 Impact associated with volcanic eruptions

According to Zuccaro et al. (2013), economic losses associated with volcanoes eruption cannot be easily determined because losses range from emergency cost, evacuation, temporally housing through direct impact on infrastructure, residential buildings, as well as disruption of business activities up to recovering cost. The magnitude, according to these authors, may also depend on anticipate magnitude, intensity and duration of eruption threat, as well as the amount and quality of the information available to local business, investors and consumers.

Similar studies on assessing cost of natural hazards indicate five cost categories including direct cost, business interruption cost, indirect cost, intangible cost and risk mitigation cost provided the framework for our economic impact of volcanic

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eruption model. We defined volcanic eruption costs as direct and indirect economic losses from ash falls and pyroclastic flows, as well as, all reconstruction cost, loss of productivity and mitigation cost. The model is defined as function of direct and indirect cost.

$$C_{ve} = \int \left(dc_{i,j}^{y,z}, ic_{i,j}^{y,z}, mc_{i,j}^{y,z} \right)$$

where, $dc_{i,j}^{y,z} dc_{i,j}^{y,z}$ is the direct cost on infrastructure power generation stations, power transmission lines, storage facilities, critical nonresidential buildings such as hospitals, police stations, schools, government administrative buildings, strategic buildings such as water purification and wastewater treatment plants, water supply networks, service buildings, residential units, and others; $ic_{i,j}^{y,z} ic_{i,j}^{y,z}$ is the indirect cost which includes induced production losses such as loss of value added, reaction of expenditures of local government and impact in local business such as potential losses of handicrafts marketplace, agriculture and livestock potential losses, and local commerce; $mc_{i,j}^{y,z} mc_{i,j}^{y,z}$ is the mitigation cost which includes reconstruction cost, set-up infrastructure to prevent future volcanoes damages, and induced cost in other sectors. The i and j subscripts refers to ash and pyroclastic damages, while y and z superscripts refers to Imbabura and Cuicocha economic impact respectively.

This study concentrates in direct impact and cost of infrastructure such as bridges, roads, power generation, power transmission lines, storage facilities, critical nonresidential and strategic buildings such as hospitals, schools and government administrative buildings, water supplies, wastewater infrastructure, service buildings, residential buildings, and others. This critical information was obtained from the Canton Otavalo office and national government and agencies offices.

$$dc_{i,j}^{y,z} = \sum_{y,z} I_{i,j} \times p$$

Where, $I_{(i,j)}$ is the infrastructure bridges, roads, power generation, power transmission lines, storage facilities, critical nonresidential and strategic buildings such as hospitals, schools and government administrative buildings, water supplies, wastewater infrastructure, service buildings, residential buildings affected by Imbabura and Cuicocha volcanoes ash (i) and pyroclastic (j) effects, and p is the value (price) of each item. The direct cost includes not only capital losses, as well as labor, equipment and machinery, and time use during the afterward recovery process.

Land use and cover was obtained from regional land use and cover map from the Imbabura province office and from local Otavalo government cadaster office. The geospatial information was done at scale of 1:5000 for rural areas and 1:1000 for urban areas. Cadaster information from Canton Otavalo was georeferenced and digitalized. The study did not take in consideration several critical cost such as temporal housing for population affected, evacuation cost, local business cost, and long effects recovering cost because limited information on some economic sectors of the Otavalo.

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3. Results and discussion

We encountered slopes formed by Cuicocha volcanic material characterized by enormous thicknesses, composed of fine-grained pumice deposits and volcanic lithics mainly of andesitic and dacitic compositions (Figure 4a). This indicates that Cuicocha volcano located at the western side of Otavalo had past various violent eruptions in its past. The volcano may be characterized as a Plinian type with an VEI of 5 or 6. This demonstrates that Cuicocha has had colossal eruptions reaching volcanic plume heights of more than 25 km. Cuicocha is an active volcano with a, its caldera lake, which is mainly feeded by rain and hot spring waters. A sub lake fumarolic activity characterized by gases release mainly CO_2 as illustrated in Figure 4b.

Regarding Imbabura volcano, we encountered slopes formed by thin sized volcanic deposits lacking coarse pumice material (Figure 4c). Imbabura volcanic slopes are an indication of very low volcanic material, reaching less than 1 million m3. The volcano is of Strombolian type reaching usually a VEI not higher than of 2. Figure 4c indicates volcanic deposits of the Imbabura volcano, interlayering with some clastic sedimentary deposits be-low a maize field.

Based on the statistical data of the distribution of volcanic ashes (Fig. 2), the ash expelled of the Cuicocha volcano, would generate a cloud that would start to cover some 10.5 km of land towards the main distribution direction with a thickness of at least 30 cm (Fig. 5). Furthermore, following the same direction for about 18.5 km, the ash thickness would reach at least 25 cm. In the next 30.5 km the ash precipitation would reach at least 20 cm of thickness, at 48 km of distance a thickness of 15cm, while with a distance of 95 km the thickness of ash would appear of at least some 0.8 cm. Figure 6 illustrates in detail how the ash cloud will spread around close and distance land since its emission of the central part of the volcano. Due to the violent appearance of this Plinian type volcano, the potential ash cloud of Cuicocha volcano will cover the entire northwestern area of Ecuador finally reaching the Pacific Ocean.

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Figure 4. Evidence of volcanic activity in Otavalo: (a) Pyroclastic deposits of Cuicocha volcano, (b) Cuicocha caldera lake gases emissions (c) Ash deposits of Imbabura volcano.

The Imbabura volcano with a lower explosivity index in an eventual eruption would have a generally smaller impact compared to the eventual eruption of Cuicocha volcano. The ash cloud of Imbabura volcano would start covering 8 km towards the predominant direction of the precipitation, resulting to a thickness the fine ash material to be of at least 10 cm, reaching at 28 km of the same direction an ash thickness of 0,8 cm (Figure 6).

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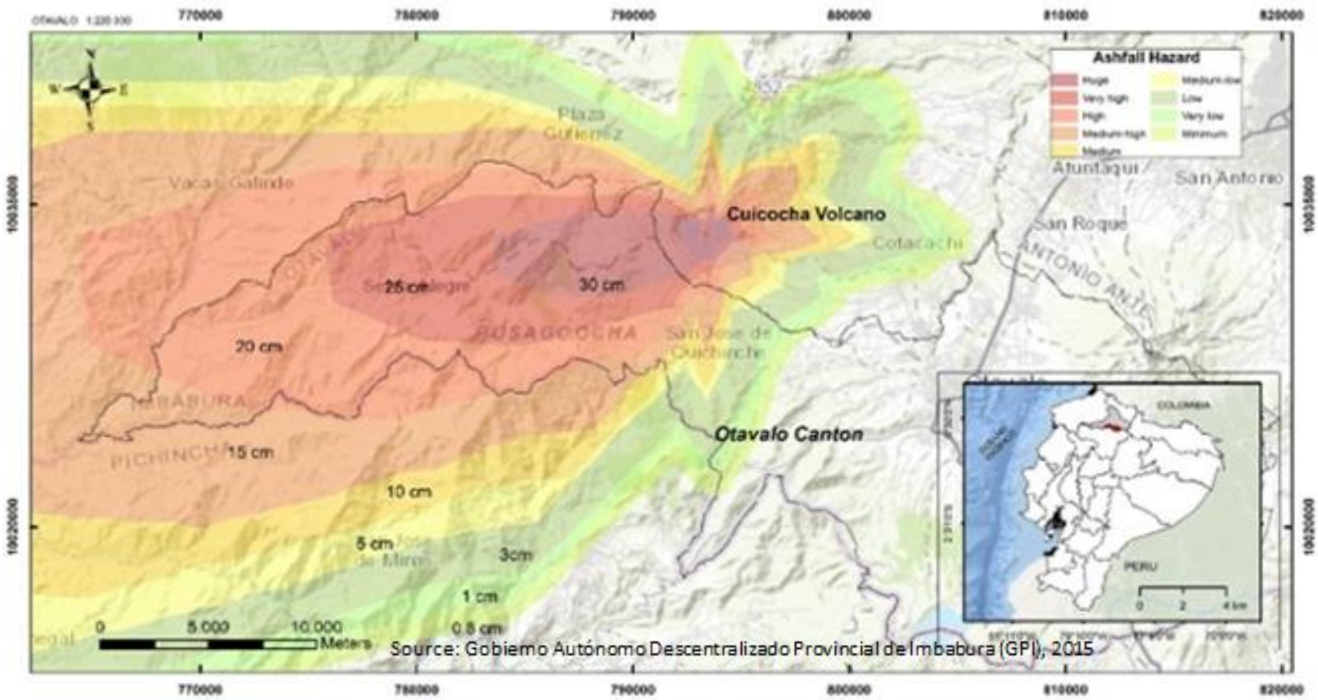

Figure 5. Ash fall distribution on Otavalo Canton and beyond of the Cuicocha volcano. Map scale is 1:220,000.

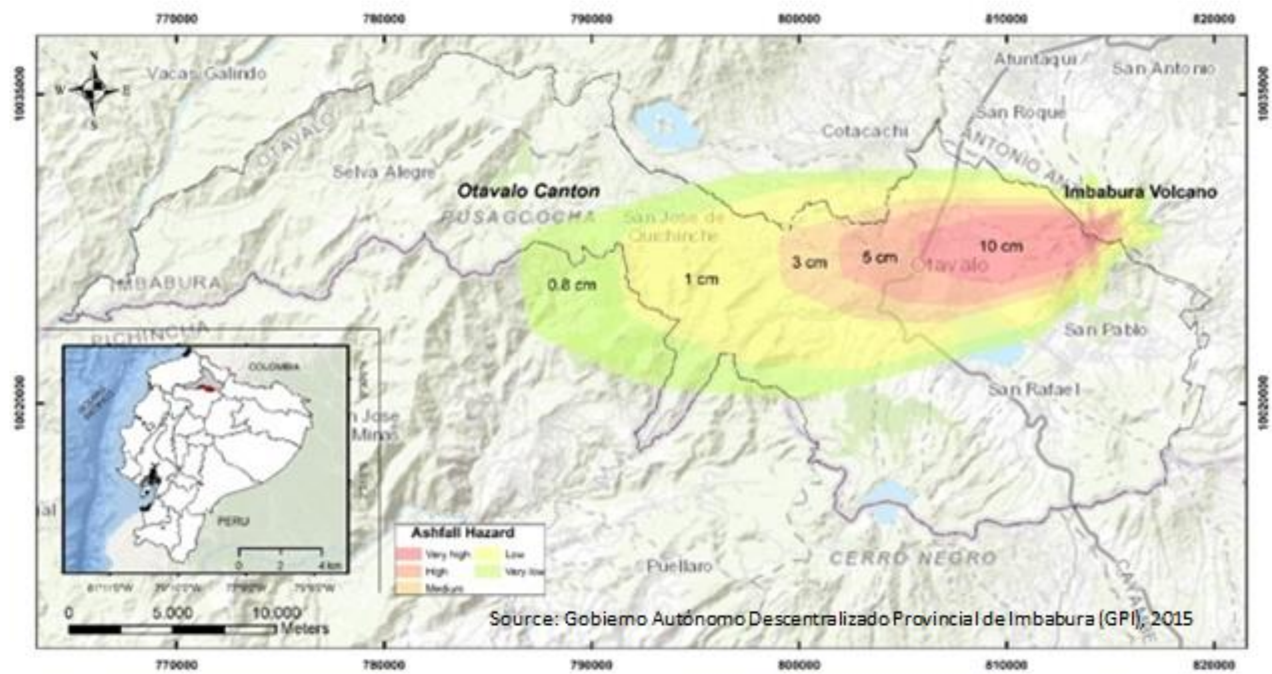

Figure 6. Ash fall distribution on Otavalo Canton and beyond of the Imbabura volcano. Map scale is 1:220,000.

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The economic impact of ash fall from both volcanoes, Cuicocha and Imbabura are summarized in Table 1. The strongest direct impact results from the Cuicocha volcano, mainly due to its violent and massive eruption. The total economic losses from Cuicocha would reach almost USD 159 million from which 94% would be based on government buildings, schools, hospitals and other strategic important structures. A further impact by ash fall from Cuicocha volcano would be in agriculture, cattle and ranching sector ranging at barely 4% of all economic losses. On the other hand, Imbabura ash fall economic losses would be much less than Cuicocha volcano with approximately USD 12 million (Table 1). The Imbabura volcanic activity would affect primary the agricultural, cattle and ranching production with 62% of the potential economic losses. However, economic losses from government buildings, schools, hospitals and other important strategic structures are still important, reaching some 33% of all economic losses.

Cuicocha and Imbabura volcanoes would strongly impact on the Canton of Otavalo with their pyroclastic flows (Figure 7). Water, energy and highways as well as vial infrastructure would specifically be affected by these volcanoes' eruptive activity (Table 2). Based on our simulations and calculations, a total of 52.11 km of highways and roads, as well as five schools, one health centre, and 3,799 buildings of different sizes would hereby be affected. However, pyroclastic flows from the Cuicocha volcano would affect less its surroundings than the ash fall impact. The economic impact would reach some 77 million USD, approximately. On the other hand, pyroclastic flows from the Imbabura volcano would be kind of devastating. Major infrastructure of Otavalo is located within the area of influence of pyroclastic flows. About 10 km of high voltage power lines, 27 km of irrigation water channels, and over 335 km of highways and roads would be directly affected. The economic impact of pyroclastic flow originated from the Imbabura volcano would reach some calculated 288 million USD (Table 2).

Table 1: Economic impact of ash fall from Cuicocha and Imbabura volcanoes

Direct economic impact	**Economic losses by Cuicocha ash (USD)**	**Economic losses by Imbabura ash (USD)**
Agriculture and cattle and ranching production	5,787,034.10	7,740,793.20
Water, energy, highway and roads infrastructure	761,689.77	360,217.67
Civil infrastructure	1,006,023.60	195,805.36
Government buildings, schools, hospitals	151,245,117.00	4,081,168.35
Total	**158,799,864.47**	**12,377,984.58**

There are some noticeable differences between the Cuicocha and Imbabura volcanoes. The major impact of pyroclastic flows would be from the Imbabura volcano, being mainly in water distribution, energy, highways and roads infrastructure with approximately 164 million USD, which is a higher economic damage than all other economic losses produced by ash fall of

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Cuicocha volcano. This impact represents 57% of all economic impacts compared to the pyroclastic flows generated by Imbabura volcano. A much lower impact would result from the Cuicocha volcano, being of about 39 million USD, representing some 51% of all economic losses from pyroclastic flows from the Cuicocha caldera lake. Clearly, the highest economic impact of pyroclastic flows would be in this category of both volcanoes (Table 2). As Second would be the impact on government buildings, schools, hospitals and other important service buildings with about 28 – 30% of all economic losses for Cuicocha and Imbabura volcanoes respectively. However, in terms of economic losses, the impact of Imbabura volcano with more than USD 86 million is much higher than Cuicocha volcano with USD million.

This study reflects one of the major problems for local communities facing natural hazards. The Government of the Canton of Otavalo had a total budget of USD 28,660,000.00 for 2021 with none contingency plan in case of a volcano eruption or any other natural hazard. If total economic losses would be over USD 200 million, this local government would have an enormous struggle to cover their losses. The total economic impact of Cuicocha and Imbabura volcanoes are summarized in Table 3. The economic impact is higher with the Imbabura volcano with more than USD 300 million, of which greatest part results from pyroclastic flows, which is 96% of the total economic losses. The opposite occurs with the Cuicocha volcano, where the total of USD 235 millions of potential losses (Table 3), 67% results from ash fall precipitation. As it has been stated before, the highest cost of ash fall by the Cuicocha volcano, would result from cleaning, equipment, materials and labour in urban areas and critical buildings like health centres, schools, and government buildings. Regarding pyroclastic flows in general, which represents usually total losses, the value obtained would mostly be based on reconstruction (Alvarado et al., 2023; Toulkeridis et al., 2007).

Table 2. Economic impact of pyroclastic flow from Cuicocha and Imbabura volcanoes

Direct economic impact	Economic losses by Cuicocha pyroclastic flows (USD)	Economic losses by Imbabura pyroclastic flows (USD)
Agriculture and cattle and ranching production	328,939.70	4,224,250.24
Water, energy, highway and roads infrastructure	38,840,144.00	164,405,073.51
Civil infrastructure	16,191,660.83	33,295,677.35
Government buildings, schools, hospitals	21,363,688.28	86,614,639.83
Total	**76,724,432.81**	**288,539,640.93**

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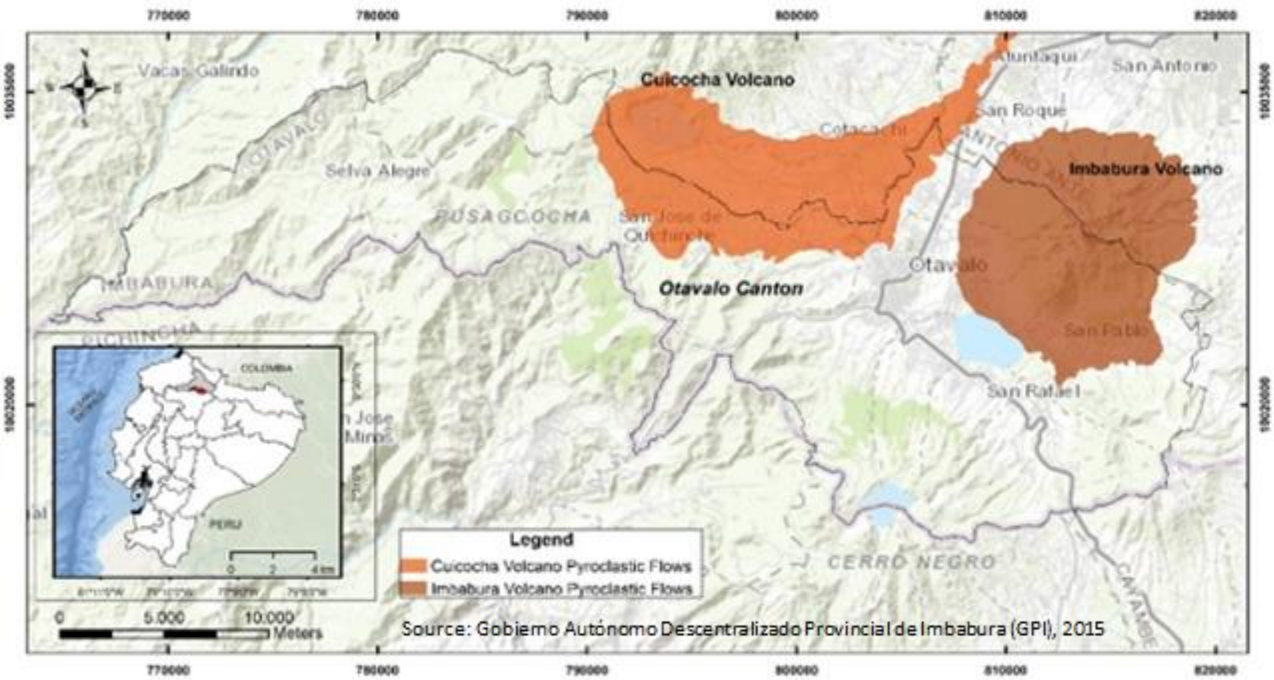

Figure 7. Potential and given distribution pyroclastic flow on Otavalo from Cuicocha and Imbabura volcanoes. Map scale: 1:220,000.

It is important fundamental to highlight, that the current study considered the direct economic damage only, even though USD 235 million and USD 300 million are severely devastating for any small local government. These potential economic impacts from Cuicocha and Imbabura volcanoes represent between 0.24 to 0.31% of the actual Ecuadorian GDP.

The present study is dealing with the impact of potential volcanoes eruptions, which correspondingly would now provide time to start a culture resilience (Wardekker et al., 2023; Oldfield & Stevenson, 2024; Firdaus et al., 2023). This would include the design of contingency plans which should include actualizing current information regarding natural hazards, establishing early alert systems, besides the establishment of safety areas where population should find cover (Wright et al., 2023; Alegría & Vergara-Pinto, 2024; Muhambya et al., 2023).

Furthermore, implementing safety measures such as the practicing of evacuation routes and drills as well as logistics associated with it, the protection of water sources and other hydric resources besides buildings to store water and food, the establishment of alternative routes for the application of emergency equipment and transportation, determination of secured or safe health centers to receive injured people, and the determination of potential relocation areas (Depari & Lindell, 2023; Horwell et al., 2023; Macias et al., 2024; Cassidy et al., 2023).

Table 3. Total direct economic cost from Cuicocha and Imbabura volcanoes.

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Direct economic impact	Direct economic impact by Cuicocha (USD)	Direct economic impact by Imbabura (USD)
Agriculture and livestock sector	6,115,973.80	11,965,043.44
Water, energy, highway and roads infrastructure	39,601,833.77	164,765,291.18
Civil infrastructure	17,197,684.43	33,491,482.71
Government buildings, schools, hospitals	172,608,805.28	90,695,808.18
Total	**235,524,297.28**	**300,917,625.51**

These results, especially the economic values, are much less of the amounts compared to other volcanoes previously mentioned such as Mt Fuji and Mt. Unzen in Japan, and Mt. St. Helen in the USA. However, this has more to do with the fact that in this part of Ecuador, the existing infrastructure, agricultural appearances and population density is also far below to the other volcanoes with higher economic impacts. Nonetheless, for a country such as Ecuador, once these potential events are manifested, the economic impact and losses will be tremendous and be relatively higher than USA´s or Japan´s percentual amounts.

However, independent of the specific compared values of economic impacts of the two Ecuadorian volcanoes, what is of greater concern that even a low VEI, such as a “2” is able to do tremendous harm. That is may the most important message of the current study, as there are hundreds if not thousands of volcanoes worldwide, which do not have the power to reach a VEI of 6, rather of a 2, with the ability of similar of worse economic and environmental impacts and harms, where similar or worse conditions are existing. Therefore, we suggest to re-evaluate worldwide the potential economic and environmental impacts of any volcano with potential VEI´s, being less of the so-called very dangerous volcanoes with a VEI >6.

4. Conclusion

This study focused in the evaluation of potential damages and consequences of the Canton of Otavalo in north-central Ecuador, that might face in case of potential eruptions of two volcanoes within its territory using geospatial tools. The evaluation was realized also with economic tools in order to determine the direct cost of such potential catastrophe. It did not consider indirect, intangible cost, business interruption cost and long term recovery cost as many authors have demonstrated. This occurred mainly due to limited available local information. Nevertheless, economic estimates from both volcanoes suggests that a major change in risk perception should occur in local authorities. A 0.24 to 0.31% impact of the current Ecuadorian GDP for a small area of only some 507 km2 should be a major wake-up call.

The results indicate different impacts on Otavalo depending on which volcano and type of natural hazard. For instance, ash fall is the most important natural hazard if Cuicocha eruption occur because of the magnitude of the volcanic eruptive phase, based on the difference of their VEI range. This difference is clearly appreciated in terms of economic losses, where USD 158 million would be lost in case of an eventual eruption of Cuicocha volcano and barely over USD 12 million in case of a volcanic event of the Imbabura volcano.

Regarding pyroclastic flows, the opposite occurs, where the eruption of Imbabura, even though is of a much lower explosivity index, would have a major economic im-pact rather than the eruption of the Cuicocha volcano. The reason for this difference is that major water, power lines, highways and roads infrastructure are located in the pathway of pyroclastic flows of the Imbabura volcano. As a result, USD 164 millions of economic losses would occur due to the activity of the Imbabura volcano, being much higher to the compared barely USD 39 million in case of the reactivation of the Cuicocha volcano.

Food production would affect more in rural areas by Imbabura ash fall with almost USD 8 millions, even though Cuicocha ash fall cover more land extension. The reason for this is that Cuicocha ash fall covers most natural forest and vegetation and not that much agricultural land.

Finally, pyroclastic flows represent a total loss in both cases. The reason of higher economic impact coming from Imbabura volcano is because its closeness to urban areas. As it was expressed before, major infrastructure is located in the pathway of pyroclastic flows of the Imbabura volcano, leading subsequently to higher economic losses.

5. Authors' contribution

Contribution of each author is as follows:

Dr. Fabián Rodríguez-Espinosa Conceptualization, Methodology, data analysis and interpretation, Writing-Original draft preparation.

B.Sc. Cristina Cabrera-Paladines, field investigation, data curation, data interpretation and data Validation.

B.Sc. Juan Calderón-Tupiza, field investigation data spatial modelling analysis, data interpretation and data validation.

Dr. Theofilos Toulkeridis, volcanic data interpretation and data validation, formal analysis, writing Review and editing.

6. Competing interests

The authors declare that they have no conflict of interest.

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9. References

Aguilar, I., & Alvarado, G. E. (2014). Human and Economic Losses Caused by the Volcanism in Costa Rica from 1953 to 2005. Revista Geológica de América Central, (51), 93-128.

Alegría, C., & Vergara-Pinto, F. (2024). Living in-between: Implications of local risk perceptions for the management of future eruptions at the Calbuco and Osorno volcanoes (Ensenada, Chile). Andean Geology, 51(1), 63-85. https://doi.org/10.5027/andgeoV51n1-3668

Alvarado, G. E., Toulkeridis, T., Miyabuchi, Y., & Pérez, W. (2023). Review of bomb and ash flows: Genesis and case studies of a subset of block and ash flow deposits. Andean Geology, 50(3), 346-371. https://doi.org/10.5027/andgeov50n3-3653

Annen, C. and Wagner, J. J. (2003) The Impact of Volcanic Eruptions During the 1990s. Natural Hazards Review, 4 (4), 169-175.

Barberi, F., Coltelli, M., Frullani, A., Rosi, M., & Almeida, E. (1995). Chronology and dispersal characteristics of recently (last 5000 years) erupted tephra of Cotopaxi (Ecuador): implications for long-term eruptive forecasting. Journal of Volcanology and Geothermal Research, 69(3-4), 217-239.

Baxter, P. J., Bernstein, R. S., & Buist, A. S. (1986). Preventive health measures in volcanic eruptions. American journal of public health, 76(Suppl), 84-90.

Bedon, M. (2014) Propuesta de un plan para la gestión de riesgos volcánicos, con enfoque a la afectación al sector agro-pecuario del cantón Mejía [Tesis de pregrado, Universidad ESPE]. Repositorio Institucional de la Universidad de las Fuerzas Armadas ESPE.

Bonadonna, C. and Houghton, B. F. (2005) Total grain-size distribution and volume of tephra-fall deposits. Bulletin of Volcanology, 67(5), 441–456. https://doi.org/10.1007/s00445-004-0386-2

Bretón, M. (2018) Las erupciones volcánicas y sus consecuencias en la Cuenca del Pacífico. Portes, Revista Mexicana de Estudios Sobre La Cuenca Del Pacífico, 12(23), 165–177.

Brown, S. K., Jenkins, S. F., Sparks, R. S. J., Odbert, H., & Auker, M. R. (2017). Volcanic fatalities database: analysis of volcanic threat with distance and victim classification. Journal of Applied Volcanology, 6(1), 1-20.

Bustos, E., Arnosio, J. M., & Norini, G. (2015) Using digital elevation models for morphological analysis of La Hoyada volcanic complex | Análisis morfológico del complejo volcánico la hoyada puna austral mediante la aplicación de modelos de elevación digital. Revista de La Asociacion Geologica Argentina, 72(2), 279–291.

Cao Z., Burzik M., Yang Q. and Patri A. (2021) Simulating the Transport and Dispersal of Volcanic Ash Clouds with Initial Conditions Created by a 3D Plume Model. Frontiers in Earth Sciences, 9:704797. doi: 10.3389/feart.2021.704797.

Cao Z., Patra, A., Bursik M., Pitman E. B. and Jones M. (2018). Plume-sph 1.0: a Three-Dimensional, Dusty-Gas Volcanic Plume Model Based on Smoothed Particle Hydrodynamics. Geoscientific Model Development, 11, 2691–2715. doi:10.5194/gmd-11-2691-2018

Cassidy, M., Sandberg, A., & Mani, L. (2023). The ethics of volcano geoengineering. Earth's Future, 11(10), e2023EF003714. https://doi.org/10.1029/2023EF003714

Corominas, O. & Martí, J. (2015) Estudio comparativo de los planes de actuación frente el riesgo volcánico (Costa Rica, El Salvador, Ecuador, España, México, Nicaragua y Chile). Revista Geológica de América Central, 52, 33–56. https://doi.org/10.15517/rgac.v0i52.18980

Cunningham E. J. (2018) Nature Interrupted: Affect and Ecology in the Wake of Volcanic Eruption in Japan. Conservation and Society, 16(1), 41-51. DOI:10.4103/cs.cs_16_50.

De Guzman, E. M. (2006) Eruption of Mount Pinatubo in the Philippines in June 1991. Eruption of Mount Pinatubo in the Philippines, Technical Report, Asian Disaster Reduction Center. Kobe City, Japan. 18 pp.

Decker, R. W. and Decker, B. B. (1991) Mountains of Fire: The Nature of Volcanoes. Cambridge, United Kingdom, Cambridge University Press.

Depari, C. D., & Lindell, M. K. (2023). “Moving or not?”: Factors affecting community responses to environmental disruption. International journal of disaster risk reduction, 95, 103898. https://doi.org/10.1016/j.ijdrr.2023.103898

Doocy, S., Daniels, A., Dooling, S., & Gorokhovich, Y. (2013). The human impact of volcanoes: a historical review of events 1900-2009 and systematic literature review. PLoS currents, 5.

Echegaray-Aveiga, R. C., Rodríguez-Espinosa, F., Toulkeridis, T., & Echegaray-Aveiga, R. D. (2020). Possible effects of potential lahars from Cotopaxi volcano on housing market prices. Journal of Applied Volcanology, 9(1), 1-11.

El Hadri H., Goujon M., Paris R. (2021) A database of the economic impacts of historical volcanic eruptions. Études et Documents, n°14, Centre d'Etudes Prospectives et d'Informations Internationales CERDI, Paris, France.

Ferrari, L., Orozco Esquivel, T., Navarro, M., López-Quiroz, P., & Luna, L. (2018). Digital Geologic Cartography and Geochronologic Database of the Trans-Mexican Volcanic Belt and Adjoining Areas. Terra Digitalis, 2(1), 34. https://doi.org/10.22201/igg.terradigitalis.2018.1.34

Ferreiro, N. A., Gonzalez Polo, M., Satti, P. S. y Mazzarino, M. J. (2020) La erupción del Complejo Volcánico Puyehue-Cordón Caule (2011) y su efecto sobre los suelos de Patagonia Norte. En: P. A. Imbellone y O. A. Barbosa (Eds.) Suelos y Volcanismo Argentina. Ciudad Autónoma de Buenos Aires, Argentian, Asociación Argentina de la Ciencia del Suelo AACS. pp 291-306.

Fiantis D., Irawan Ginting F., Gusnidar, Nelson M. and Minasny B. (2019) Volcanic Ash, Insecurity for the People but Securing Fertile Soil for the Future. Sustainability, 11, 3072. doi:10.3390/su11113072.

Firdaus, A., Lestari, F., Afiff, S. A., & Herdiansyah, H. (2023). Integration of knowledge and local wisdom for disaster resilience in Anak Krakatau volcano. Jàmbá-Journal of Disaster Risk Studies, 15(1), 1457. https://doi.org/10.4102/jamba.v15i1.1457

Freeth, S. J. (1993). The Lake Nyos gas disaster: conclusions and predictions. geochemical precursors of earthquakes and volcanic eruptions, 73, 383-390.

Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T., & Talamo, S. (2006). Santorini eruption radiocarbon dated to 1627-1600 BC. Science, 312(5773), 548-548.

GAD-Otavalo, 2020 Actualización del Plan de Desarrollo y Formulación Del Plan De Ordenamiento Territorial Del Cantón Otavalo, Ecuador.

Godoy, B., Clavero, J., Rojas, C. y Godoy, E. (2012) Facies volcánicas del depósito de avalancha de detritos del volcán Tata Sabaya, Andes Centrales. Andean Geology, 39 (3), 394-406. https://doi.org/10.5027/andgeoV39n3-a03.

Goujon, M., El Hadri, H. and Paris, R. (2021) A database of the economic impacts of historical volcanic eruptions. Études et Documents n° 14, Centre D'Études et de Recherches Sur le Developpment International, Universite Clermont Auverne. 43 pp. ffhal-03186803

Guerrero, D. (2019) Determinación De La Vulnerablidad Volcánica En La Parroqui Angochagua – Ibarra, Ecuador. Universidad Técnica del Norte. Facultad de Ingeniería en Ciencias Agropecuarias y Ambientales.

Gueugneau, V., Kelfoun, K., Charbonnier, S., Germa, A., & Carazzo, G. (2020). Dynamics and impacts of the May 8th, 1902 pyroclastic current at Mount Pelée (Martinique): new insights from numerical modeling. Frontiers in Earth Science, 8, 279.

Harmon, R. S., & Rapela, C. W. (Eds.). (1991). Andean magmatism and its tectonic setting (Vol. 265). Geological Society of America.

Hill, B. E., Connor, C. B., Jarzemba, M. S., La Femina, P. C., Navarro, M., & Strauch, Wl. (1998) 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions. Bulletin of the Geological Society of America, 110(10), 1231–1241. https://doi.org/10.1130/0016-7606(1998)110<1231:EOCNVN>2.3.CO;2.

Horwell, C. J., Elias, T., Covey, J., Bhandari, R., & Truby, J. (2023). Perceptions of volcanic air pollution and exposure reduction practices on the Island of Hawai 'i: Working towards socially relevant risk communication. International Journal of Disaster Risk Reduction, 95, 103853. https://doi.org/10.1016/j.ijdrr.2023.103853

Jácome, E. (2011). Evaluación del impacto de la ceniza volcánica emitida por el volcán Tungurahua, sobre los suelos destinados a la explotación agrícola (Cantón QUERO). (Universidad Técnica de Cotopaxi]. http://repositorio.utc.edu.ec/bitstream/27000/4501/1/PI-000727.pdf

Jenkins, S. F., Wilson, T., Magill, C., Miller, V., Stewart, C., Blong, R., Marzocchi, W., Boulton, M., Bonadonna, C. and Costa, A. (2015) Volcanic ash fall hazard and risk. In: S.C. Loughlin, R. S. J. Sparks, S. K. Brown, S. F. Jenkins and C. Vye-Brown (Eds.) Global Volcanic Hazard and Risk, Cambridge, Cambridge University Press. pp. 173-221.

Jiang, Z., Yu, S., Yoon, S. and Choi, K. (2013) Damage and Socio-Economic Impact of Volcanic Ash. Journal of Korean Earth Science Society, 34(6), 536−549. http://dx.doi.org/10.5467/JKESS.2013.34.6.536.

Le Pennec, J. L., Ruiz, A. G., Eissen, J. P., Hall, M. L., & Fornari, M. (2011). Identifying potentially active volcanoes in the Andes: Radiometric evidence for late Pleistocene-early Holocene eruptions at Volcán Imbabura, Ecuador. Journal of Volcanology and Geothermal Research, 206(3-4), 121-135.

Leone, F., & Gaillard, J. C. (1999). Analysis of the institutional and social responses to the eruption and the lahars of Mount Pinatubo volcano from 1991 to 1998 (Central Luzon, Philippines). GeoJournal, 49(2), 223-238.

Luongo, G., Perrotta, A., Scarpati, C., de Carolis, E., Patricelli, G. and Ciarallo. A. (2003) Impact of the AD 79 explosive eruption on Pompeii, II. Causes of death of the inhabitants inferred by stratigraphic analysis and areal distribution of the human casualties. Journal of Volcanology and Geothermal Research, 126(3-4),169-200. https://doi.org/10.1016/S0377-0273(03)00147-1.

Macías, L., Quiñonez-Macías, M., Toulkeridis, T., & Pastor, J. L. (2024). Characterization and geophysical evaluation of the recent 2023 Alausí landslide in the northern Andes of Ecuador. Landslides, 21(3), 529-540. https://doi.org/10.1007/s10346-023-02185-6

Manning, S. W., Höflmayer, F., Moeller, N., Dee, M. W., Ramsey, C. B., Fleitmann, D., ... & Wild, E. M. (2014). Dating the Thera (Santorini) eruption: archaeological and scientific evidence supporting a high chronology. Antiquity, 88(342), 1164-1179.

Mazzocchi, M., Hansstein, F., & Ragona, M. (2010). The 2010 volcanic ash cloud and its financial impact on the European airline industry. In CESifo Forum (Vol. 11, No. 2, pp. 92-100). München: ifo Institut für Wirtschaftsforschung an der Universität München.

Medeiros J., Carmo R., Pimentel A., Cabral Vieira J. and Queiroz G. (2021) Assessing the impact of explosive eruptions of Fogo volcano (São Miguel, Azores) on the tourism economy. Natural Hazards and Earth System Sciences, 21, 417-437. https://doi.org/10.5194/nhess-21-417-2021.

Melián, G. V., Toulkeridis, T., Pérez, N. M., Hernández, P. A., Somoza, L., Padrón, E., ... & Cordero, M. (2021). Geo-chemistry of Water and Gas Emissions From Cuicocha and Quilotoa Volcanic Lakes, Ecuador. Front. Earth Sci, 9, 741528.

Muhambya, K., Chaubey, N., Kasereka, S., & Kyandoghere, K. (2023). Towards a Dedicated Social Media and Groupware for Effective Communication during the Nyiragongo Volcanic Crisis. Procedia Computer Science, 224, 443-449. https://doi.org/10.1016/j.procs.2023.09.062

Nagamura M. (2021) Volcanic eruption risk management in Japan. Consorseguros Revista Digital, 15.

Naismith, A. K., Watson, I. M., Escobar-Wolf, R., Chigna, G., Thomas, H., Coppola, D., & Chun, C. (2019). Eruption frequency patterns through time for the current (1999–2018) activity cycle at Volcán de Fuego derived from remote sensing data: Evidence for an accelerating cycle of explosive paroxysms and potential implications of eruptive activity. Journal of Volcanology and Geothermal Research, 371, 206-219.

Noji, E. K. (1997) The Nature of Disaster: General Characteristics and Public Health Effects. In E.K. Noji (Ed.) The Public Health Consequences of Disasters. (1997). Oxford United Kingdom, Oxford University Press. pp 3-20.

Oldfield, J., & Stevenson, A. (2024). After the fire: An ecological, phenomenological exploration of resilience-building following the Fuego volcanic eruption in Guatemala. American Journal of Community Psychology. https://doi.org/10.1002/ajcp.12748

Oppenheimer, C. (2003). Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. Progress in physical geography, 27(2), 230-259.

Padrón, E., Hernández, P. A., Toulkeridis, T., Pérez, N. M., Marrero, R., Melián, G., ... & Notsu, K. (2008). Diffuse CO2 emission rate from Pululahua and the lake-filled Cuicocha calderas, Ecuador. Journal of Volcanology and Geothermal Research, 176(1), 163-169.

Paladio-Melosantos, M. L. O., R. U. Solidum, W. E. Scott, R. B. Quiambao,J. V. Umbal, K. S. Rodolfo, B. S. Tubianosa, P. J. Delos Reyes, R. A. Alonso, and H. B. Ruelo (1996), Tephra falls of the 1991 eruptions ofMount Pinatubo, inFire and Mud: Eruptions and Lahars of MountPinatubo, Philippines, edited by C. G. Newhall and R. S. Punongbayan,pp. 687–731, Philipp. Inst. of Volcanol. and Seismol, Quezon City, Philippines.

Pavón, F. (2017) Análisis Del Impacto Socioeconómico De Los Lahares Y Caída De Ceniza Ante Una Eventual Erupción Del Volcán Cayambe En La Actividad Floricola En Los Cantones De Cayambe Y Pedro Moncayo. Escuela Politécnica Nacional.

Pinatubo Volcano Observatory Team. (1991). Lessons from a major eruption: Mt. Pinatubo, Philippines. Eos, Transactions American Geophysical Union, 72(49), 545-555.

Ramírez J., Vásconez F. J., López A., Valencia F., Quilumba F., Vásconez Müller A. Hidalgo S. and Bernard B. (2022) Impact of volcanic ash from Cotopaxi-2015 and Tungurahua-2016 eruptions on the dielectric characteristics of suspension insulators, Ecuador. Journal of Applied Volcanology, 11(7). https://doi.org/10.1186/s13617-022-00117-y.

Ramírez, J., Vásconez, F. J., López, A., Valencia, F., Quilumba, F., Vásconez Müller, A., Hidalgo, S. and Bernard, B. (2022) Impact of volcanic ash from Cotopaxi-2015 and Tungurahua-2016 eruptions on the dielectric characteristics of suspension insulators, Ecuador. Journal of Applied Volcanology, 11, 7. https://doi.org/10.1186/s13617-022-00117-y.

Ridolfi, F., Puerini, M., Renzulli, A., Menna, M., & Toulkeridis, T. (2008). The magmatic feeding system of El Reventador volcano (Sub-Andean zone, Ecuador) constrained by texture, mineralogy and thermobarometry of the 2002 erupted products. Journal of Volcanology and Geothermal Research, 176(1), 94-106.

Rodriguez, F., Toulkeridis, T., Sandoval, W., Padilla, O., & Mato, F. (2017). Economic risk assessment of Cotopaxi volcano, Ecuador, in case of a future lahar emplacement. Natural Hazards, 85(1), 605-618.

Romano, L. E. (2019) 14 Observaciones Que Surgen Del Reciente Desastre En El Volcán De Fuego, 2018, Guatemala. Revista de Estudios Latinoamericanos Sobre Reducción Del Riesgo de Desastres, 3(2), 109–112. https://doi.org/10.55467/reder.v3i2.36.

Santos, J., Roquel, K. I. D. Z., Lamberte, A., Tan, R. R., Aviso, K. B., Tapia, J. F. D., Solis, C. A. and Yu, K. D. S. (2022) Assessing the economic ripple effects of critical infrastructure failures using the dynamic inoperability input-output model: a case study of the Taal Volcano eruption. Sustainable and Resilient Infrastructure, 2127999. https://doi.org/10.1080/23789689.2022.2127999.

Self, S., Rampino, M. R., Newton, M. S., & Wolff, J. A. (1984). Volcanological study of the great Tambora eruption of 1815. Geology, 12(11), 659-663.

Sigurdsson, H., Cashdollar, S., & Sparks, S. R. (1982). The eruption of Vesuvius in AD 79: reconstruction from historical and volcanological evidence. American journal of archaeology, 86(1), 39-51.

Soncin, S., Talbot, H. M., Fernandes, R., Harris, A., von Tersch, M., Robson, H. K., ... & Craig, O. E. (2021). High-resolution dietary reconstruction of victims of the 79 CE Vesuvius eruption at Herculaneum by compound-specific isotope analysis. Science advances, 7(35), eabg5791.

Sword-Daniels V., Wilson, T. M., Sargeant S., Rossetto T., Twigg J., Johnston D. M., Loughlin S. C. and Cole J. W. (2022) Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience, Chaper 26. In: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) 2014. The Eruption of Soufriere Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 471–488. http://dx.doi.org/10.1144/M39.26

Tanyileke G., Ntchantcho, R., Fantong, W., Aka, F. and Hell, J. (2019) 30 years of the Lakes Nyos and Monoun gas disasters: A scientific, technological, institutional and social adventure. Journal of African Earth Sciences, 150, 415–424.

Toulkeridis, T., & Zach, I. (2017). Wind directions of volcanic ash-charged clouds in Ecuador–implications for the public and flight safety. Geomatics, Natural Hazards and Risk, 8(2), 242-256.

Toulkeridis, T., & Zak, V. (2008). Cuicocha-Lake of the Gods (bilingual Spanish-English). Geo-series# 1 CGVG-USFQ, 80.

Toulkeridis, T., Arroyo, C. R., Cruz D'Howitt, M., Debut, A., Vaca, A. V., Cumbal, L., ... & Aguilera, E. (2015). Evaluation of the initial stage of the reactivated Cotopaxi volcano–analysis of the first ejected fine-grained material. Natural Hazards and Earth System Sciences Discussions, 3(11), 6947-6976.

Toulkeridis, T., Buchwaldt, R., & Addison, A. (2007). When volcanoes threaten, scientists warn-Scientists use volcanoes' pre-eruptive behaviors, such as increasing seismic activity, to warn that an eruption may be imminent. But what happens when a. Geotimes, 52(11), 36-40.

Toulkeridis, T., Martinez, N., Barrantes, G., Rentería, W., Barragan-Aroca, G., Simón-Baile, D., Palacios, I., Salazar, R., Salcedo-Hurtado, E.d.J. and Pararas-Carayannis, G., 2022. Impact and response in Central and South America due to the tsunami generated by the submarine eruption of Hunga Tonga-Hunga Ha'apai volcano. Science of Tsunami Hazards, 41(1), 1-38.

Toulkeridis, T., Seqqat, R., Arias, M. T., Salazar-Martinez, R., Ortiz-Prado, E., Chunga, S., ... & Debut, A. (2021). Volcanic Ash as a precursor for SARS-CoV-2 infection among susceptible populations in Ecuador: A satellite Imaging and excess mortality-based analysis. Disaster Medicine and Public Health Preparedness, 1-13.

Toulkeridis, T., Rosenfeld, H. G., Rizzi, F. N., Castillo-Fortina, A., Jaeggi-Castagno, J., Vizuete, K., ... & Cruz-D, M. (2025). Implications of the eruptive behavior based on volcanic ash emitted during the 2015 activity of the Cotopaxi volcano, Ecuador. *Multidisciplinary Science Journal*, *7*(3), 2025121-2025121.

Voight, B. (1990). The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection. Journal of volcanology and geothermal research, 42(1-2), 151-188.

Volentik, A. C. M., Bonadonna, C., Connor, C. B., Connor, L. J., & Rosi, M. (2010). Modeling tephra dispersal in absence of wind: Insights from the climactic phase of the 2450BP Plinian eruption of Pululagua volcano (Ecuador). Journal of Volcanology and Geothermal Research, 193(1–2), 117–136. https://doi.org/10.1016/j.jvolgeores.2010.03.011.

Von Hillebrandt, C. (1989) Estudio Geovolcanológico del Complejo Cuicocha-Cotacachi y sus Aplicaciones, Provincia de Imababura. [Tesis de Magister]. Escuela Politécnica Nacional.

https://doi.org/10.5194/egusphere-2025-298
Preprint. Discussion started: 13 March 2025

Wardekker, A., Nath, S., & Handayaningsih, T. U. (2023). The interaction between cultural heritage and community resilience in disaster-affected volcanic regions. Environmental Science & Policy, 145, 116-128. https://doi.org/10.1016/j.envsci.2023.04.008

Wilson, T. M., Stewart C., Sword-Daniels V., Leonard G. S., Johnston D. M., Cole J. W., Wardman J., Wilson G. and Barnard S. T. (2012) Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, 45-46, 5-23. https://doi.org/10.1016/j.pce.2011.06.006.

Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G., Barnard, S.T. (2012). Volcanic ash impacts on critical infrastructure. Physics and Chemistry of the Earth, 45–46, 5-23.

World Bank, GFDRR (2022) The January 15, 2022 Hunga Tonga-Hunga Ha'Apai eruption and Tsunami, Tonga. A Global Rapid Post Disaster Damage Estimation (GRADE) Report. The Government of Tonga, The World bank Group, the Global Facility for Disaster Reduction and Recovery (GFDRR). Washington DC, 42 pp.

Wright, H. M., Driedger, C. L., Pallister, J. S., Newhall, C. G., Clynne, M. A., & Ewert, J. W. (2023). Development of a volcanic risk management system at Mount St. Helens—1980 to present. Bulletin of Volcanology, 85(10), 53. https://doi.org/10.1007/s00445-023-01663-y

Zhang, Y. (1996). Dynamics of CO2-driven lake eruptions. Nature, 379(6560), 57-59.

Zuccaro J., Leone M. F., del Cogliano D. and Sgroi A. (2013) Economic impact of explosive volcanic eruptions: A simulation-based assessment model applied to Campania region volcanoes. Journal of Volcanology and Geothermal Research, 266, 1-15. http://dx.doi.org/10.1016/j.jvolgeores.2013.09.002.