Assessing personal exposures to volcanic hazards on a global scale

Bachelor thesis
Emilia Leijnse
6192742

Utrecht University
Bachelor Earth Sciences

First supervisor: Prof. dr. Derek Karssenberg
Second supervisor: dr. Menno Straatsma
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Summary

Due to Earth's growing population, every day more people are exposed to volcanic hazards. This exposure of humans to volcanic hazards, the personal exposure to volcanic hazards, can be assessed by many different methods. What remains uncertain is what assessment methods are best suited for a global assessment of the personal exposure to volcanic hazards. The aim of this thesis is to determine the best suited method for the assessment of exposure to volcanic hazards. This method is tested with the use of a case study on a continental area, Central America. If the personal exposure can be compared on a global scale, countries around the world will be able to exchange volcanic hazard management strategies easier. Hereby, mapping out the personal exposure to volcanic hazard on a global scale will contribute to the reduction of populations at risk for volcanic hazards. The assessment of personal exposure to volcanic hazards is divided into sub-topics; the driving mechanisms for people to life in the vicinity of volcanoes and different volcanic hazards, different methods to assess personal exposure to volcanism on a global scale and testing the best suited method. The assessment of different levels of volcanic explosivity was studied with the use of the VEI, the spatial assessment of volcanic hazards is investigated by explaining the five most frequently used volcanic hazards map types; geology-based maps, integrated qualitative maps, modelling-based hazard maps, probabilistic hazard maps and administrative maps. The three most used personal exposure assessment methods, the PEI, VPI and the VRC are discussed. The method considered best suited for the assessment of personal exposure to volcanic hazards on a global scale is the Population Exposure Index. The case study concludes that five out of the 110 volcanoes in Central America are assigned to a PEI-7, which is the highest level of the Population Exposure Index.

1 Introduction

Ever since the first settling of villages, the human population distribution has been determined by environmental influences. Factors like climate, vegetation, relief, biodiversity and soil properties influence where people choose to settle down. In areas in the vicinity of active volcanoes, all of these factors are directly influenced by volcanism (Acocella, 2014). The relationship between population distribution and volcanism has been an area of interest for many years (Freire et al., 2019) Volcanic eruptions during 1900-2020 are responsible for nearly one hundred thousand deaths and affected more than 9 million people worldwide (D. Guha-Sapir, 2020). Volcanic eruptions are accompanied with mechanical, thermal, toxicological and electrical impacts that can cause death or injury to humans (Horwell et al., 2015). Inhabitation of areas in the vicinity of active volcanoes does not solely impact health factors, it also comes with the risk of causing extensive economic losses, social impacts and disturbances to livelihoods (Freire et al., 2019). In spite of the aforementioned risks, sizable populations do settle in areas in the vicinity of volcanoes (Small & Naumann, 2001). Due to population growth and urbanization the number of people exposed to volcanic hazards is rising (Chester et al., 2000). The movement of people to areas in the vicinity of volcanoes is caused by the fact that volcanic activity has beneficial effects on the provision of nutrients to surrounding soil. These nutritious soils attract agrarian societies. Besides agricultural benefits, volcanic areas are also favorable because of economic reasons, such as geothermal energy, resource extraction and tourism (Freire et al., 2019). Not only communities, but also individual humans can be exposed to the risk of volcanic hazards. This is so-called personal exposure to volcanism (Loughlin et al., 2015). It is essential to be able to evaluate the global personal exposure to volcanism because of the powerful and destructive nature of volcanic hazards. Additionally, due to the growing population in the vicinity of volcanoes it is even more important to study this. Most studies on this topic focused on the description of occurred volcanic disasters based on small areas or on national scales. Volcanic eruptions can be difficult to forecast, therefore the assessment of volcanic hazards is done on a set of different scales (Doyle et al., 2014). As volcanoes cause different hazards such as flows of liquids, gasses and solids, the damages that are induced by them vary (Fujita et al., 2019). Because of these variations in hazards and damages, different types of volcanic hazard mapping exist. To assess personal exposure in the proximity of volcanoes, high-quality population distribution data is essential.

It is interesting to investigate how the personal exposure to volcanism can be assessed best on a global level for purposes such as the improvement of disaster risk reduction management. If the personal exposure to volcanic hazards is defined for multiple countries, comparing and improving different hazard mitigation strategies will become more feasible. This means that information about global personal exposure contributes to the improvement of adequate emergency response (Valentijn et al., 2020). Additionally, it would place volcanic risk in the perspective of other risks. If the magnitude of different types of risks are known, it can be decided to focus on what risks need to be reduced first. The aim of this study is to identify the best-available method that can be applied for assessing the personal exposure to volcanic hazards on a global scale. This is done by evaluating different existing methods and deciding what method would be the most appropriate given the limited data at global scale. To evaluate the proposed method, a case study is done on a small area.

The main question this study will focus on is 'What are the determinants of personal exposure to volcanic hazards and how can this exposure be assessed at global scale?'. To answer this question as complete as possible, the main question is divided in to three sub-questions:

1. What are the driving mechanisms that determine population distribution in the vicinity of volcanoes and what are the hazards for humans concerning a volcanic eruption?
2. How can personal exposures to volcanism be assessed at a global scale?
3. What is the distribution of personal exposures to volcanic hazards across the population living in the vicinity of a number of volcanoes and does this calculation indicate global assessment of personal exposures is feasible at an acceptable level of credibility?

First, the driving mechanisms that determine the population distribution in the vicinity of active volcanoes are studied in chapter 3.1, together with different types of hazards pertaining to humans that come with volcanic eruptions. This knowledge will give more insight in how to assess the different hazards at a global scale, which will be discussed in section 4.1. The assessment of volcanic exposure at a global scale will be studied in chapter 3.2. This chapter consists of four parts. The first part focusses on a method that ranks volcanoes by risk. The second part describes different mapping methods that assess the spatial distribution of hazards. After this, three predominant methods that assess the personal exposure to volcanic hazard are described. This section ends with information on a few reliable datasets. The information that is provided in this part of the study will be discussed in section 4.2, where a proposal is made as to which method is most suitable for achieving personal exposure data for volcanism on a global scale. This proposal is tested in chapter five, in which the distribution of volcanic hazard exposures across the population in the vicinity of a number of volcanoes will be studied for a small area. This will be done by applying the most suitable method for global assessment that is identified by answering the second sub-question. The discussion in this section of the study will evaluate if the proposed method works. The method for this part of the study is yet to be determined in the results of literature study.

2 Method

2.1 Literature methodology

The information needed to answer the first two sub-questions is obtained by means of an extensive literature study. The search engines that are used in this study are Scopus, Web of Science, WorldCat and Google Scholar. Literature is acquired by using the search terms comparable to 'volcanism', 'hazards', 'population', 'population distribution', 'risk map', 'global map', 'exposure' and combinations of these terms. Conducting a snowball search with these terms yields a large amount of literature (Greenhalgh Trisha, 2005). This literature is read through, analyzed and sorted in order to distinguish essential information necessary for this study. For the first sub-question information about different driving mechanisms for population distribution in the vicinity of volcanoes and different volcanic hazards is acquired. For the second sub-question different methods for the assessment of global exposure to volcanism are studied. The properties of these different methods will be reviewed. In addition to the literature, databases for assessing personal exposure to volcanism are discussed. After discussing the different methods that are found in the literary study, the method that is most suited for assessing global personal exposure to volcanic hazards is proposed. RefWorks is used for literary references in this study.

2.2 Distribution of personal exposure to volcanism

The second part of the study is a case study that will act as a test to prove if the proposed method is indeed suited to assess the personal exposure to volcanic hazards on a global scale. Therefore, the methodology for this part of the study is given after the results of the second sub-question and thereafter discussed.

3 Results

3.1 Driving mechanisms for population distribution and different volcanic hazards

3.1.1 Driving mechanisms for population distribution

The different driving mechanisms for people who choose to live in areas in the vicinity of potential volcanic hazards are important factors in the population distribution in relation to volcanoes. The most common determinants are urbanization, lifestyle, resource extraction, geothermal energy, tourism, agriculture and climatic advantages.

Urbanization is the concentrating of people and economic investment at particular points on the Earth's surface (Chester et al., 2000). Cities in the vicinity of volcanoes pull more people to come to the city because people in less developed regions close-by expect that the authorities in the city will offer safety from volcanic hazards (Chester et al., 2000). This driving mechanisms reinforces the other mechanisms; it is not the initial cause of clustering around volcanoes. However, urbanization is the reason for most people to move to a volcanic area. Another driving mechanism as why people would choose to live in an area that is at risk for volcanic hazards is lifestyle. This term is related to urbanization. Lifestyle can cause the diminishing of awareness of environmental hazards and how they are responded to (Chester et al., 2000). This form of lifestyle only happens in urban areas. Urban societies do not interact much with nature and are not well-aware of their surroundings, this form of lifestyle causes diminishing awareness to volcanic hazard that may occur in an urban area. It has been argued by some studies that volcanic eruptions do not present a serious hazard to humankind (Wijkman, 1984). This is also a form of lifestyle, because it causes humans to adapt their awareness and to not be afraid of living in volcanic areas anymore. The spectacular scenery of volcanic areas attracts tourists to visit volcanic areas. Tourism is a driving mechanism for people to live in volcanic areas because it is a source of employment and income. Every year millions or tourists travel to visit active and dormant volcanoes. Volcanic tourism exists for many centuries (Brtnický et al., 2020).

Resource extraction is a driving mechanism for communities to settle in the vicinity of volcanoes as well (Ilham et al., 2020). Volcanic areas contain resources that cannot be found in quantities as large in non-volcanic areas. The valleys surrounding volcanoes are often filled with thick pyroclastic and volcaniclastic deposits, which are characterised by a large grain-size distribution. These deposits contain chemical and mineralogical properties originating from volcanic ashes. This is used as the raw material for geopolymers (De Bélizal et al., 2011). Volcanic areas are used for sulfur mining as well (Freire et al., 2019). Another driving mechanism is the extraction of geothermal energy. Geothermal energy is a clean, sustainable, and ubiquitous resource. Volcanoes that are accompanied by magma reservoirs, produce high geothermal located not deep into the Earth's crust. Because the geothermal energy is relatively higher at low elevations in the vicinity of volcanoes, extracting geothermal energy is more efficient in volcanic areas (Collard et al., 2020). Another pulling factor to volcanic areas are agricultural benefits. A positive consequence of volcanic eruptions is that the ash and lava ejected from the volcanoes tend to form edifices that weather rapidly. This weathering creates nutrient rich soils, called andosols that contain a lot of carbon relative to other soil types. Soils that originate from volcanic deposits have a high carbon storage capacity due to poorly crystalline minerals that have large surface areas (Fiantis et al., 2019). Because of their high nutrient content, andosols are very attractive for agriculture (Small & Naumann, 2001). Tropical volcanoes provide climatic advantages relative to surrounding regions (Freire et al., 2019). The relation between progressively decreasing air temperature and increasing elevation that occurs on the flanks of volcanoes are adequate to precipitation and provide more habitable temperatures in tropical areas, compared to tropical lowlands (Small & Naumann, 2001).

The population distribution in the vicinity of volcanoes is also determined by other environmental factors such as relief, elevation, climate. The steepness of volcanic slopes differs per volcano type. Volcanoes often have a steeper slope when they are more active and more explosive. Settlement is not possible for communities when slopes are too steep (Small & Naumann, 2001). Right next to Mount Mayon in the Phillipines the great city of Legazpi can be found, the El Misti volcano's closest nearby settlement is Peru's second largest city, Arequipa. These areas are the typical examples of volcanic areas where urbanization and lifestyle are important determinants. An example of agricultural benefits in relation to volcanism is Italy. Agriculture in southern Italy is limited because limestone is the basement rock and the soil quality is generally low there. However, the soil quality in the region around Mount Vesuvius is much higher. Large historical eruptions left the region blanketed with very thick tephra deposits.

3.1.2 Volcanic hazards

Volcanic hazards can be grouped by geomorphological processes as well as by impact to human life. The different hazards to humans concerning volcanism are the pushing factor in population distribution. Volcanic hazards can be arranged in four different types of effects. Mechanical injuries or death occurs when the volcanic process causes the ejection of material and transport through air or water. All pyroclasts that are ejected by volcanic vents during eruptions are called tephra (Fiantis et al., 2019) Mechanical injuries occur during explosive eruptions when the eruption produces fragmented rock, ranging from the size of ash to boulders. Thermal injuries or death are the result of hot volcanic emissions. Toxicological effects are caused by emissions that react with the human body. Electrical effects are caused by lightning (Horwell et al., 2015).

The most common hazards that are related to volcanic activity are described here. An overview is shown in Table 1. The ranges described in this chapter and given in Table 1 are the maximum ranges at which hazards may occur. The actual range depends on the magnitude of the eruption, topography of the area and other environmental factors that are different for each volcano. The intensity of all hazards is higher at smaller distance from the vent (Horwell & Baxter, 2006). The hazards that almost always occur close to the vent are ashfall, lava flows, lahars, floods, gases, aerosols, ballistics and lightning. Some hazards are able to occur at a large range from the vent, these are lahars, floods, gases, aerosols and ashfall. When the latter hazards occur relatively close to the volcano their effects are more intense, when they occur at a greater distance the impact of these hazards is significantly less. Lahars and pyroclastic density currents and lahars both have more localised effects. However, they account for far greater loss of life than further reaching hazards (Small & Naumann, 2001).

Hazard	**Intensity**	**Range from vent**
Lava flows	Low fatality number	Within 10 kilometers
Ashfall	Affects most people of all hazards	Up to hundreds of meters
Lightning	Low fatality number	Within hundreds of meters
Pyroclastic density currents	Most deadly, one-third of all volcanic fatalities	Maximum of 100 kilometers from event
Gasses and aerosols	Extremely deadly	10 kilometers (maximum is worldwide)
Ballistics	Extremely deadly on impact	Range from very few meters up to 2 kilometers
Lahars and floods	15% of all historical volcanic fatalities, very deadly on impact	Tens of kilometers
Debris avalanches	Extremely deadly on impact	Tens of kilometers
Tsunami's	Extremely deadly on impact	Do not occur near volcano, up to hundreds of kilometers from event

Table 1: An overview of the most important direct hazards caused by volcanic activity. The intensity and range are given for each hazard for their most frequent occurrence. The magnitude of the volcanic eruption at which they occur is base for the actual intensity and range at which they take place (Loughlin et al., 2015).

The most common hazards are:

- Lava flow is the volcanic hazard that causes the lowest number of fatalities, due of its low velocity which allows humans time to evacuate. Nevertheless, lava flows can contain uncommon chemical compositions that are able to decrease the viscosity and thereby increase the velocity of the lava flow. Viscous lava is able to form lava domes surrounding the vent. Lava flows can reach areas up to approximately ten kilometers from the vent (Lim & Flaherty, 2021).
- Ashfall that occurs during and after a volcanic eruption can be very harmful for people. Ash, also referred to as tephra is mostly deposited as relatively thin layers, less than one millimeter thick. Ashfall is a mechanical mechanism that causes one of the greatest threats to public health (Loughlin et al., 2015). Volcanic eruptions eject volcanic ash into the atmosphere that can be transported by prevailing winds. The transport of ash by winds causes the large range at which the effects of ashfall can be observed (Horwell & Baxter, 2006). At times, the effects of ashfall can even have worldwide effects. This only happens after eruptions with an extremely high magnitude, usually the direct effects of ashfall are up to hundreds of meters from the vent.
- Another hazard that is common to occur during volcanic eruptions is lightning. The lightning is generated from friction between particles in ash plumes. Therefore, the range is as far as the range of dense ash plumes, tens of kilometers from the vent (Loughlin et al., 2015). Lightning only accounts for a very small number of fatalities (Horwell et al., 2015).
- Other hazards that may occur during a volcanic eruption are pyroclastic density currents. Pyroclastic density currents include flows, blasts and surges consistent of consolidated and unconsolidated materials. Pyroclastic flows are concentrated avalanches of gasses, ash and volcanic rocks, that are typically confined to valleys. Pyroclastic surges are turbulent clouds of ash and gases that can spread across a landscape and are able to travel slope upwards or across water. A very energetic pyroclastic density current is a blast, blasts are not influenced by topography and have

very high velocities (Fiantis et al., 2019). Volcanic density currents are the most lethal volcanic hazard, they account for approximately one-third of all volcanic fatalities and their range can be up to one hundred kilometers (Loughlin et al., 2015).

- Gasses and aerosols are extremely deadly volcanic hazards. The main component of volcanic gasses is water vapor, however eruptions can release many other aerosols and gas species within their gas plums including sulfur dioxide, carbon dioxide, hydrogen sulphide and halogens. Volcanic gasses can cause instant fatalities and health impacts. As a result of the high density of the volcanic gas plumes, they tend to accumulate in depressions, such as valleys, where most people live (Loughlin et al., 2015). Gasses and aerosols from volcanic eruptions are able to cause air pollution, which causes their impacts to be observed at a global scale. However, the effects of volcanic gasses are most deadly within a range of ten kilometers from the vent (Horwell & Baxter, 2006).
- Ballistics are volcanic bombs that are ejected by explosive eruptions. Fatalities, injuries and structural damages are caused on impact. Ballistics often cause fires on impact because their cores are very hot. Ballistics range from a few meters to two kilometers from the volcanic vent (Loughlin et al., 2015).
- Volcanic mudflows called lahars are fast moving mixtures of water and volcanic debris. Together with floods they are able to destroy anything in their path and range up to tens of kilometers from the vent. Floods and lahars are accountable for fifteen percent of all historical volcanic fatalities (Loughlin et al., 2015). Lahars occur when intense rain falls on unconsolidated volcanic deposits. Volcanoes in glacial areas even have lahars or floods between eruptions caused by geothermal activity underneath the ice or in the breaching of crater lakes (Loughlin et al., 2015).
- Debris avalanches consist of rocks with different sizes (Siebert, 1984). They are caused by poor slope stability on unconsolidated edifices. Debris avalanches are often large and mobile flows formed during the major collapse of volcanic edifices. Landslides are common on the flanks of volcanoes during and between eruptions. They can be extremely deadly on impact and range up to tens of kilometers (Small & Naumann, 2001).
- Tsunami’s that are caused by volcanic activity can be the result of violent explosions, landslides into the sea or collapses of volcanic slopes. The sudden entry of voluminous debris avalanches into the sea displaces large volumes of water that may cause tsunamis on coastal areas up to hundreds of kilometers from the volcanic event (Chester et al., 2000).

The hazards of most widespread concern, due to frequency of occurrence on hazards maps and fatality data are lahars, pyroclastic density currents and ash-fall (Auker et al., 2013). Currently, ash-fall hazards, which are able to have the widest distribution and far-reaching impact, is the best quantified. Neither lahars or pyroclastic density currents have far-ranging impacts, however they account for the greatest impact in the loss of life, infrastructure and livelihoods due to volcanic activity (Brown et al, 2015; Loughlin et al., 2015).

3.2 Assessing volcanic exposure at a global scale

This study describes different methods to globally assess volcanic hazards mentioned in chapter 3.1. Personal exposure to volcanism can be defined as the measure of all exposure of an individual to volcanic hazards. The hazards that an individual can be exposed to are insults from environmental sources related to volcanism that have a potential threat to the life of that individual. Personal exposure to volcanism is also referred to as ‘volcanic exposure’ in this study. The assess volcanic exposure, the topic is divided into four different subsections here.

First, a method to assess the specific volcanic danger is described. Secondly, methods to assess the spatial spreading of different hazards are explained. Thereafter, different methods used to assess the exposure of the population to volcanic hazards are examined. These methods are the PEI, the VPI and the VRC. Lastly, a few datasets that are available for the assessment of volcanic exposure are portrayed. Two of these datasets concern population data and two concern volcano distribution data.

3.2.1 Volcanic Explosivity Index

To assess personal exposure, it is important to have knowledge about the different levels of hazard a certain volcano or eruption can have. The most frequently used method used to assess and compare different levels of volcanic hazards is the Volcanic Explosivity Index, also known as the VEI (Newhall & Self, 1982). The Volcanic Explosivity Index is a general indicator of the explosivity of a volcanic eruption, comparable to the Richter Scale for earthquakes. This method is able to assign a value to each volcano on Earth that refers to the explosivity of its eruption. This value is an estimation of the explosive magnitude of an eruption. It does this by using historical eruptions that act as indirect predictions for future events (Newhall & Self, 1982). The index runs from zero to eight with increasing explosivity and is determined by a number of variables including the volume of ejected material, the height of the eruption column and eruption duration. The height of the eruption column is the maximum height particles ejected by the volcano have reached. The VEI does not take any specific hazards that may or may not have occurred into account in its calculation, it solely assesses the aforementioned factors. The VEI is logarithmic, for each number in the index the explosivity of an eruption increases with a factor of ten. Eruptions rated with an VEI of zero to three only have very localized effects and involve lava flows and minor explosive activity. Hazards that may occur are not fixed for eruptions of this order, but rarely have a range that extends beyond ten kilometers. Eruptions with a VEI of four or five have the ability to disturb economies on a regional scale. The range of hazards of these eruptions can easily extend to hundred kilometers depending on topographic factors. Eruptions rated with a six or higher can be observed around the entire globe because events of this magnitude can disrupt climate systems. These eruptions consist of a combination of all hazards described in section 3.1.1, occurring with enormous magnitude, with all maximum ranges possible for each hazard. In this index population data is irrelevant (Brown et al., 2015). Table 2 gives all different VEI values and their frequencies, related tephra volumes and column heights (Ewert & Harpel, 2004).

VEI	**Frequency**	**Volume of erupted tephra in cubic kilometers**	**Eruption column height in kilometers**
VEI 0	Continuous	<0.0001	<0.1
VEI 1	Daily	0.0001-0.001	0.1-1
VEI 2	2 weeks	0.001-0.01	1-5
VEI 3	3 months	0.01-0.1	3-15
VEI 4	1 year	0.1-1	10-25
VEI 5	1 decade	1-10	>25
VEI 6	Once or twice per century	10-100	>25
VEI 7	Once or twice per millennium	100-1000	>25
VEI 8	Less than each 50,000 years	>1000	>25

Table 2: Volcanic Explosivity Indices and their frequencies, tephra volume and column height (Brown et al., 2015).

The original thresholds for the VEI are shown in table 2. These threshold values were proposed by Chris Newhall and Stephen Self in 1982 and are still used today (Ewert & Harpel, 2004).

3.2.2 Hazard maps

The assessment of the spreading of hazards in volcanic areas is done by quantifying the hazards in different types of maps. The five most frequently used map types are discussed here. These are geology-based maps, integrated qualitative maps, modelling-based hazard maps, probabilistic hazard maps and administrative maps (Calder et al., 2015). Examples of the different map types are shown in Figure 1. Most hazard maps are according to information from geological and historical knowledge of past eruptions. Usually, hazard maps that consider a certain volcano are based on the mapping of young volcanic deposits to identify the spreading of different hazards for that area (Brown et al., 2015). One limitation that is accompanied by this method that holds for all hazard maps, is that in the case of volcanoes the past is not always the key to the future. Future eruption types, frequencies and magnitudes are barely foreseeable due to the unpredictable nature of volcanoes. Most hazard maps nowadays are created with computer programs that are run under certain limiting conditions and parameters that can vary for each different eruption type, to assess a plausible outcome of the spreading of hazards. These parameters are calibrated according to observed deposit distributions (Brown et al., 2015). The different map types have different boundaries between certain risk zones. These boundaries are decided by different interpretations of hazards. The spatial extent of zones on hazard maps are mostly grounded on fully quantitative probabilistic analysis. Hazard map types can be used for different purposes depending on their characteristics, some may be designed for evacuation routes where others are solely designed to give an indication of the population at risk (Calder et al., 2015b).

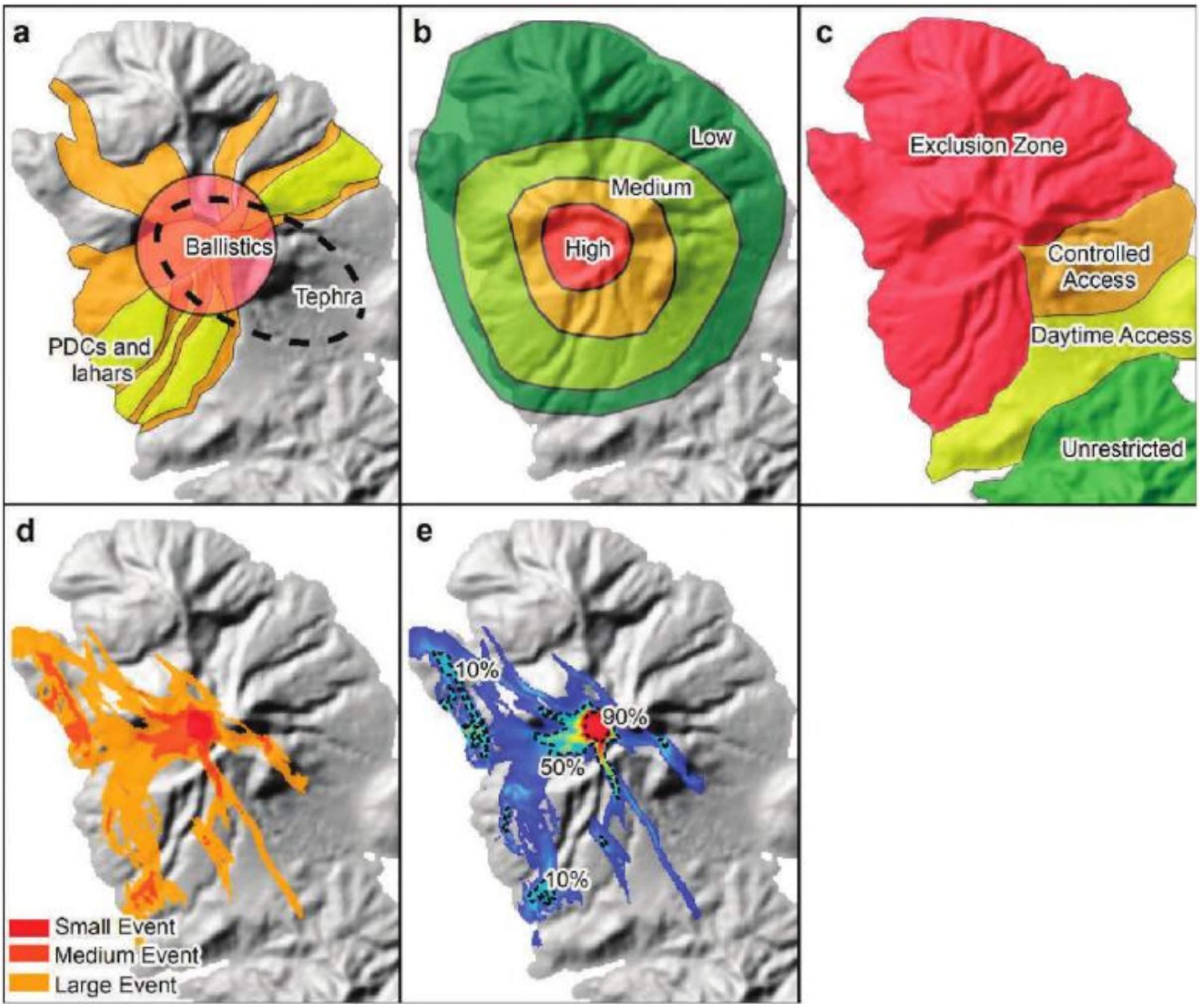

Figure 1: This image is conducted from Global Volcanic Hazard and Risk by (Brown et al., 2015) page 336. A: geology-based map, B: integrated qualitative maps, C: modelling based hazard maps, D: probabilistic hazard maps and E: administrative maps (Calder et al., 2015).

What will be investigated here is what hazard map type is most suited for a global assessment of personal exposure. Some of these map types use topography to assess the spreading of hazards. The use of topography in the creation of a hazard map makes a map very accurate and detailed. However, the consequence is that this type of map is only suitable for an assessment of hazards where there is room for detail. This is often not the case for an assessment intended for a global scale. Some of these map types assess specific hazards, using their specific characteristics as given in section 3.1.2. These map types are suited for a detailed assessment, however these are not suitable for a global assessment. The 2015 study of Brown et al. reviewed 120 different hazard maps and found that geology-based maps are the most frequently used map types. After this, integrated qualitative maps and modelling based hazard maps are used most, together they represent approximately half the number of geology-based maps. Only a fraction of the hazard maps reviewed by Brown et al. used administrative, probabilistic or other types of maps. This is shown in Figure 2 (Brown et al., 2015). This study did not take into account whether the hazard maps were used for a global of regional assessment.

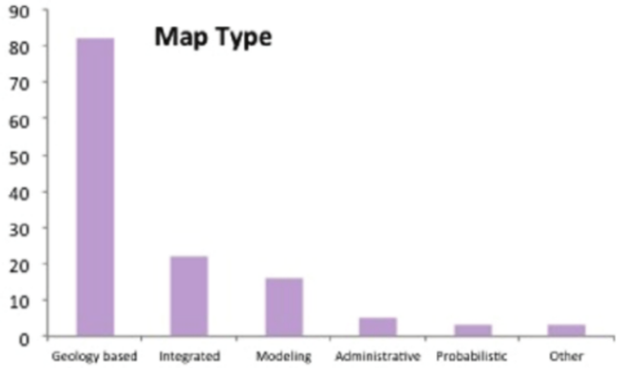

Figure 2: Frequency of occurrence during review of 120 hazard maps according to (Brown et al., 2015)

Geology based maps contain mapped hazard footprints (Calder et al., 2015). These are derived from information of past occurrence of events. The spatial spreading of zones on this map type is based on direct information from the site. The spatial spreading of hazards of historical events from a certain volcano are combined with up-to-date information on the current geology of the volcano, therefore, the hazard footprints in this map type are quite accurate. The information in this map is based on information of deposits in the vicinity of a volcano. However, there is a chance that a significant part of the material deposited by the relevant volcano is eroded. This is because material deposited by violent blasts of a volcano are very easily eroded. The geological information record is incomplete and refers only to past events, it is not stated that the hazard footprints will have the same extent in the past as in the future.

Integrated qualitative maps contain information on all different hazards that may occur (Calder et al., 2015). This is because the zones on integrated qualitative maps are based on estimations and averages of all currently available hazard information. Data for this type of mapping is geology and modeling based. This map type contains simple and concentric type hazard zones. This map type does not give information that is specific for certain volcanoes, due to their designed simplicity. Because the maps are uncomplicated and therefore easy to use, this map type is very suited for communication purposes, such as evacuation plans or emergency aid assistance (Potter et al., 2014).

Modelling based hazards maps are scenario-based maps created with the application of simulation tools for a single hazard type. The simulation tools are tools that simulate the characteristics of how certain hazard would behave in a certain topographical environment. This map type is very precise for certain scenario that could possibly occur. This type of hazard map only assesses a single hazard in a certain possible scenario, thereby excluding all other hazards that may occur during an eruption and all other possible scenarios in which an eruption can take place.

Probabilistic hazard maps are created with stochastic application of computer simulations. The probabilistic approach is a realistic way to assess volcanic hazards. This is the only mapping type that assesses the probability of a certain hazard type to occur during a volcanic eruption. It is based on the same simulation tools as the modelling-based hazard maps, except that this map type assesses the probability of that hazard to occur as well. These map types are based on one hazard type, which could be any of the hazard types described in chapter 3.1. These map types are very complex and not suited for easy interpretation. Also, this map type can contain uncertainties due to model data input and simulation parameters. Administrative maps do not show volcanic hazard distribution. These types of maps combine hazard levels with so-called administrative needs. They are constructed specifically to aid in emergency situations.

Administrative maps commonly inherently contain information about hazard distribution. However, the geoscience contents may be rather obscure. This map type is often used for small volcanic areas due to their complexity (Calder et al., 2015).

3.2.3 Personal exposure assessment methods

The most widely used methods to assess personal exposure to volcanic hazards are the Population Exposure Index, PEI (Aspinall, 2011), the Volcano Population Index, VPI(Ewert & Harpel, 2004) and the Volcanic Risk Coefficient, VRC (Scandone et al., 2016). The PEI, VPI and VRC enable personal exposure to volcanic activity to be identified (Brown et al., 2015). What these three methods have in common is that all of these methods directly or indirectly use distances over which all the different hazards can occur as a measure of risk. The PEI and the VPI both directly use distance for zones to indicate the risk. Zones that lie close to the volcano are considered to be more dangerous to inhabit. This corresponds to the information on hazards and their ranges in section 3.1. The VPI was designed for smaller eruptions and the PEI for larger eruptions. The VRC works differently from the PEI and the VPI, this coefficient assesses risk indirectly with distance by using the Volcanic Explosivity Index, of which the different indices indicate the approximate range of the hazards. None of these methods assess specific hazards and their characteristics as described in section 3.1. These personal exposure assessment methods are all indicators of the population at risk for volcanic hazards, they are most often used for assessments at a large scale. To get a complete image of the actual personal exposure in an area with one or multiple volcanoes, these methods are often used in combination with one of the hazard map types. The purposes of hazard maps and the methods described here are not directly related to each other. They can be created independently of each other, however they reinforce each other when used combined, if an extensive exposure assessment is aspired. None of the methods that are described here consider the probability of a volcanic eruption, these methods are all designed to assess the personal exposure in the case an eruption would take place.

The Population Exposure Index, referred to as PEI is one of the most frequently used indices used for assessing volcanic risk. The PEI is divided into seven different levels, ranging from sparsely to densely populated areas. The Population Exposure Index is determined with the calculation of a weighted summed population (Freire et al., 2019). Table 3 shows the different Population Exposure Indexes and to which count of weighted population they refer. The index is based on different distances from a volcano in which the population is distributed. These distances are 10, 30 and 100 kilometers from a volcano, based on the occurrences and intensities of different hazards within these distances, as proposed by Aspinall et al. in 2011. However, a number of studies uses the PEI with other distances from the volcanic vent as well (Brown, Sarah et al., 2015). The distances chosen by the PEI can be correlated to information about the spreading and intensities of hazards from chapter 3.1.1. The PEI relies on a number of parameters that can have a high uncertainty or are not up to date for a significant number of volcanoes around the globe. This insinuates that PEI is limited to volcanic areas with extensive historical records (Freire et al., 2019). The PEI itself gives an indication of direct risk of fatalities, however the PEI is suited for the assessment of economic impacts based on the distance from a volcanic eruption. This assessment only addresses direct economic impacts and does not cover secondary economic impacts such as famine, disease or losses to the aviation sector. The PEI is suited as a basis for hazard mitigation management. The PEI is not suited for the in-depth assessment of personal exposure to volcanic hazards on a detailed scale. When using the PEI, one has to be aware of the fact that volcanoes that are given the same index value may be very different in their actual exposed population. This is due to the fact that this index does not take topographic factors into account whilst this is a very important factor to determine the personal exposure. According to the study of (Calder et al., 2015), where the PEI is calculated for all volcanoes in a database called VOTW4.0., more than forty percent of all volcanoes worldwide have a weighted summed PEI of 2. Their analysis shows that sixty percent of all people that live within a 100 km radius from an active volcano is in fact located at only four percent of the Earths active volcanoes. These volcanoes have a Population Exposure Index of seven, the highest level.

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

Table 3: Population Exposure Index according to Aspinall et al. (2011) (Aspinall, 2011) Table recreated to the work of (Calder et al., 2015)

Another commonly used index for volcanism and population distribution is the VPI, the Volcano Population Index. The Volcanic Population Index was developed by John. W. Ewert and Christopher J. Harpel in 2004 to evaluate and compare the number of people at risk from volcanic hazards. The index quantifies and compares one component of volcanic risk within a certain radius from the vent of the volcano, from one volcano to another. This component is the population density in the area within the radius. The VPI is included in the Volcanoes of the World database of the Smithsonian Institution (Simkin et al., 1981). As aforementioned, the Volcanic Population Index merely takes one population variable into account, this is the LandScan population database. To create the Volcanic Population Index, five- and ten-kilometer radii are used to circumscribe around the coordinates of the volcanic vents. This results into circular areas around the volcano vents on the LandScan population grids. The five- and ten-kilometer radii are chosen so that they are able to address the area for small or moderate eruptions. The VPI only addresses small and moderate eruptions because these eruptions have the highest frequency and therefore these types of eruptions are the kind that emergency responders will have to deal with most (Scandone et al., 2016). The VPI assesses volcanic eruptions in the Volcanic Explosivity Index (VEI) which is a two to four range, because for eruptions with a VEI higher than this, the effects will extend the 10-kilometer range of the VPI. The effects of these eruptions vary from within five kilometers for VEI-2 from the vent to ten kilometers from the vent for VEI-4. The circular hazard spreading assessment of the VPI was decided on because the spatial spreading of different hazards is too complicated to forecast for different volcanoes with the use of one model. The VPI is suited for a simple and easy assessment of volcanic hazards on large scales. The VPI is not suited to assess or forecast the specific spatial hazards spreading for certain volcanoes. To achieve this, much more complicated models are necessary. And even with the use of those, volcanologists are only able to give an imprecise range of the magnitude and style of eruption to expect, based on historical events. For each volcano there are two VPI values, the VPI5 and the VPI10, which refer to their distance radii from the volcanic vent. The VPI value estimates the minimum number of people that are at risk from volcanic hazards (Ewert & Harpel, 2004).

Another method to assess the personal exposure to volcanic hazards, the Volcanic Risk Coefficient, was proposed by Scandone et al. in 2016. The Volcanic Risk Coefficient uses the number of people as the main variable to compare different volcanic areas. Through the use of VRC, specific hazard information is obtained in addition to population data (Freire et al., 2019). The VRC uses the population distribution to assess the number of people affected by the maximum expected eruption. Therefore, to properly use the VRC detailed and accurate population distribution data is necessary. The coefficient makes it possible to compare different volcanoes to each other (Brown et al., 2015). The maximum theoretical volcanic risk coefficient is valued at 17, referring to the large caldera-forming eruption types such as Toba or Yellowstone, that are able to affect the population of the entire planet (Scandone et al., 2016). According to Scandone et al., there are three basic ingredients to volcanic risk: the eruption probability, the damage caused by an eruption and the character of the volcanic phenomena. The VRC is calculated as:

$$VRC = K_T + VEI + \log(P) \qquad \text{(eq. 1)}$$

In this equation K_T stands for log(1/time since last eruption). The time since last eruption is expressed in years. P stands for the count of population that may be affected. The area over which the population number is defined depends on local conditions and the VEI. Therefore, this area is different for each volcano. The VRC takes population distribution into account as well as the ranges of hazards associated with the relevant VEI (Scandone et al., 2016). The VRC is the first method that assesses of personal exposure to volcanism on a logarithmic scale, using logarithms of two of the three variables in the sum (Scandone et al., 2016).

3.2.4 Datasets

To assess population exposure in relation to the vicinity of volcanoes, accurate data is a necessity. This applies to both population distribution data and volcano distribution data. High resolution and up-to-date population distribution data is required for every method discussed above. There are many different population distribution data sets that have these characteristics, a few of the most widely used grids are the Global Human Settlement Layer (GHS-POP) (lorczyk et al., 2019), the Gridded Population of the World (Center for International Earth Science Information Network - CIESIN, - Columbia University, 2018a)and the LandScan Population data (Rose et al., 2020). The datasets were chosen because of their frequent use in population and volcano distribution assessments and their accuracy. What all of these datasets have in common is that they are open datasets and their spatial resolution is suited for population exposure assessments.

The GHS-POP gives the the density and distribution of total population per 250-m cell. The GHG-POP is known for its use of a single spatially and temporally explicit proxy; this proxy is of high spatial resolution and is derived from different sources with a consistent approach. It is also known for its employment of a simple methodology for population disaggregation (lorczyk et al., 2019). GHS-POP cell values represent population counts as well as densities by using the World Mollweide equal-area projection as native projection. The latest release of GHS-POP grids are able to mitigate important shortcomings of earlier population grids by critically reviewing areas that where previously labelled ‘unpopulated’, however had significant evidence of human settlement. Due to these facts, the GHS-POP is suited to support authorities in disaster risk management. GHS-POP is at this time the only dataset that provides open and comparable data of the population distribution for over forty years, which allows the investigation of personal exposure to volcanoes in this period (Freire et al., 2019).

The Gridded Population of the World is provided by the Center for International Earth Science Information Network, CIESIN. It provides estimations of the human population density, given in number of people per square kilometer. The information is based on counts that are consistent with population registers and national censuses. The Gridded Population of the World is available for the years 2000, 2005, 2010, 2015 and 2020. To estimate population counts at a resolution of 30 arc-second grid cells, a proportional allocation gridding algorithm was used, which utilized approximately 13,5 million national and subnational administrative units. The data files are given as global rasters at 30 arc-second which is approximately 1 kilometer at the equator resolution (Center for International Earth Science Information Network - CIESIN, - Columbia University, 2018b).

LandScan provides population distribution data at a spatial resolution of 1 kilometer (Rose et al., 2020). LandScan does not give information about total residential population distribution, however it provides information about an average population distribution over 24 hours. The LandScan database is renewed every year and available for open access. Essentially, LandScan population data is a combination of geographical nature of individual countries and regions and locally adoptive models designed to match the data conditions (Calka & Bielecka, 2019).

There are many different datasets containing information about volcanoes on a global scale. This data is usually provided as coordinates of active volcanoes. Two of these datasets that are widely used are the Holocene Volcano List and the Significant Volcanic Eruption Database (Venzke, 2013). Both of these datasets are available online and open for everyone. These datasets both contain coordinates of a range of volcanoes. The difference between these datasets is what they consider to be significant volcanoes. The Holocene Volcano List is listing all volcanoes that are believed to have been active during the last 10,000 years. This database includes information about the coordinates, elevation, volcano type and last known eruption. The Holocene Volcano List is provided by the Smithsonian Institution's Global Volcanism Program (Venzke, 2013). The list is frequently updated and includes more than 1,400 volcanoes, including submarine volcanoes and volcanic fields. The Significant Volcanic Eruption Database is a register provided by NOAA, also part of the Smithsonian Institution's Global Volcanism Program, that contains information about more than 500 significant eruptions from about 200 different volcanoes. This list contains information on the volcanoes, comparable to the information of the Holocene Volcano List, and information on eruptions, such as dates, VEI, associated events and the impact an eruption may have had. The meaning of significant is based on a minimum of caused fatalities, a VEI valued with a 6 or higher, caused damage and associated events (Freire et al., 2019).

4 Discussion: volcanic hazards and exposure assessment

4.1 Driving mechanisms for population distribution and different volcanic hazards

4.1.1 Driving mechanisms for population distribution

The most important driving mechanisms that determine the population distribution related to volcanism are urbanization, lifestyle, resource extraction, geothermal energy, tourism, agriculture and climatic advantages. These factors are discussed in section 3.1.1. In despite of these factors being the most important concerning this matter, these factors are not fundamental for the determination of population distribution in the vicinity of volcanoes.

Other environmental circumstances are of importance as well. These are for example relief, water availability, infrastructure and many more. In this study these factors were chosen to be ignored. To obtain an even more representative view of the driving mechanisms for population in the vicinity of volcanoes further research is required. This research could possibly assess how the population in first world countries has other priorities than population in third world countries when choosing a habitational area. One would expect that the factors that are described in section 3.1 are of greater influence on less prosperous population than on prosperous population. This is because countries with a less affluent population have a larger agricultural sector than richer countries. Moreover, rural communities are less likely to have a factor like lifestyle affecting them because the lifestyle of rural communities is generally closer to the natural environment than urban societies because their livelihoods depend upon successful interaction with it. Therefore, rural communities are more aware of their environment and hazards that volcanoes may cause. These differences between rural and urban societies can be assessed in future research. Besides from agriculture, less wealthy countries are more dependent on income from tourism and resource extraction. These countries are also more affected by over-urbanization than others. Urbanization presents great potential for catastrophes in volcanic areas than dispersed rural populations. Overcrowding caused by urbanization causes that the authorities are unable to provide the most basic infrastructure and services (Chester et al., 2000). This could mean that less wealthy population would be more likely to choose to live in the vicinity of volcanoes than affluent population. Further research into this matter will be required to accomplish a more complete view of human exposure.

4.1.2 Volcanic hazards

Hazards for humans concerning a volcanic eruption can be grouped by geomorphological characteristics and based on impact to human life. The most important hazards are lava flows, ashfall, lightning, pyroclastic density currents, gasses and aerosols, ballistics, lahars, debris avalanches and tsunamis. Volcanic activity is responsible for many hazards to which Earth's population can be exposed. In this study, only the most important direct hazards related to eruptions are discussed. However, volcanic activity is responsible for a large range of indirect consequences as well. For example, air pollution caused by gas or ash clouds can have a negative impact on the aviation industry, which will cause economic losses (De Bélizal et al., 2011). Moreover, ash layers can cause famine, which can cause major setbacks for the economy of an area. In this study, indirect consequences of volcanic activity are not taken into account because they rarely pose a threat to human life, and therefore these indirect impacts do not suit the term 'hazard'. To obtain a more sophisticated image of the actual consequences and hazards caused by volcanic activity, further research to indirect hazards can be done. Hazards with a small range and low intensity are considered just as important as far-ranging hazards with high intensity for the assessment of personal exposure in this study.

4.2 Assessing volcanic hazards at global scale

Differences in volcanic activity can be rated and compared with the use of the Volcanic Explosivity Index. This index is able to assign a scaled value to volcanic eruptions. For the spatial assessment of personal exposure to volcanism five different map types exist. These map types are geology-based maps, integrated qualitative maps, modelling-based hazard maps, probabilistic hazards maps and administrative maps (Calder et al., 2015). For the assessment of personal exposure on a global scale the integrated qualitative maps are considered best. Three methods that are most frequently used in the global assessment of personal exposure to volcanism are the VEI, VPI and the VRC. There are many accurate and up-to-date datasets available for the assessment of personal exposure to volcanism. The four different sections to answer the second sub question were chosen because this study considers them as the most important aspects to the assessment of personal exposure. To obtain a more extensionally image of this assessment, more components to personal exposure can be studied in further research.

4.2.1 The Volcanic Explosivity Index

The Volcanic Explosivity Index is an indication of the magnitude of historical volcanic eruptions and can indirectly provide information about future eruptions. However, it is not able to directly predict information about future eruptions, because it is based information of historical events. No volcanic eruption is the same as another and therefore the VEI of a volcano can never be a direct indication of a future event. This has to do with the form and landscape of a volcano changing in between eruptions and different amounts of energy build up under pressure before an eruption. If a future eruption is to be predicted with more detail and certainty, further research would have to assess these factors as well (Newhall & Self, 1982).

4.2.2 Hazard maps

At a global scale, integrated qualitative maps are most suitable for a personal exposure assessment, based on the information described in chapter 3.2 on hazard maps. This is because the integrated qualitative maps use zones that are based upon information of all different hazards and intensities. By using this map type in global assessment, the possible hazards and their intensity ranges from section 3.1 can be subdivided into different zones based on information about their ranges and intensities given there. The other four map types described here require specific volcano information, which makes them non-suitable for a global assessment because it will be too detailed and complicated for an global-scale map. The five map types discussed are all hazard map types that are based on historical information. The accuracy of these types of maps is dependent on how much historical information there is for each volcano. This information can be derived from deposits of historical eruption and from data recorded by humans (Brown et al., 2015). Therefore, some volcanoes are more suited for a certain hazard map type. For a global assessment, the range of historical information on specific volcanoes is too extensive for creating useable maps. Therefore, to assess volcanic hazards on a global scale, a map type that requires as little specific information as possible is considered most suited. Integrated qualitative maps are indirectly based on historical information of all volcanic hazards. These maps are based on average occurrences and ranges of hazards that could apply to any volcano, what makes the integrated qualitative maps most suitable for global assessment of personal exposure to volcanic hazard (Calder et al., 2015)

4.2.3 Personal exposure assessment methods

The three methods discussed in section 3.2.3, the PEI, VPI and VRC are considered suitable for the assessment of global volcanic exposure. Each method has its own advantages and disadvantages. The PEI and VPI assess personal exposure spatially by using zones, where the VRC uses a numerical value derived from a single calculation. A spatial assessment provides a clearer overview of the actual exposure and is therefore preferred. The PEI corresponds best with the information on hazards in chapter 3.1. The ranges of hazards described in chapter 3.1

agree with the radii of the zones of the PEI, at ten, thirty and one hundred kilometers from the vent. Because the VPI value is an estimation of the minimum number of people at risk for volcanic hazards, the VPI tends to underestimate the actual number of people that are at risk for volcanic hazards. The VPI also underestimates the danger for people in the vicinity of volcanic hazards because its maximum reach is ten kilometers. All volcanic hazards that reach further than this ten-kilometer boundary are neglected (Ewert & Harpel, 2004). An advantage of PEI compared to the VPI is that the PEI uses only spatial data to determine the exposure of people around a volcano, instead of the various VPI populations that contribute to the weighted index. The VPI was designed for small to moderate eruptions within a range of ten kilometers, on the basis that these occur most often. Therefore, the VPI can determine the population exposure for most eruptions. However, these small eruptions cause far less fatalities than larger eruptions. In fact, larger eruptions can easily cause fatalities at a range larger than ten kilometers from the vent. The VPI and the PEI complement each other, they are both suited for global exposure assessment for different eruption types. The method that is considered most suited for global personal exposure assessment is the Population Exposure Index. This is substantiated by the fact that the PEI assesses a higher threat compared to the VPI. This is better because this means the PEI assess the direct impact of the hazards from section 3.1.2 to human life. Also compared to the VRC, the assessment of volcanic threat by distance is preferred because it corresponds best with the information on volcanic hazard in chapter 3.1.

In this study, the PEI is the preferred method to assess personal exposure because the information obtained by using this index corresponds most closely to the hazards described in section 3.1. With respect to information in chapters 3.1 and 3.2 it was decided upon that an assessment based directly on hazards zones was preferred above a numerical assessment that only indirectly assessed the ranges of hazards. The PEI and the VPI are based directly on hazard zones, where the 100-kilometer-reach of the PEI extends the 10-kilometer-reach of the VPI. With the information from chapter 3.1 taken into account, a method which assesses personal expose on multiple scales is favored.

Even though the PEI, VPI and VRC are all widely used methods to assess personal exposure at sizable scales, they do not come without their limitations. Two limitations of all of these methods are that they only indicate direct risk and not the indirect fatalities and that none of them are suited for in depth assessment of personal exposure to hazards of specific volcanoes. The first limitation can possibly be mitigated in further research, however the second limitation is a result of the decision to assess personal exposure at a global level. To assess personal exposure at such a large scale, certain components of personal exposure have to be neglected to ensure that the method does not carry too many details that can complicate the assessment.

4.2.4 Datasets

All three methods from chapter 3.2.3 require spatially explicit population data that is up to date and are globally consistent. Also, the population data needs to have sufficient resolution and needs to support detailed analyses and comparisons. The datasets discussed in chapter 3.2 are merely a few of many accurate datasets. To make a good evaluation of a broader range of datasets, further research is required to examine more datasets in more detail. Population distribution models are developed with certain limitations and cannot account for the differences in spatial data availability, scale, accuracy and quality. This and the worldwide differences in cultural settlement practices cause a standard impreciseness that no population distribution model is able to minimize (Freire et al., 2019). The Holocene Volcano List is a more complete database of active volcanoes compared to the Significant Volcanic Eruption Database, because the HVL takes every active volcano of the last ten thousand years into account, where the SVED merely takes a fraction of these volcanoes into account. For the assessment of global personal exposure to volcanic hazards there are no limitations made in this study as to what magnitude a volcanic eruption needs to have to be significant. Therefore, for the personal exposure assessment the Holocene Volcano List offers a broader view as to what parts of population are at risk of volcanic hazards.

5 Case study: personal exposures to volcanism in Central America

5.1 Introduction

To test if the proposed method is suited for a global assessment of personal exposure to volcanism a case study is done. This case study will determine the personal exposure at a continental scale. This continental scale was chosen to limit the extent of this study. The continental approach will suit as a test if the PEI is in fact appropriate for a global approach. The study area of this case study is Central America. The area was chosen because of its high abundance of active volcanoes during the Holocene. In the Holocene Volcano List this area covers exactly 110 different volcanoes. In 2020, 2.3% of the world population was located in Central America. For this study, the methodology of the Population Exposure Index is used to make three different zones. As mentioned before in chapter 3.2, more than forty percent of all volcanoes on Earth are assigned a PEI of 2 (Calder et al., 2015). Therefore, it is expected that most volcanoes in Central America will have a PEI of 2 as well. Calder et al. also stated that sixty percent of all people that live within a 100 km radius from an active volcano is in fact located at only four percent all active volcanoes. This case study will test to see if that statement accounts for Central America as well.

5.2 Method

When the summed weighed population is determined for the area surrounding each volcano the PEI values can be determined. For this table 3 is used. The population distribution data for this study is derived from the Gridded Population of the World dataset (Center for International Earth Science Information Network - CIESIN, - Columbia University, 2018). The resolution of this dataset is 1 kilometer. With the use of the computer program PCRaster and Python, the coordinates from the volcanoes from the Holocene Volcano List were distributed over the population map of Central America (Karssenberg et al., 2010). Key functions used in PCRaster for this calculation were “spreadmaxzone” and “areatotal”. The first zone, with the highest impact of hazards ranges from ten kilometers from the vent. The second zone is quantified at thirty kilometers from the vent. The last zone, with the lowest hazard intensity, ranges up to one hundred kilometers from the vent. In this study’s Digital Supplement a Python script, input data and an Excel sheet can be found that were used to determine the population counts of the three different zones for each volcano in the study area. The summed weighted population counts are calculated for each volcano with the following equation (Brown et al., 2015):

$$SWP = 0.967\ P_{10} + 0.03\ P_{30} + 0.003\ P_{100} \qquad \text{(eq. 2)}$$

Where P_{10} is the total population within ten kilometers of the volcanic vent, P_{30} is the total population within thirty kilometers of the volcanic vent and P_{100} is the total population within one hundred kilometers of the volcanic vent. The coefficients given to the three components of the sum are determined by the fact that an area with a ten-kilometer radius is nine times smaller than the area with a thirty-kilometer radius, and one hundred times smaller than an area with a hundred-kilometer radius. This gives each component of the sum a weighting of approximately 0.91, 0.08 and 0.01 for 10-, 30- and 100-kilometer radii. The zones closer to the vents weight more heavy than the zones further from the vent. Combining these weightings a scaled weighting of 0.967 for the ten-kilometer circle, 0.03 for the thirty-kilometer circle and 0.003 for the hundred-kilometer circle is yielded. Without calculating the summed weighed population data errors due to area increase with increasing radii will be neglected. To give a better image of the volcanoes with the highest PEI values, the VEI values of these volcanoes are looked up (Newhall & Self, 1982).

5.3 Results

Figures 3-5 show the total population for each volcano for the three distances from the vent. There is a total of 110 volcanos in Central America on the Holocene Volcano List. 38 of these volcanoes are in Mexica, 22 are in Guatemala, 18 in El Salvador, 3 in Honduras, 17 in Nicaragua, 10 in Costa Rica and 2 in Panama. All tables and figures can be found in the Digital Supplement of this thesis.

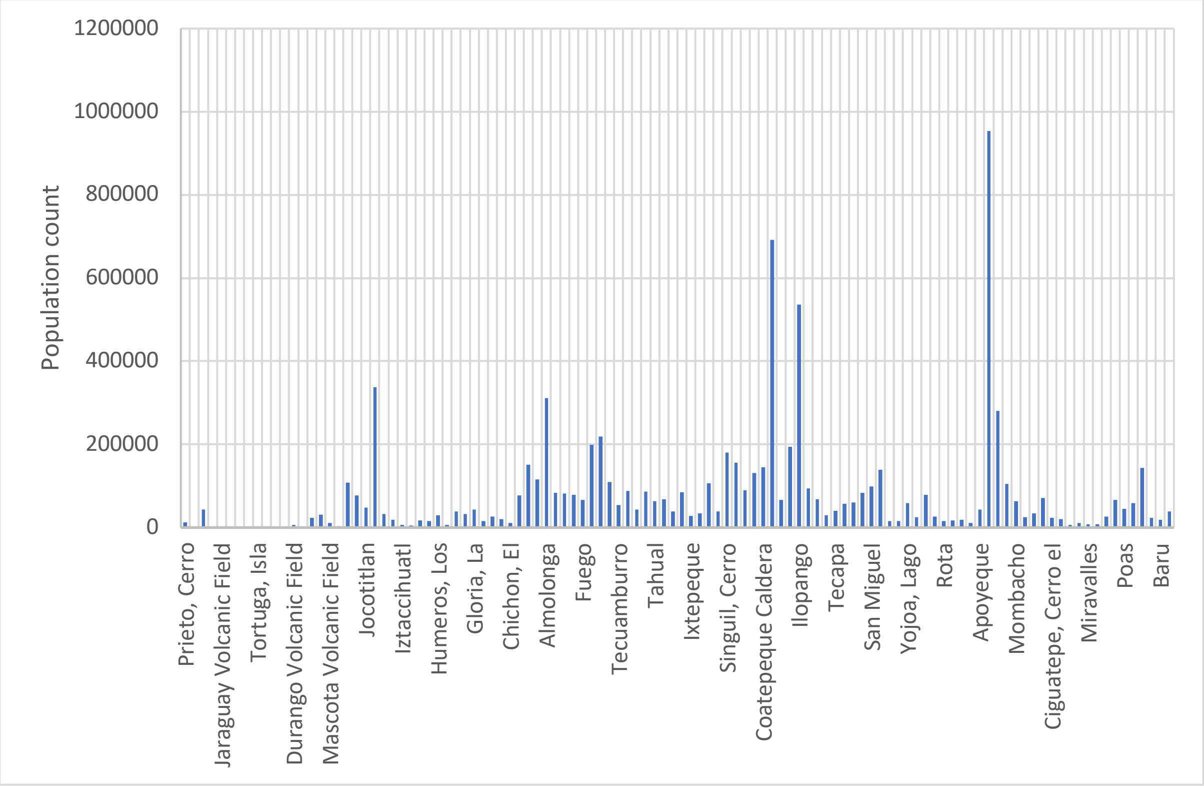

Figure 3: Population counts for each Central American volcano within a ten-kilometer radius from the volcano vents

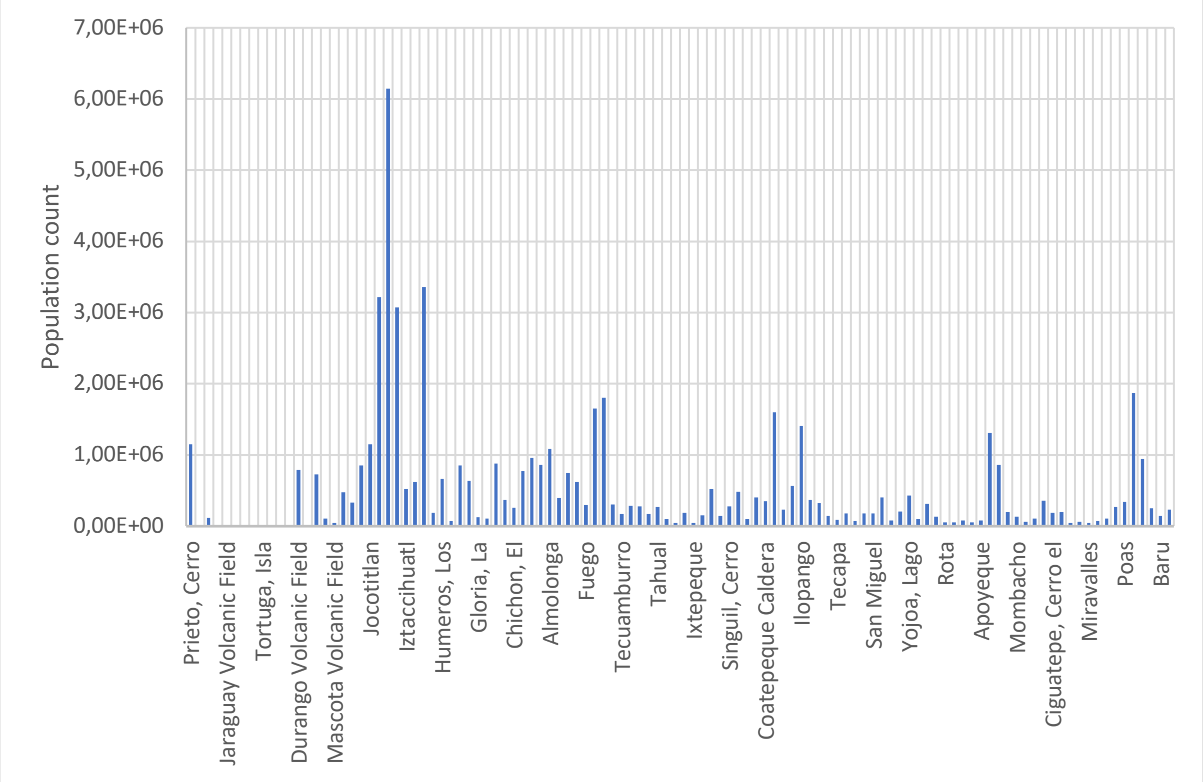

Figure 4: Population counts for each Central American volcano within a thirty-kilometer radius from the volcano vents

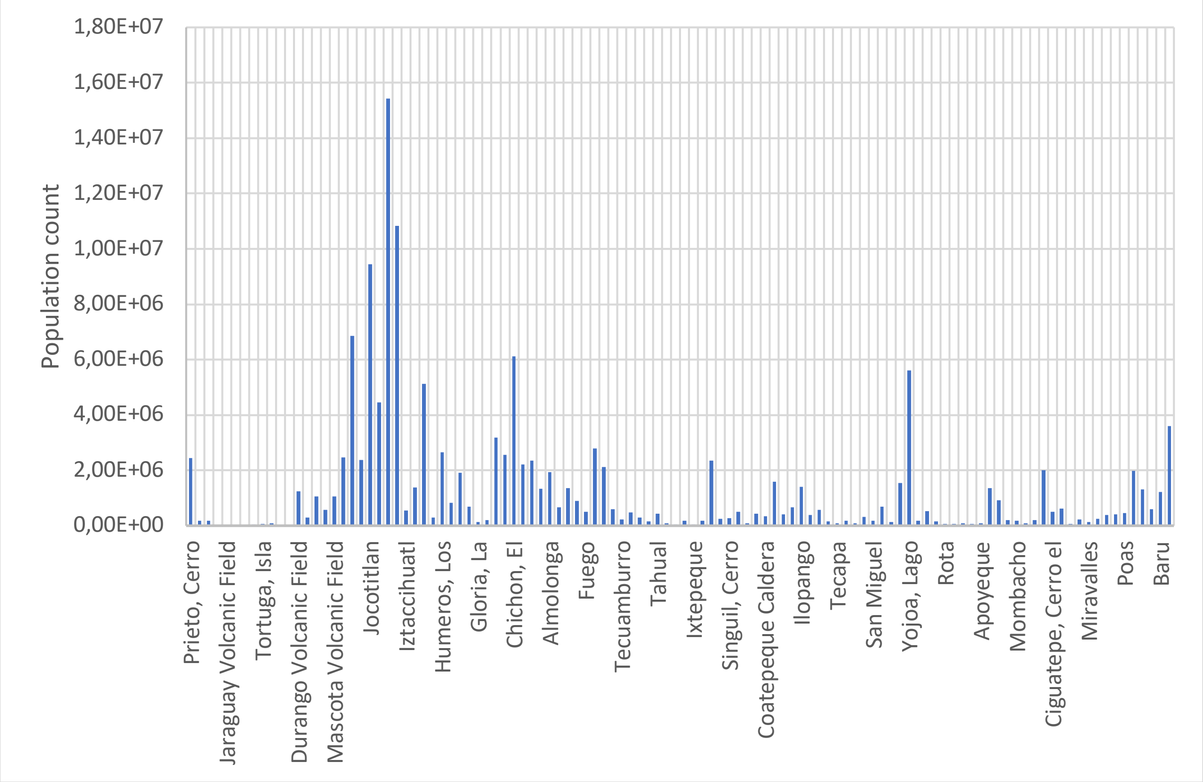

Figure 5: Population counts for each Central American volcano within a hundred-kilometer radius from the volcano vents

The total population of Central America was 179,670,200 in 2020. 4.7% of this population lives within a distance of 10 kilometer of a volcano, 30.9% lives within 30 kilometers of a volcano and 77.8% of the total population lives within a 100-kilometre radius of a volcano.

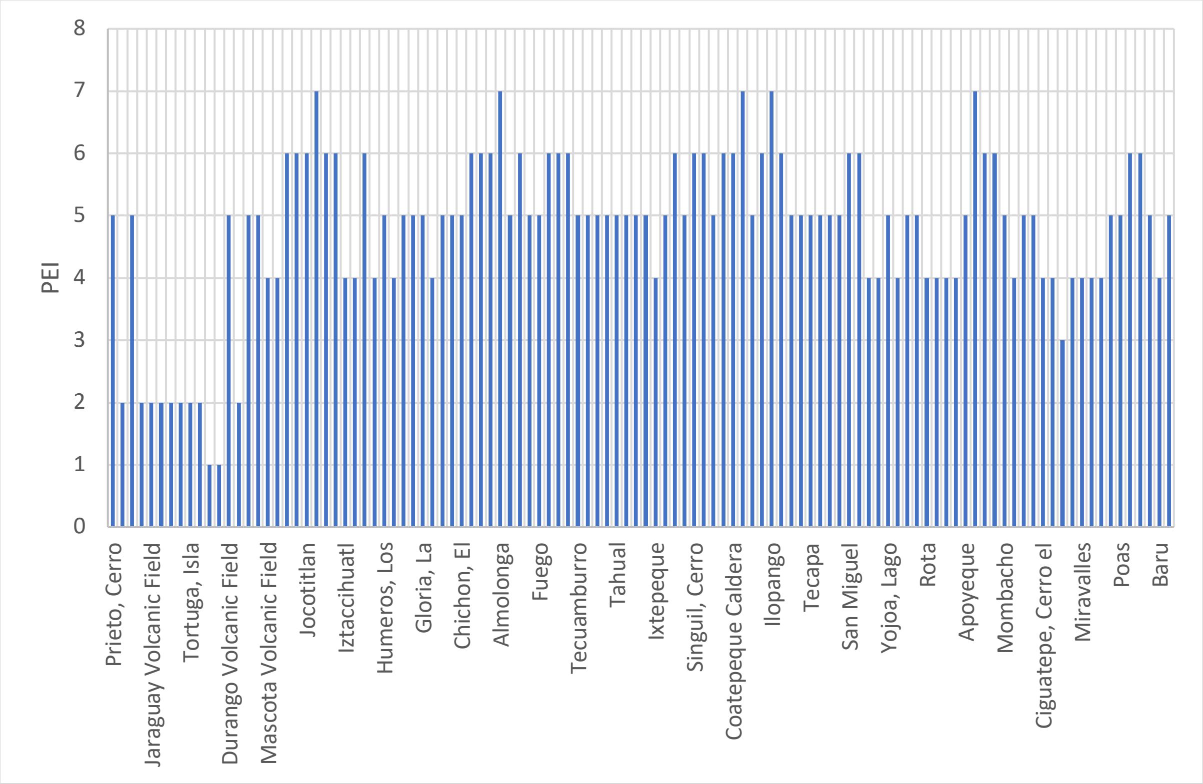

Figure 6: PEI values of the summed weighed population for each volcano in Central America on the Holocene Volcano List

After calculating the weighted summed population count for each volcano, the Population Exposure Indexes are assigned to each volcano. The PEI values in Central America are shown in figure 6. The total number of volcanoes assigned to each index is shown here in table 4. Forty percent of the volcanoes in this study have a PEI of 5.

Population Exposure Index	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Number of volcanoes	2	9	1	23	44	26	5

Table 4: Counted PEI values in Central America

The most densely populated areas, valued with a PEI of 7 belong to five volcanoes, as seen in table 3 and figure 6. These are Nejapa-Miraflores, Ilopango, San Salvador, Almolonga and Nevado de Toluca volcanoes. These are shown in figure 7. 3,026,787 people live in the vicinity of these five volcanoes. This is equal to 1.6 percent of the total population in Central America and 2.2 percent of all people that live within 100 kilometers from a volcano.

Figure 7: The five volcanoes with PEI-7: Nevado de Toluca, San Salvador, Ilopango, Almolonga and Nejapa-Miraflores volcanoes. Source: Google Earth.

The VEI values and dates of the last eruptions of the volcanoes with PEI-7 are given in table 4. Their volcano type is given a well.

Volcano name	**Nevado de Toluca**	**San Salvador**	**Ilopango**	**Almolonga**	**Nejapa-Miraflores**
Volcano type	Stratovolcano	Stratovolcano	Caldera (Stratovolcano)	Stratovolcano	Crevasse volcano
VEI	6	6	3	Estimated 3	5
Last eruption	1350 BC	1880 AD	1880 AD	1818	1060 AD

Table 5: (Simkin et al., 1981; Venzke, 2013)

6 Discussion: case study and feasibility of global assessment of personal exposures

This part of the study acts as a test to evaluate if the proposed method, the PEI, is suited for the assessment of personal exposure to volcanic hazards at global scale. This case study is done on a scale that is smaller than global, but large enough to indicate whether this method works on a global scale. To substantiate this, further research is necessary to test the PEI on a global scale. The results show that by determining the weighted population count for all volcanoes in Central America, a Population Exposure Index value can be assigned to each of these volcanoes. The results show each PEI value, thereby giving a direct indication of how many people are at risk in the case of a volcanic eruption. Further research can be done to assess volcanic risk even further by taking more factors that assess specific volcanic danger into account. One of these factors could be the VEI; by using this in combination with the PEI, personal exposure can be determined on the grounds of eruption hazard. The wish for a more synoptic assessment of personal exposure to volcanic hazard on a global scale is fulfilled with the use of the Population Exposure Index. This scale of assessment has to provide a basis for identifying gaps in country and regional scales, for the prioritizing of the biggest personal exposures on the planet. With the use of the PEI, these populations can be identified.

What remains uncertain is whether the studied volcanoes have a chance of eruption in the near future. Populations in the vicinity of volcanoes in Central America and most probably around the globe can be identified with this method. However, this method does not assess the probability or the magnitude of a future eruption. Further research needs to be done to assess these aspects. For instance, the use of volcanic data input that distinguishes active from non-active volcanoes can be used in further research instead of the Holocene Volcano List that is used in this study. Volcanic data as described here is currently not available, therefore such a dataset needs to be derived from multiple datasets that are available. This brings limitations to the reliability of the output data. If in future research the HVL is used, an additional form of data input and calculation has to be taken into account which assesses the probability and magnitude of future eruptions. This is important, because it can be determined whether the population in the vicinity is actually in danger of volcanic hazards or if the volcano is inactive and has a minimum chance of erupting.

The results of the of the personal exposure assessment in this study are based on a number of assumptions. These are that this model does not take into account that some volcanoes have a higher chance of eruption than other volcanoes. Also, the method assumes that in the case of a volcanic eruption, hazards will not range more than one hundred kilometers from the volcanic vent. Moreover, this calculation does not take any evacuation times into account, in which population is allowed to flee from the danger area. It is also assumed that each volcanic eruption will have the same range, intensity and occurrence of hazards, regardless of the type of volcano and comparison to a volcano’s historical eruptions. Most of these assumptions are restrictions to the results of this study, however, most of the assumptions have to be made because by doing this, the method remains simple enough to be used for a big scale exposure assessment. If future studies have the opportunity to use more complex and extended calculations of personal exposure, probability of eruptions, hazards ranges and intensities and evacuation times can be taken into account.

The use of zones over a gradual assessment was chosen because the zones refer to the information on volcanic hazards in section 3.1.2. The intensities and ranges of different volcanic hazards depend on the magnitude of a volcanic eruption. These can be subdivided using zones, the intensities of all hazards are the highest within a ten-kilometer range from the vent, most often are only of direct impact within one hundred kilometers of the vent and hazards of mediocre intensities occur within tens of kilometers from the vent. To lower the number of assumptions, zones were used in this study. A gradual assessment requires more detailed and specific hazard data, which is not the same for each volcano or eruption type. A gradual approach to personal exposure can be done in future research, more detailed data on hazard ranges and intensities is necessary in that case.

The population data derived from the Gridded Population of the World dataset is based on residential population. Therefore, the data used in this study is restricted to residential population and does not take into account that in certain areas population may be present for temporal periods. To achieve a count of all people that may exposed to volcanic hazards in the case of an eruption, the Landscan population dataset can be used in future studies. The Landscan population dataset gives a pattern of the total population distribution for each 24 hours. This way, Landscan does not eliminate any population that may be in the vicinity of a volcano for temporal periods. The reason that the Gridded Population of the world dataset was preferred for this study instead of the Landscan dataset is that the resolution of the Landscan dataset is lower than the resolution of the Gridded Population of the world dataset and the Gridded Population of the World has les uncertainties.

The statement that was made by Calder et al. in 2015 about Earths volcanoes and population exposure does not apply to Central America in this study (Calder et al., 2015). Calder stated that the areas of four percent of the volcanoes are so densely populated that these account for sixty percent of persons that lives within hundred kilometers from a volcano. The summed weighed population counts of five volcanoes were given a PEI of seven, which is exactly four percent of all volcanoes in Central America on the Holocene Volcano List. However, the total population of these areas accounts for 2.2 percent of population within hundred kilometer from a volcano. This significant difference is the result of a number of factors. Firstly, the discussion to use the Holocene Volcano List for this study makes the population count larger than the use of a more compact volcanic database that only takes certain volcanoes into account. Secondly, the original statement that was made was not about Central America, but about the entire world. Central America contains, on average, significantly more volcanoes per surface area than the rest of the earth's continents. Because of this, the percentage of people that live in the vicinity of a volcano is very high. Further research could substantiate the statement of Calder et al. more by changing at least these two factors. In this study only 20.9 percent of the volcanoes had a PEI of 2, as opposed to the forty percent that Calder stated. This difference can be a result of the aforementioned reasons as well. Because of the use of the Holocene Volcano list, population counts of volcanoes that other volcanic databases would address as irrelevant, are taken into account. Future research could be done with the use another volcanic database to investigate the matter further.

7 Conclusion

To study the global assessment of personal exposure to volcanic hazards three subtopics were discussed. The first subtopic was on the different driving mechanisms for people who choose to live in areas in the vicinity of volcanoes and different volcanic hazards were discussed. Thereafter different components to global assessment of volcanic exposure were studied; the assessment of different levels of volcanic explosivity, the spatial assessment of volcanic hazards, personal exposure assessment calculation methods and different datasets that are necessary for the assessment of personal exposure to volcanic hazards were studied. Lastly, the personal exposure to volcanic hazards in Central America was studied to test whether the method that was proposed in the discussion of the aforementioned subsection worked.

Driving mechanisms for people who choose to live in areas in the vicinity of potential volcanic hazards are important factors in the population distribution in relation to volcanoes and their hazards. The most common determinants are urbanization, lifestyle, resource extraction, geothermal energy, tourism, agriculture and climatic advantages. The weightings of these determinants can be dependent on the economic wealth of a certain area. Population in less affluent countries is more likely to choose to live in the vicinity of volcanoes because of economic reasons than more affluent countries.

The hazards of most widespread concern, due to frequency of occurrence on hazards maps and fatality data are lahars, pyroclastic density currents and ash-fall (Auker et al., 2013). Currently, ash-fall hazards, which are able to have the widest distribution and far-reaching impact, is the best quantified. Neither lahars or pyroclastic density currents have far-ranging impacts, however they account for the greatest impact in the loss of life, infrastructure and livelihoods due to volcanic activity (Brown et al, 2015; Loughlin et al., 2015).

To spatially assess personal exposure to volcanic hazards maps can be used. The five most frequently used map types are geology-based maps, integrated qualitative maps, modelling-based hazard maps, probabilistic hazard maps and administrative maps (Calder et al., 2015). Integrated qualitative maps are suited best for a global assessment compared to the other map types because these map types do not require specific information on certain volcanoes and can be applied the same to each volcano.

To assess personal exposure, knowledge about the different levels of hazard a certain volcano or eruption can have is required. The most frequently used method to assess and compare different levels of volcanic hazards is the Volcanic Explosivity Index, also known as the VEI (Newhall & Self, 1982). The Volcanic Explosivity Index is a general indicator of the explosivity of a volcanic eruption, comparable to the Richter Scale for earthquakes. The index runs from zero to eight with increasing explosivity and is determined by a number of variables including the volume of ejected material, the height of the eruption column and eruption duration.

The most widely used methods to assess personal exposure to volcanic hazards are the Population Exposure Index, PEI (Aspinall, 2011), the Volcano Population Index, VPI(Ewert & Harpel, 2004) and the Volcanic Risk Coefficient, VRC (Scandone et al., 2016). The PEI, VPI and VRC enable personal exposure to volcanic activity to be identified (Brown et al., 2015). What these three methods have in common is that all of these methods directly or indirectly use distances over which all the different hazards can occur as a measure of risk. The PEI and the VPI both directly use distance for zones to indicate the risk. The VRC uses a numerical approach. In this study, the PEI is the preferred method to assess personal exposure because the information obtained by using this index corresponds most closely to the hazards described in section 3.1. The VPI and the PEI complement each other, they are both suited for global exposure assessment for different eruption types. The method that is considered most suited for global personal exposure assessment is the Population Exposure Index. This is substantiated by the fact that the PEI assesses a higher threat compared to the VPI. This is better because this means the PEI assess the direct impact of the hazards from chapter 3.1. to human life. Also compared to the VRC, the assessment of volcanic threat by distance is preferred because it corresponds best with the information on volcanic hazard in chapter 3.1.

Population data needs to have sufficient resolution and needs to support detailed analyses and comparisons. The datasets discussed in chapter 3.2 are merely a few of many accurate datasets. Population distribution models are developed with certain limitations and cannot account for the differences in spatial data availability, scale, accuracy and quality.

The Holocene Volcano List and the Significant Volcanic Eruption Database are databases of active volcanoes. The HVL database takes every volcano that is proven to have been active in the last ten thousand years into account. The SVED takes a fraction of these volcanoes into account. The SVED is a volcanic database that records volcanoes and their eruptions. Only volcanoes that have had major eruptions are included in the database. This is based on a few thresholds like a minimum fatality number and minimum VEI value. Both of these datasets are available online and open for everyone. These datasets both contain coordinates of a range of volcanoes.

The assessment of the personal exposure to volcanic hazards in Central America stated that five out of the 110 volcanoes in Central America are assigned to a PEI-7, which is the highest level of the Population Exposure Index. Additionally, the number of volcanoes assigned to each PEI are; two for PEI-1, nine for PEI-3, one for PEI-3, twenty-three for PEI 4, forty-four for PEI-5 and twenty-six for PEI-6. The computer assessment with the use of the Holocene Volcano List and Gridded Population of the World datasets succeeded for a continental area and will most likely work for a global assessment as well.

With this information, it can be stated that the PEI is suited for a global assessment of personal exposure to volcanic hazard. By using this method, the personal exposure can be mapped out on a global scale, which will make it easier for countries to exchange hazard management strategies and therefore will help reduce the amount of population that is exposed to volcanic hazards.

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