Geofísica internacional
ISSN: 0016-7169
Instituto de Geofísica, UNAM

Ramos Jiménez, Esteban

A vulnerability-based risk assessment of the threatened area surrounding Popocatépetl Volcano to support decision-making during a volcanic crisis

Geofísica internacional, vol. 58, no. 1, 2019, January-March, pp. 7-32
Instituto de Geofísica, UNAM

DOI: https://doi.org/10.22201/igeof.00167169p.2019.58.1.2064

Original paper

A vulnerability-based risk assessment of the threatened area surrounding Popocatépetl Volcano to support decision-making during a volcanic crisis

Esteban Ramos Jiménez

Received: June 13, 2017; accepted: October 04, 2018; published on line: January 18, 2019

Resumen

El volcán Popocatépetl, ubicado en la parte central de México, se encuentra rodeado por una región densamente poblada que excede los 20 millones de habitantes. Su actividad histórica de los últimos 500 años se ha limitado a varias erupciones de pequeñas a moderadas, análogas al episodio actual (1994 al presente). Sin embargo, desde la destrucción del cono ancestral hace unos 23 000 años B.P., el Popocatépetl ha dado lugar a una amplia gama de erupciones tanto en tamaño como en tipo, incluyendo eventos plinianos y colapsos masivos de sector.

Muchas de de las erupciones mayores han dado lugar a grandes volúmenes de material de caída de tefra que se han extendido al menos unos 20 kilómetros hacia el sureste, entre 10 y 15 kilómetros al noreste y 15 a 18 kilómetros en el sector oeste. Sin embargo, la mayoría de los eventos plinianos cubrieron áreas más extensas con material de caída de pómez, flujos de piroclásticos y depósitos de lahar. Basados en la distribución actual de población y de los asentamientos humanos, y considerando la experiencia de evacuación efectuada durante los picos de actividad volcánica, en este trabajo se ha desarrollado una evaluación del riesgo basado en la vulnerabilidad de las áreas amenazadas alrededor del Popocatépetl, con la finalidad de apoyar la toma de decisiones ante una potencial crisis volcánica.

Palabras clave: Popocatépetl, volcán, crisis, riesgo, evaluación, decisiones.

Abstract

Popocatépetl Volcano, located in central Mexico, is surrounded by a densely populated region exceeding 20 million people. The activity of Popocatépetl in the past 5 centuries has been limited to several small to moderate eruptions, similar in style to the current eruptive episode (1994-present). However, since the destruction of an ancestral volcano 23 000 years B. P., Popocatépetl has produced eruptions ranging widely in size and style, including Plinian events and massive sector collapses. Many of the major eruptions have resulted in large volumes of tephra-fall deposits that typically extended at least 20 kilometers to the southeast, about 10 and 15 kilometers to the northeast, and 15 to 18 kilometers to the west. Moreover, some Plinian events have covered much larger areas with pumice-fall, pyroclastic flows and lahar deposits. Based on the present distribution of population and settlements, and considering the experience of evacuations carried out during peaks of the ongoing volcanic activity, in the present work a vulnerability-based risk assessment of the threatened area surrounding Popocatépetl Volcano has been developed. This assessment can provide additional information to support decision-making during the on-going volcanic crisis.

.

Key words: Popocatépetl, volcano, crisis, risk, assessment, decisions.

E. Ramos Jiménez
Posgrado en Ciencias de la Tierra
UNAM
Instituto de Geofísica

Coordinación General de Protección Civil
del Estado de México
Km 36.5 Carretera Federal México-Pachuca
C.P. 55740, Tecámac, México
*Corresponding author: investigacion10@yahoo.com.mx

Introduction

The management of volcanic risk must be supported by a variety of information elements that permits the decision making during an event of volcanic crisis. A useful approach to such management requires that the information elements are defined and prepared well in advance of a potential volcanic activity. For instance, together with hazard maps, it is essential to consider, and analyze, the likely scenarios that may occur in a potential crisis.

Another important crisis-management tool is the event tree (Newhall and Hoblitt 2002), and the more probabilistically oriented Bayesian Event Tree (Marzocchi *et al*., 2008). Such tools assign probabilities to the scenarios inferred from the hazards maps according to the progression of the volcanic activity. An application of the event-tree analysis to the hazard assessment of a specific type of pyroclastic flows at Arenal Volcano in Costa Rica is illustrated in Meloy (2006), who estimated the occurrence probabilities of possible eruptive events based on the activity of previous years. Similarly, Martí *et al*. (2008) developed a risk event tree for Teide-Pico Viejo volcanoes (Canary Islands, Spain), which also involved geology, eruptive history and present activity, as a useful tool for decision-making by civil protection authorities. Neri *et al*. (2008), and Sandri *et al*. (2009) applied event-tree methodologies to Vesuvius Volcano in Italy, extending the event concatenation from precursors along a progressive activity, then focusing on diverse eruption types and associated phenomena, such as ballistics ejection, lava flows, lahars, collapses and tsunamis in the Naples coastal zone and surrounding area. The tree branching was based on the eruptive record and data from the ongoing monitoring. Ideally, the integral management of the volcanic risk should include extensions of the event tree to describe the possible crisis scenarios and the corresponding methods of management.

However, studies focused on the management of volcanic crises are not as profuse in the scientific literature as those mentioned previously to assess the volcanic hazards. Managing a major emergency is a very complex task, and requires the deployment of considerable resources.

Frequently, evacuations are prompted by diverse circumstances, including: incorrect perception of the hazard by the threatened population and civil authorities, and failures of the response systems (Kent 1994, Leonard *et al*. 2008, Marrero *et al*. 2013); inadequate emergency plans (Sorensen 2000, Solana *et al*. 2008, Marrero *et al*. 2012); lack of protocols (Mener 2007, Solana *et al*. 2008); deficiencies in the communication of alerts, warnings and instructions (De la Cruz-Reyna and Tilling 2008, Paton *et al*. 2008, Haynes *et al*. 2008, Johannesdottir and Gisladottir 2010).

In this work we describe some methods to develop a vulnerability-based risk assessment methods of the threatened areas surrounding Popocatépetl Volcano, aiming to support decision-making during the ongoing volcanic crisis. The proposed methods would be compatible with a branching method to be inserted in an integral-management event tree (Newhall and Hoblitt 2002, Marzocchi *et al*. 2008, Sandri *et al*. 2009). Figure 1 shows an example of an event tree that initiates from a condition of low-level background activity at Popocatepetl volcano, and the branches represent subsequent events according to possible paths of activity evolution, according to the past events reaching a possible outcome, in this case the maximum observed event of December 2000-January 2001.

Popocatépetl Volcano

Popocatépetl Volcano, rising 5,452 m. a. s. l., is located at 19^0 01.38’ N and 98^0 37.29’ W, on the southern end of the Sierra Nevada, which separates the valleys of Mexico and Puebla. The recent eruptive history of this volcanic edifice begins 23,000 years B.P, when the pre-existing ancestral Popocatépetl collapsed, generating massive debris avalanches (Robin and Boudal 1987; Boudal and Robin 1989; Siebe *et al*., 1995). Since then, its activity has been characterized by several major explosive eruptions and many smaller eruptions. The most recent explosive eruptions occured ca. 3000 B.C., between 800 and 200 B.C., and ca. 800 A. D. (Siebe *et al*., 1996; Siebe and Macías 2004). Afterwards, the activity of Popocatépetl has remained moderate for nearly 1,200 years. Historical reports since 1354 describe at least 19 episodes of activity, some of which probably involved dome growth-and-destruction processes similar to those of the current, ongoing activity (De la Cruz-Reyna *et al*., 1995; De la Cruz-Reyna and Tilling 2008, De la Cruz-Reyna *et al.,* 2017).

The proximity of Popocatépetl with large population centers (Table 1) such as The Metropolitan Area of Valley of Mexico to the NW; Puebla City, 42 kilometers to the NE; Cuernavaca City, 65 kilometers to the SW (INEGI, 2010); and a myriad of smaller

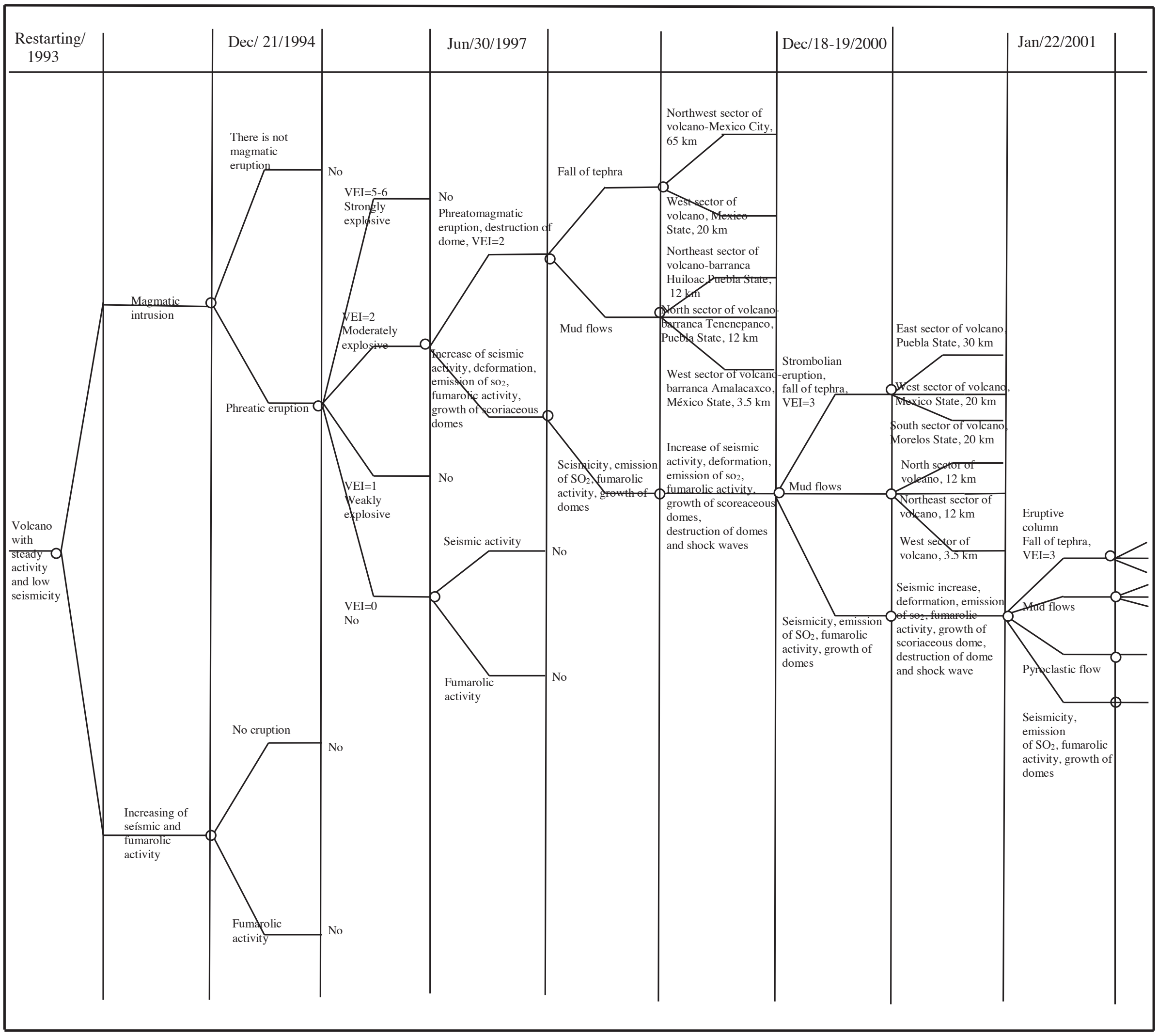


Figure 1. Example of an event tree for Popocatépetl Volcano, according to the methodology of Newhall and Hoblitt (2002) that starting from a background condition, it evolves to different conditions from 1993 until 2001.

settlements in the States of Mexico, Morelos, and Puebla, with the above mentioned diversity of eruptive styles makes Popocatépetl a high risk volcano. It is therefore necessary to continue developing, and refining, decision-making tools to reduce risk, in the event of a possible future major escalation in the ongoing crisis. Popocatépetl's most recent eruptive activity previous to the current 1994-present episode was during 1919-1927, which has been described in detail by several authors (Waitz 1920b, 1921; Weitzberg, 1922, 1923; Camacho, 1925; Atl, 1939; Gómez-Vázquez A. *et al*., 2016). The 1919-1927 activity has helped to define the lower bound of the most likely scenarios for evolution of the present activity.

Table 1. Areas influenced by the activity of the Popocatépetl Volcano and its corresponding populations (INEGI, 2010).

Zone	Population
Metropolitan area of Valley of Mexico	19,764,540
Puebla City	1,539,819
Cuernavaca City	365,168
Myriad of smaller settlements, in the States of Mexico, Morelos, and Puebla	1,040,979

Methodology

To carry out a vulnerability-based risk assessment in a readily accessible platform we use Google Earth (GoogleTM Earth, *V 7.1.5 1557*), since its easy of use, and has a wide accessibility to the general public. To do this, all the field information is incorporated in the same platform, which can be interacted with new field information that may arise over time.

We selected a quadrant (Figure 2) that delimits a sufficient area to include the risk areas shown on the hazard map of Popocatépetl Volcano (Macías *et al*., 1995a; Arana *et al*., 2016). Within that quadrant (indicated by red rectangle) the following parameters of information are included:

- The areas with high, medium, and low risk, are delimited by digitized red, orange and yellow lines, respectively.

- The villages of high risk for the three states (indicated by red squares in Figure 3, are located within the area bounded by the red line. Digital information for each village includes: its official name and municipality; geographic coordinates and altitude above sea level; their most recent population according to the emergency planning map; their meeting place with address; the alerting device; the detailed evacuation route to its designated temporary shelter with address and capacities; distance in km to the shelter and travel time in minutes from the village to its designated shelter. The latter may vary depending on weather conditions.

- The villages of medium risk (indicated by orange squares) are represented in the zone between the orange and red lines (Figure 4). Each of these villages includes the same type information as in (b).

- The villages of low risk (indicated by green squares) are represented in the zone between the yellow and orange lines (Figure 5). Each village also includes the same type of information as in (b).

- Figure 6 shows the most important drainages capable of channeling lahars (marked in dark blue), as well as the communities (blue squares) exposed to this hazard; some larger communities also appear as polygons (light blue). Each community includes the same type of information as in (b), but it also includes the populations bordering the valley that must move to higher ground in case of mudflows.

All data used in these maps were obtained in the field through direct visits to each town in the area. Each of the evacuation routes was tracked directly in the field to identify the optimum traffic control points.

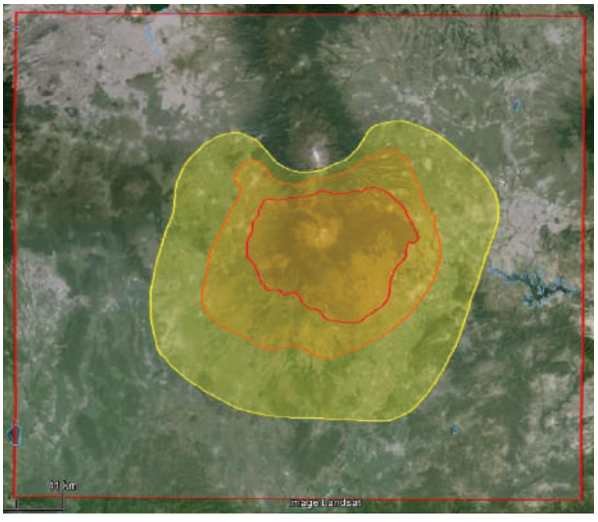


Figure 2. Quadrant delimited by points P1(190 27’ N, 990 16’ W; P2(190 27’ N, 980 05’ W); P3(180 30’ N, 990 16’ W) and P4(180 30’ N, 980 05’ W) covering a sufficient area to include the hazard map of the Popocatépetl Volcano (Macías *et al.*, 1995a, Arana *et al.*, 2016).

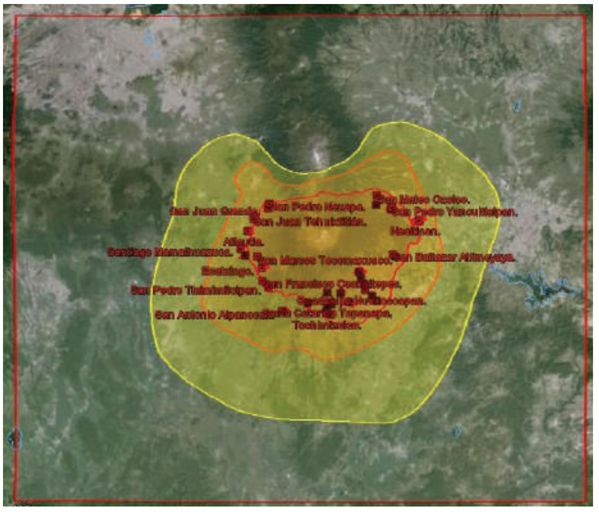


Figure 3. High risk villages for the states of México, Morelos and Puebla.

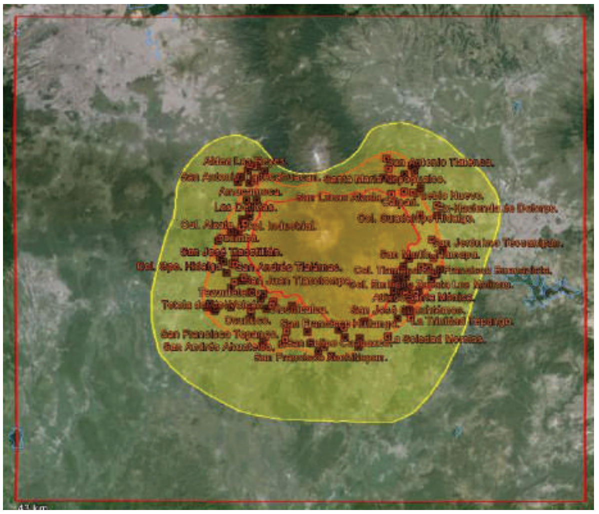


Figure 4. Villages with medium risk in México, Morelos and Puebla States.

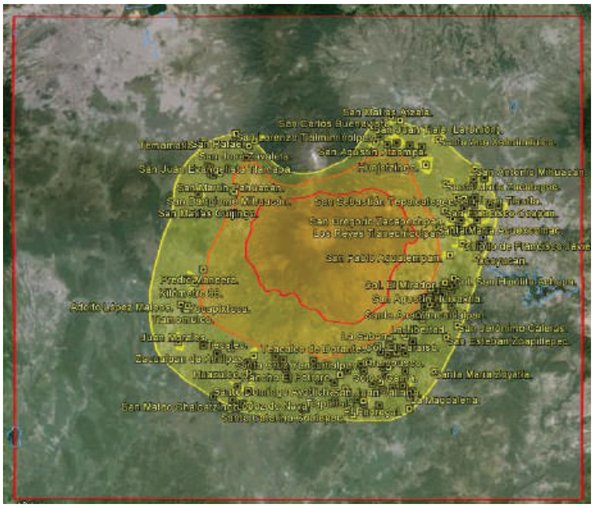


Figure 5. Villages with low risk in México, Morelos and Puebla States.

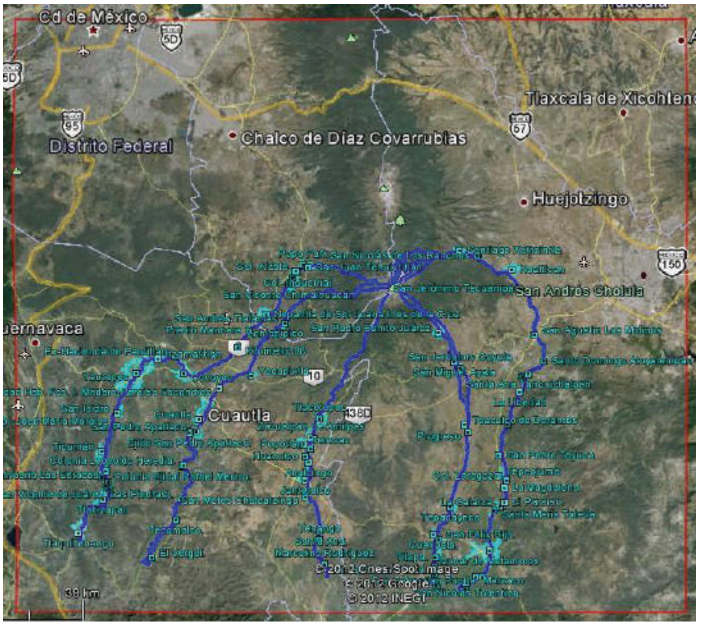


Figure 6. The most important drainages from the point of view of potential risk from lahars in México, Morelos and Puebla States.

Eruptive period, from December 21, 1994 to the present

The most important features of the current eruptive episode of Popocatépetl are summarized in Table 2 (Appendix 1), in reverse chronological order from 2017 to 1994. The analysis and communications of such features have influenced the perceptions of the volcanic hazards among the population and civil authorities, their reactions to different levels of activity and the choice of meeting places, escape routes and shelter locations, which in addition to the available hazard maps (Macías *et al*., 1995a; Arana *et al*., 2016) provided the basic data and criteria utilized in this present work.

Settlements within high-risk areas around Popocatépetl Volcano

The villages located within the high-hazard areas around Popocatépetl Volcano are as follows: Eight in the State of México (Table 3), two in the State of Morelos (Table 4) and twenty in the State of Puebla (Table 5).

Table 3. Villages with high risk in State of México.

VILLAGE	MUNICIPALITY	RISK SECTOR	POPULATION
San Pedro Nexapa	Amecameca	1-7	4,633
San Juan Grande	Amecameca	1-7	429
Atlautla de Victoria	Atlautla	1-7	10,967
San Juan Tehuixtitlán	Atlautla	1-7	6,743
San Juan Tepecoculco	Atlautla	1-7	3,790
Ecatzingo de Hidalgo	Ecatzingo	1-7	7,058
San Marcos Tecomaxusco	Ecatzingo	1-7	1,022
Santiago Mamalhuazuca	Ozumba	1-7	2,182
Total: 8	4		36,824

Information taken from INEGI, 2010.

Table 4. Villages with high risk in Morelos State.

VILLAGE	MUNICIPALITY	RISK SECTOR	POPULATION
San Francisco Ocoxaltepec	Ocuituco	1-6	1,338
San Pedro Tlalmimilulpan	Tetela del Volcán	1-6	1,637
Total: 2	2		2,975

Information taken from INEGI, 2010.

Table 5. Villages with high risk in Puebla State.

VILLAGE	MUNICIPALITY	RISK SECTOR	POPULATION
San Mateo Ozolco	Calpan	1-2	2,713
San Nicolás de los Ranchos	San Nicolás de los Ranchos	1-2	5,685
San Pedro Yancuitlalpan	San Nicolás de los Ranchos	1-2	2,694
Santiago Xalitzintla	San Nicolás de los Ranchos	1-2	2,196
San Baltazar Atlimeyaya	Tianguismanalco	1-3	1,104
San Pedro Atlixco	Tianguismanalco	1-3	867
San Pedro Benito Juárez	Atlixco	1-3	3,153
San Juan Ocotepec	Atlixco	1-3	825
Colonia Agrícola Ocotepec	Atlixco	1-3	1,898
Guadalupe Huexocoapan	Atlixco	1-3	442
San Miguel Ayala	Atlixco	1-3	1,628
San Jerónimo Coyula	Atlixco	1-3	6,622
Tochimilco	Tochimilco	1-4	3,289
La Magdalena Yancuitlalpan	Tochimilco	1-4	2,210
San Martín Zacatempan	Tochimilco	1-4	721
San Miguel Tecuanipan	Tochimilco	1-4	1,378
Santa Catalina Cuilotepec	Tochimilco	1-4	439
Santa Catarina Tepanapa	Tochimilco	1-4	681
Santa Cruz Cuautomatitla	Tochimilco	1-4	1,405
Santiago Tochimizolco	Tochimilco	1-4	747
Total: 20	6		40,697

Information taken from INEGI, 2010.

Operational (response) plans for Popocatépetl Volcano

When the most recent activity of Popocatépetl began, on December 21, 1994, the States of Mexico, Morelos, and Puebla States began to develope their respective response operational plans within the framework of the National System of Civil Protection, involving the three levels of government: federal, state and municipal, and the social and private sectors of each state (Figure 7).

In such operational plans, all participating offices are governed according to liability matrices defining their specific functions, under the constitutional headship of the Governor of each state. Such governance includes the emergency coordination, emergency plans, warning, evacuation, temporary shelters, public safety, supplies, strategic services, equipment and goods, search of missing people, rescue and assistance, medical attention, damage assessment and emergency social communications. Since Civil Protection authorities may change when are state elections (usually every 6 years), occur one of the objectives of the present work is to maintain the conceptual framework to help new officials in understanding and implementing the operational plans.

Temporary shelters

The sites to serve as temporary shelters –in case of volcanic emergency- in the states of México, Morelos, and Puebla were selected in different localities (Figure 8), necessarily outside the volcanic risk area. The shelters for the same three states which are generally schools are indicated as green small house icons with a flag, with their geographical location, height above sea level, address and capacity.

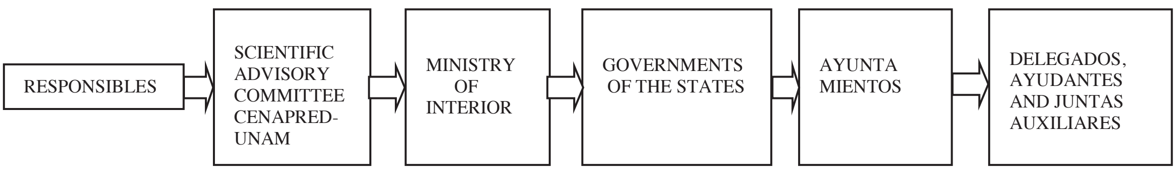


Figure 7. Activation Diagram for Popocatépetl Volcano Operative Plan (Decision Making).

Figure 8. Locations of the temporary shelters of the States of México, Morelos and Puebla, which are outside the risk area.

A prime prerequisite for their selection was that they had the necessary infrastructure to provide the necessities and services required by the expected amount of people during their stay, such as: drinking water, electricity, telephone, toilets, showers, sleeping area, kitchen area and mess halls; recreational areas, medical service, psychological support, and religious and worship services. The establishments that were considered for use during a possible contingency include schools of all levels (from kindergarten to high schools), CONALEP (National College of Technical Vocational Education), CEBETIS (Center for Technical, Industrial and Services Studies), gymnasiums, halls of multiple uses, social and cultural centers, municipal and farmer halls; exhibition fairs sites, sports center sites, trade union buildings, Rotary and Lion clubs, among others. The number and capacities of the temporary shelters of the States of México, Morelos, and Puebla are summarized in Table 6.

Response and evacuations during the eruptive episode of December 18-19, 2000

On December 18-19, 2000, Popocatépetl activity occured and a contingency situation was developed. The available operational plans for each of the States at the time allowed to deal with that contingency. However, some difficulties arose during the contingency, particularly the overreactions in some towns; these problems were among the reasons to undertake the present study. The plans required, as a first stepts, rais the awareness of the risks related to volcanic activity, among the populations of the three States, through talks, lectures, brochures, calendars, evacuation drills (at least three in México State, eight in Puebla, and five in Morelos in 2000), radio spots at the most popular broadcasting stations in high-risk areas, and improvement of roads and highways with the construction of some bridges and beltways like in Atlautla, State of México. Additionally, there were early agreements reached with associations of taxis and minibuses, commercial carriers and private vehicles that could be used at for evacuation, in the case of a contingency.

The increase in volcanic activity, the associated intensity in the volcano-monitoring, and the persistence of energetic harmonic tremor, prompted the Scientific Advisory Committee (SAC) to recommend to the authorities of the National Coordination of Civil Protection of SEGOB to rise the level of alert, particularly for the most vulnerable communities at risk, considering the increased probability of a major eruptive event. The SAC advised that such activity may pose a threat on settlements located in zone 1 of higher risk, according to the existing map of hazards of Popocatépetl (Macías *et al*. 1995a). In addition the SAC noted the increasing probability of damage to settlements located along river valleys that could channel destructive lahars. Such lahars potentially could be generated by erosion and melting of glaciers in the north and northwest sectors of the volcanic cone caused by potential pyroclastic flows.

Therefore, on December 15, 2000, a declaration of emergency was issued in the Diario Oficial de la Federación (2000)

Table 6. Temporary shelters established in México, Morelos, and Puebla States. (Tabulated from data in: Plan Operativo Popocatépetl (2012); Plan Fuerza de Tarea Popocatépetl (2001); Plan de Protección Civil para el Volcán Popocatépetl (2000); Programa Especial para la Emergencia del Volcán Popocatépetl (2007).

STATE	TOTAL NUMBER OF SHELTERS	TOTAL CAPACITY (PEOPLE)
Edo. Mex.	114	34,830
Morelos	42	12,048
Puebla	34	38,561
Total: 3	190	85,439

Note: Additionally, for Puebla State temporary shelters are contemplated for 237 schools in Puebla municipality, 33 schools in San Pedro Cholula municipality, six schools in San Martin Texmelucan and 67 schools in Izúcar de Matamoros municipality.

that involved the release of funds from the Emergency Reserve of Fund for the Emergency Care (FONDEN) (http://www.proteccioncivil.gob.mx/work/models/ProteccionCivil/Resource/21/12/images/Definicion%20del%20FAE.pdf). Accordingly, the three States, through their State Systems of Civil Protection (General Directorate of Civil Protection in México State, General Directorate of Civil Protection in Morelos State, and State System of Civil Protection in Puebla), coordinated with the federal Civil Protection to start evacuation operations. These actions involved: 13 communities in the México State (with 28,539 persons); three communities in the State of Morelos (with 2,720 persons), and 20 communities in six municipalities of the State of Puebla (with 55,281 inhabitants). Of the total of 86,540 persons affected, 8,592 people who were transported via 13 evacuation routes remained at 23 temporary shelters of the México State (Memoria de las Acciones del Plan Operativo Volcán Popocatépetl del 15 al 27 de Diciembre del año 2000). In the State of Morelos, four temporary shelters and four evacuation routes were used to transport and accommodate a total of 2,664 people (Contingencia Volcánica Morelos, Diciembre 2000); and the State of Puebla housed 8,289 people in 23 shelters, transported via 10 evacuation routes (Resumen de las acciones llevadas a cabo durante la evacuación de las comunidades aledañas al volcán Popocatépetl en Diciembre de 2000). Of the remaining population (nearly 66,995), some self-evacuated to other places, mainly to homes of friends or relatives outside the risk areas, while others decided not to leave. In high-risk areas of the State of Puebla, about 1,598 people expressed their reluctance to leave (Resumen de las acciones llevadas a cabo durante la evacuación de las comunidades aledañas al volcán Popocatépetl en Diciembre de 2000), while in the State of México 11,360 people were not evacuated (Memoria de las Acciones del Plan Operativo Volcán Popocatépetl del 15 al 27 de Diciembre del año 2000). There is no report from Morelos State.

In the areas of highest risk, 20 towns in Puebla State, 8 in México State, and 2 in Morelos State were evacuated; in areas of intermediate risk, also 5 towns in México State, 1 in Puebla State, and 2 in Morelos State were evacuated. In addition, the San Buenaventura Nealtican community in Puebla was evacuated, because it was in the lahar flow path along the Huiloac ravine, which originates on the north side of the volcanic cone, at the glacier which potentially could be eroded and melted by pyroclastic flows. In México State, San Diego Huehuecalco, San Juan Tlacotompa, San Andrés Tlalámatl, Colonia Guadalupe Hidalgo and San José Tlacotitlán (Memoria de las Acciones del Plan Operativo Volcán Popocatépetl del 15 al 27 de Diciembre del año 2000); and in Morelos Huecahuaxco and Hueyapan were also evaluated (Contingencia Volcánica-Morelos Diciembre 2000).

Evacuation operations began in all the towns simultaneously on December 15, 2000, and involved the respective State Units of civil protection, the National Coordination of Civil Protection of SEGOB, and the National Center of Disaster Prevention. The Scientific Advisory Committee closely followd the evolution of the volcanic activity.

The eruption reached its maximum intensity on December 18 and 19, after which it decreased gradually, until it was decided on December 27 to allow all evacuees to return to their homes.

Evacuation routes

Evacuation routes around Popocatépetl Volcano were chosen after a comprehensive analysis of the existing roads and dirt tracks, to determine which were the most efficient and fastest access between the endangered towns and the sites of the temporary shelters designated by civil protection authorities of the states of Mexico, Morelos, and Puebla. Along each evacuation route, transit control points are included to prevent evacuation vehicles using a wrong route. In these control points state and municipal traffic officers should remain to ensure the secure flow during a contingency. To improve the capacity of the routes, some of them were paved or repaved, some bridges were expanded, and others constructed. Some dangerous curves were realigned, and some beltways roads were built to bypass towns and population centers, as was the case for the Atlautla-Popo Park beltway. In such manner this way, six routes for the western sector of the volcano, corresponding to State of México, were selected (Appendix 2, Figures 9 to 14). In the State of Morelos, evacuation routes for two villages with high risk were established in the southern sector of the volcano (Appendix 2, Figures 15 and 16), and for the State of Puebla on eastern side of volcano, ten evacuation routes were established (Appendix 2, Figures 17 to 25; the Figure 19 contents evacuation routes 3 and 4).

Distances and travel times between the meeting sites of high-risk villages

For decision-making to be effective during a volcanic crisis in an effective risk-management scheme, it is essential to know the travel times between key geographic points (Marrero et al., 2013). To measure the travel times between the settlements located in the high-risk areas and the temporary shelters, timed journeys at average speeds of 40 km/h with support of urban buses were performed along the evacuation routes marked in each of the state's operational plans (Mexico, Morelos and Puebla). With this information, time-distance tables and plots have been prepared to support evacuation decision-making and planning.

For the purpose of this paper, we present only four examples of high-risk settlements in the State of México (Appendix 3, Tables 7 to 10 and Figures 26 to 29), two in the State of Morelos (Appendix 3, Tables 11 and 12, and Figures 30 and 31), and four in the State of Puebla (Appendix 3, Tables 13 to 16, and Figures 32 to 35). The complete set of travel-time data and plots may be consulted in Ramos (2018).

Meeting sites for the population in case of volcanic contingency

Civil-protection authorities of each state, together with municipality officials, jointly defined meeting points (or assembly or gathering places) for the population in case of contingency, as occurred in December 18-19, 2000. In most cases, such meeting points were set in the central parts of towns or at the municipal city halls, such as: near the Municipal Delegations at the State of México; near the Municipal Inspector and Auxiliary Presidencies at Puebla State; and near the Municipal Assistantships in the state of Morelos. In some cases, meeting sites were designated at other locales, such as: municipal and communal auditoriums; civic squares, near civil courts, chapels and shrines, elementary and secondary schools, sports fields, markets, at jagüeyes (small natural water dams), meeting rooms, roundabouts, squares, parks and gardens, in culture houses, trade unions and in offices of agricultural commissions.

Warning system and alerting devices

The general warning system used in Mexico is the Traffic Light Alert System TLAS (De la Cruz-Reyna 1995, 1996; De la Cruz-Reyna and Tilling, 2008; De la Cruz-Reyna et al., 2017). The colors universally used for Traffic lights indicate the level of warning and awareness of the population, and the phases within each of the three colors (green, yellow and red) indicate the level of response of the Civil Protection authorities. The way in which these levels are communicated to the population may vary between different towns. During a contingency, in the case when the population must move to assembly points or meeting sites different alerting devices activated by every local authority are used, and these can include special ringing of bells in churches, rockets, sirens and loudspeakers, whistles of some local companies, systems of particular sounds, paging with sound in private vehicles, sirens of ambulances, local broadcasting stations, and home announcements. Mass media such as radio and television stations, internet, newspapers, etc. are also widely used.

Discussion and conclusions

Decision-making during a volcanic crisis situation is a highly complex problem involving volcanological, social, economic, health, cultural, meteorological, and other factors. This complexity makes it very difficult to develop a general methodology for the management of risk, particularly during episodes of enhanced volcanic activity, because the nature and dimension of the response critically depends on the progression of the activity, and on the related spatial distribution of hazard and exposure. An optimal mitigation of risk requires a layout of information and criteria that provides the Civil Protection and other authorities of the factors needed for appropriate decision-making. The present work intends to provide a risk-management tool to assist the involved stakeholders in determining the appropriate and adequate level of response. This tool or layout -in the form of maps, tables, and data- that is described here builds on the experience of the risk management gained over more than 20 years of eruptive activity at Popocatépetl Volcano, including the response to some critical situations during which precautionary evacuations were necessary. The possibility of other scenarios corresponding to much larger eruptions, such as some that occurred in the geological record of Popocatépetl, are also considered indirectly.

Of particular importance is the use of the layout for the choice of evacuation routes, community-shelter links, and the determination of evacuation travel timings for different possible volcanic activity scenarios. Equally important, the layout can serve as a practical communication tool among the involved municipal, state and federal authorities, as it constitutes a single database for all levels of government. Given a potential red-level alert of the TLAS in a region determined by the consensus of the Advisory Scientific Committee, the layout will assist municipal, state and federal authorities to develop and undertake -in a short time- the optimal, mitigative actions to reduce potential risks for the population affected. However, in order to remain valid and useful, the information in the database must be updated as frequently as possible.

Acknowledgements

This work was supported by the National Center of Disaster Prevention of SEGOB, Earth Science Postgraduate Program at the Institute of Geophysics UNAM, and Special thanks for the help provided by Arturo Mendez Ferrer of the Earth Sciences Library of UNAM.

References

Arana L., Bonasia R., Capra L., Córdoba G., Cortés J., Delgado H., Ferrés M. D., Fonseca R., García J. A., Gisbert G., Jaimes M. del C., Macías J. L., Martin A. L., Portocarrero J., Salinas S., Siebe C., Telles E., 2016, Grupo de trabajo para la actualización de los mapas de peligros del volcán Popocatépetl. SEGOB-UNAM.

Atl, 1939, Volcanes de México. La actividad del Popocatépetl. *Volumen 1, Editorial Polis, México; 74 p.*

Boudal C., Robin C., 1989, Volcán Popocatépetl: Recent Eruptive History, and Potential Hazards and Risks in Future Eruptions. In: Latter JH (ed.) Volcanic Hazards. IAVCEI Proceedings in Volcanology. Springer-Verlag Berlín: 110-128

Camacho H., 1925, Apuntes acerca de la actividad actual del volcán Popocatépetl en relación con la sismología. *Anales del Instituto Geológico de México. Páginas 38-60.*

Contingencia volcánica-Morelos, diciembre 2000, Dirección General de Protección Civil del Estado de Morelos, Elaborada en febrero de 2001.

De la Cruz-Reyna S., 1995, Un Código de Alerta para el Manejo de Emergencias Antes y Durante Potenciales Erupciones del Volcán Popocatépetl. En: "Volcán Popocatépetl Estudios Realizados Durante la Crisis de 1994-1995". Coedición del Sistema Nacional de Protección Civil, El Centro Nacional de Prevención de Desastres y la UNAM (ISBN: 970-628-127-4), pp. 327-333. (1995).

De la Cruz-Reyna S., 1996, Un Código de Alerta para el Manejo de Emergencias Volcánicas. En: "Riesgo Volcánico", R. Ortiz, Ed. Serie Casa de los Volcanes No. 5. Cabildo de Lanzarote-CSIC, I. Canarias, España (ISBN: 84-87021-34-4), pp. 181-187 (1996).

De la Cruz-Reyna S., Tilling R., 2008, Scientific and public response to the ongoing volcanic crisis at Popocatépetl volcano, México: importance of an effective hazards warning system. J. Volcanol. Geotherm. Res 170: 121-134.

De la Cruz-Reyna S., Tilling R. I., Valdés-González C., 2017, Challenges in responding to a sustained and continuing volcanic crisis: The case of Popocatepétl volcano, Mexico, 1994-present. En: OBSERVING THE VOLCANO WORLD: VOLCANO CRISIS COMMUNICATION. Ed. C.J. Fearnley, B. McGuire, G. Jolly, D. Bird and K. Haynes. A Springer-Verlag book, ADVANCES IN VOLCANOLOGY series. eBook ISBN 978-3-319-44097-2; Hardcover ISBN 978-3-319-44095-8. DOI: 10.1007/11157_2016_37.

Contingencia volcánica-Morelos, diciembre 2000, Dirección General de Protección Civil del Estado de Morelos, Elaborada en febrero de 2001.

Diario Oficial de la Federación, 2000, Declaratoria de Emergencia Preventiva para efectos de las Reglas de Operación del Fondo de Desastres Naturales (FONDEN), por el sensible incremento en la actividad del volcán Popocatépetl. – 15 de diciembre de 2000,- Primera Sección- Diario Oficial, No. 11.- 2 http://dof.gob.mx/nota_detalle.php?codigo=788168&fecha=15/01/2001

FONDEN, Fondo para la Atención de Emergencias, http://www.proteccioncivil.gob.mx/work/models/ProteccionCivil/Resource/21/12/images/Definicion%20del%20FAE.pdf

Gómez-Vázquez A., De la Cruz-Reyna S., Mendoza-Rosas A., 2016, The ongoing dome emplacement and destruction cyclic process at Popocatepetl volcano, Central Mexico. Bull. Volcanol. (2016) 78:58

Google™ Earth *Version 7.1.5 1557*

Haynes K., Barclay J., Pidgeon N., 2008, Whose reality counts? factors affecting the perception of volcanic risk. J Volcanol Geotherm Res 172(3):259–272

INEGI, 2010, Instituto Nacional de Estadística, Geografía e Informática, Censos 2010, http://www.inegi.org.mx/est/lista_cubos/consulta.aspx?p=pob&c=1 http://coespo.edomex.gob.mx/zonas_metropolitanas

Johannesdottir G., Gisladottir G., 2010, People living under threat of volcanic hazard in southern Iceland: vulnerability and risk perception. Nat Hazards Earth Syst Sci 10:407–420.

Kent R., 1994, Disaster preparedness guide. 2nd Ed. Disaster Management Training Programme. UNDP, UNDRO

Leonard G., Johnston D., Paton D., Christianson A., Becker J., Keys H., (2008), Developing effective warning systems: ongoing research at Ruapehu Volcano, New Zealand. J Volcanol Geotherm Res 172(3):199–215.

Macías J. L., Carrasco G., Delgado H., Martin A. L., Siebe C., Hobblit R. P., Sheridan M., Tilling R. I., 1995a, Mapa de Peligros del Volcán Popocatépetl. *Instituto de Geofísica, UNAM- CENAPRED, México, D.F. (Mapa y folleto explicativo de 12 páginas).*

Marrero J. M., Garcia A., Llinares A., López P., Ortiz R., 2012, Assessing the vulnerability of the evacuation emergency plan: the case of the El Hierro, Canary Island, Spain. Geophysical Research Abstracts Vol. 14, EGU2012-12374-2, 2012 EGU General Assembly 2012.

Marrero J. M., García A., Llinares A., De la Cruz-Reyna S., Ramos S., Ortiz R., 2013, Virtual tools for volcanic crisis management, and evacuation decision support: applications to El Chichón volcano (Chiapas, México) Natural Hazards (2013) 68: 955-980. doi:10.1007/s11069-013-0672-4.

Martí J., Aspinall W. P., Sobradelo R., Felpeto A., Geyer A., Ortiz R., Baxter P., Cole P., Pacheco J., Blanco M. J., López C., 2008, A long-term volcanic hazard event tree for Teide-Pico Viejo stratovolcanoes (Tenerife, Canary Islands). *Journal of Volcanology and Geothermal Research 178 (2008) 543-552.*

Marzocchi W., Sandri L., Selva J., 2008, BET_EF: a probabilistic tool for long- and short-term eruption forecasting. Bull Volcanol 70: 623-632. doi: 10.1007/s00445-007-0157-y

Meloy A. F., 2006, Arenal-type pyroclastic flows: A probabilistic event tree risk analysis. *Journal of Volcanology and Geothermal Research 157 (2006) 121-134.*

Memoria de las Acciones del Plan Operativo Volcán Popocatépetl del 15 al 27 de Diciembre del año 2000, Dirección General de Protección Civil del Estado de México. Sistema Estatal de Protección Civil.

Mener A., 2007, Disaster response in the United States of America: an analysis of the bureaucratic and political history of a failing system. PhD thesis, CUREJ: College Undergraduate Research Electronic Journal, University of Pennsylvania.

Neri W. P., Aspinall R., Cioni A., Bertagnini P. J., Baxter G., Zuccaro D., Andronico S., Barsotti P. D., Cole T., Esposti Ongaro T., Hincks G., Macedonio P., Papale M., Rosi R., Santacroce G., Woo G., 2008, Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. *Journal of Volcanology and Geothermal Research 178 (2008) 397-415.*

Newhall, C. G.,·Hoblitt R. P., 2002, Constructing event tree for volcanic crisis. *Bull. Volcanol. (2002) 64:3-20.*

Paton D., Smith L., Daly M., Johnston D., 2008, Risk perception and volcanic hazard mitigation: individual and social perspectives. J. Volcanol. and Geotherm. Res. 172(3):179–188.

Plan de Protección Civil para el Volcán Popocatépetl, 2000, Gobierno del Estado de Puebla. 79 Páginas.

Plan Fuerza de Tarea Popocatépetl 2001, Dirección General de Protección Civil del Estado de Morelos. Gobierno del Estado de Morelos, 52 páginas.

Plan Operativo Popocatépetl, 2012, Gobierno del Estado de México, Dirección General de Protección Civil del Estado de México. 104 páginas.

Programa Especial para la Emergencia del Volcán Popocatépetl, Dirección del Plan Popocatépetl, 2007, Secretaría de Gobernación del Estado de Puebla, 38 páginas.

Quaas, R., González, R., Guevara, E., Ramos, E. y De la Cruz-Reyna, S., 1995. Monitoreo volcánico: instrumentación y métodos de vigilancia. Volcán Popocatépetl: Estudios realizados durante la crisis de 1994-1995. CENAPRED, p. 25-76.

Ramos E., 2018, Una evaluación de riesgos basada en la vulnerabilidad de la zona amenazada en torno volcán Popocatépetl para apoyar la toma de decisiones en una posible crisis volcánica. Tesis doctoral. 90 pág.

Resumen de las acciones llevadas a cabo durante la evacuación de las comunidades aledañas al volcán Popocatépetl en Diciembre de 2000, Gobierno del Estado de Puebla. Secretaría de Gobernación. Subsecretaría de Asuntos Políticos. Protección Civil-Dirección del Plan Popocatépetl.

Robin C., Boudal C., 1987, A gigantic Bezymianny-type event at the beginning of modern volcán Popocatépetl. J Volcanol Geotherm Res 31: 115-130

Sandri L., Guidoboni E., Marzocchi W., Selva J., 2009, Bayesian event tree for eruption forecasting (BET_EF) at Vesuvius Italy: a retrospective forward application to the 1631 eruption. *Bulletin of Volcanology. Vol. 71, pp. 729-745.*

Siebe C., Abrams M., Macías J. L., 1995, Derrumbes Gigantes, Depósitos de Avalancha de Escombros y Edad del Actual Cono del Volcán Popocatépetl. In: Volcán Popocatépetl, Estudios Realizados Durante la Crisis de 1994-1995. CENAPRED-UNAM, México, D.F, pp. 195-220.

Siebe C., Abrams M., Macías J. L., Obenholzner J., 1996, Repeated volcanic disasters in pre-Hispanic time at Popocatépetl, Central Mexico. Past key to the future? Geology 24: 399-402

Siebe C., Macias J. L., 2004, Volcanic hazards in the Mexico City metropolitan area from eruptions of Popocatépetl, Nevado de Toluca, and Jocotitlán stratovolcanoes and monogenetic scoria cones in the Sierra Chichinautzin. Volcanic Field guide, Penrose Conf. Neogene-Quaternary Continental margin Volcanism. Geol Soc Am, pp 1- 77

Solana M., Kilburn C., Rolandi G., 2008, Communicating eruption and hazard forecasts on Vesuvius, Southern Italy. J Volcanol Geotherm Res 172(3):308–314

Sorensen J., 2000, Hazard warning systems: review of 20 years of progress. Nat. Hazards Rev. 1(2):119–125

Waitz P., 1920b, La nueva actividad y el estado actual del volcán Popocatépetl. *Mem. de la Soc. Científica "Antonio Alzate". Tomo 37, México: 295-313.*

Waitz P., 1921, Popocatépetl again in activity. *Am. J. Sci. 5th Ser. V.1: 81-85.*

Weitzberg F., 1922, El ventisquero del Popocatépetl. *Memorias y Revista de la Sociedad Científica "Antonio Alzate". Tomo 41, N^{OS} 2 y 3. Noviembre-diciembre de 1922.*

Weitzberg F., 1923, El ventisquero del Popocatépetl. *Memorias de la Sociedad*

Appendix 1

Table 2. Summary of recent eruptive history of Popocatépetl Volcano, 1994-2017.

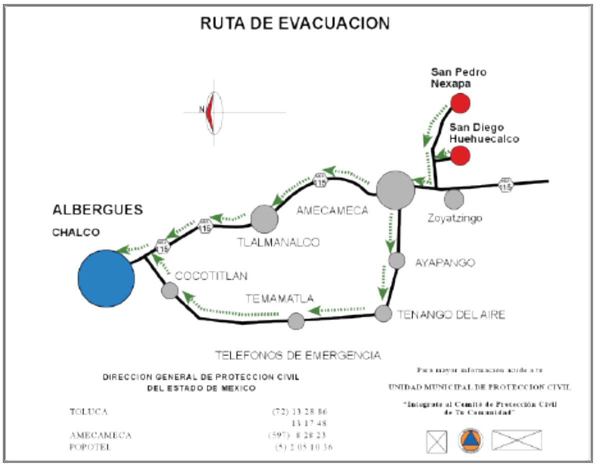
YEAR	BRIEF DESCRIPTION OF ACTIVITY	REFERENCES
2002-2017	In 2017, 58,217 exhalations of low to moderate intensity, 651 volcanic earthquakes with magnitudes between 1.0 and 3.7 and 300 hours with 51 minutes of harmonic tremor were recorded. Major exhalations occurred on May 18, July 3, August 14, September 27, October 5 and 12; and November 23 and 27. In 2016, 38,454 exhalations of low to moderate intensity, 756 volcanic earthquakes with magnitudes between 1.0 and 3.8 and 548 hours with 13 minutes of harmonic tremor were recorded. Major exhalations occurred on January 16, 19, 20 and 22; February 17; March 29; April 3 and 18; July 31; and November 25 and 29. In 2015, 23,164 exhalations, 193 volcanic earthquakes with magnitudes between 1.1 and 2.9; and 146 hours with 48 minutes of high frequency and low to moderate amplitude harmonic tremor were detected. Major exhalations occurred on February 15 and 24; and May 21. In 2014, 21,320 exhalations of low to moderate intensity, 231 volcanic earthquakes with magnitudes between 1.0 and 3.2 and 39 hours with 57 minutes of high frequency and low-moderate amplitude harmonic tremor were recorded. Major exhalations occurred on August 31, October 7, 12 and 29; November 4 and December 8 and 18. In 2013, 13,525 exhalations of low to moderate intensity; 331 volcanic earthquakes with magnitudes between 1.0 and 3.6 and 532 hours 26 minutes of harmonic tremor of high frequency and low and moderate amplitudes were recorded. Major exhalations occurred on 7 and 26 March; 13 and 18 April; 7, 11, 14 and 15 May; 17 and 18 June; and, 4, 7, 9, 10 and 12 July. In 2012, 14,188 exhalations of low to moderate intensity, 150 volcanic earthquakes with magnitudes between 1.1 and 3.6, and 370 hours of high-frequency harmonic tremor with low to moderate amplitudes were detected. Major exhalations occurred on January 25; on April 13, 16 and 18; on May 3, 6 and 12; on August 6 and December 2. In 2011, 2,616 exhalations of low to moderate intensity, 46 volcanic earthquakes with M<1.9. In addition, there were 47 hours with 41 minutes of harmonic tremor of high frequency and low-moderate amplitudes. Major exhalations occurred on January 31, May 22; 3, 4 and June 17; 9 and August 30; 26 and September 27; November 20 and December 8. In 2010, 2,042 exhalations of low to moderate intensity, 25 volcanic earthquakes with M<1.8 and 42 hours with 31 minutes of high-frequency harmonic tremor were detected. Major exhalations occurred on May 25; 7, 9 and June 11 and August 23. In 2009, 3,351 exhalations of low to moderate intensity, 23 volcanic earthquakes with M<2.2 and 12 hours with 52 minutes of harmonic tremor of high frequency and low-moderate amplitudes were recorded. Major exhalations occurred on January 21, 6 and February 13, March 23, April 1, September 10, 9 and October 29 and 14 and November 21. In 2008, a total of 3,829 exhalations of low to moderate intensity, 32 volcanic earthquakes with M<2.9 and 31 hours with 2 minutes of	National Center for Disaster Prevencion

	harmonic tremor of high frequency and low-moderate amplitudes were recorded. Major exhalations occurred on 4, 11, 14 and February 21. For 2007, 3,339 exhalations of low to moderate intensity, 93 volcanic earthquakes with M<3.1 and 51 hours with 9 minutes of harmonic tremor of high frequency and low-medium amplitude were recorded. Major exhalations occurred on January 6, November 26 and 1 and December 31. During 2006, there were 4,475 exhalations of low to moderate intensity, 112 volcanic earthquakes with M<3.0 and 69 hours with 20 minutes of harmonic tremor with low and high frequency and low and medium amplitude. Major exhalations occurred on 6, 25 and January 26; and July 25. During the 2005 5,747 exhalations of low to moderate intensity, 75 volcanic earthquakes with M<2.9 and 10 hours with 37 minutes of harmonic tremor of high frequency and low amplitude were recorded. Major exhalations occurred on 9 and January 22; March 9, June 23, 29 and July 30, 23 and October 24, 1, 4, 13, and December 25. In general, the recorded activity during this year also remained low and stable. For 2004, there were a total of 4,187 exhalations of low intensity, 55 volcanic earthquakes with magnitudes between 1.7 and 2.8 and 1 hour with 2 minutes of harmonic tremor low amplitude. In general, it is considered that the recorded activity during this year remained low and stable. In 2003 27 events involving emission of ash and incandescent fragments at short distances of the crater. Some of them provoked fires in nearby grassland. There were also reports of fall of ash on Santiago Xalitzintla and San Nicolás de Los Ranchos, of Puebla State; on Tetela del Volcán, Yecapixtla, Ocuituco, Atlatlahucan and Totolapan, inside of Morelos State; and on San Pedro Nexapa, San Diego Huehuecalco, San Juan Tehuixtitlán, Atlautla, Ozumba, Ecatzingo, Santiago Mamalhuazuca, San José Tlacotitlán, Tepetlixpa, Juchitepec, Tenango del Aire and Amecameca in México State. The most important event of July 19, caused to thin ash fall in most of Mexico City. In 2002 10 eruptive events occurred related with small explosions, accompanied by emission of ash and incandescent fragments over short distances of the crater. There were some reports of ash fall in San Pedro Nexapa, Ecatzingo and Tecomaxusco, in Edo. Mex.; Tetela del Volcán, in Morelos State; San Pedro Benito Juárez and some sectors of Puebla City.	
2001	Dome destruction activity continued throughout January 2001. A major explosion on January 22, destroyed a considerable part of the dome producing pyroclastic flows and an ash column 8 km of high above the summit and some mud flows. None of these phenomena affected the population; although a few houses were flooded with a mud deposit as much as 60 centimeters thick.	National Center for Disaster Prevencion
2000	On 10 and May 24 small lahars flowed through the Tenenepanco gully. In November 1 is detected a sudden increase in the volcano's internal activity. From December 10, large amplitude harmonic tremors with increasing duration and intensity were recorded for several days. On 12 December 200 exhalations are recorded per day, some of them reaching 5 to 6 kilometers over the volcano summit, and glow within the crater. This type of activity continued for three days, causing light ash falls on communities around the volcano. On December 15, the harmonic tremor signal saturated monitoring seismograms and were recorded at seismological stations at 150 km from Popocatépetl. These signals could be felt in some communities close to the volcano. After 10 hours of intense tremor, the activity of the volcano waned abruptly	National Center for Disaster Prevencion Gómez-Vázquez *et al*. 2016

	the morning of December 16, and 16 hours later, another episode of saturating harmonic tremor damaged some seismographs. All devices of monitoring: seismographs, tilt meters, gas detectors, etc. detect signals without precedent. Aerial photos taken on December 16 showed a lava dome with a volume exceeding all previous and growing 5 to 10 times faster than any of the previous ones. In these conditions, the Civil Protection authorities declared an increase in the level of alert and begin a preventive evacuation. Approximately 40,000 people to go out areas of risk. It is estimated that at that time the dome contained about 6~7x106 m3 of lava (Gómez-Vázquez et al. 2016). On December 18 the volcano erupted incandescent debris on its flanks about 5 or 6 kilometers from the crater. A similar eruption but lower-intensity followed on December 24, and the activity waned afterwards. Shortly after Christmas, the people returned to their communities.	
1996-1997	On 4 March 1996 a seismic crisis and ash emissions was related to the emplacement a large dome within the crater in March 25 1996 (Gómez-Vázquez et al. 2016). The growth of this dome, the trapped gases and the seismicity, were followed by a moderate explosion on April 30, 1996 partially destroyed the dome and ejected incandescent debris causing the death of 5 climbers near the lower rim of the crater. On June 30 1997 major explosion combined with a northwest wind, causes a light ash fall on Mexico City, shaking the public opinion (De la Cruz-Reyna et al. 2017). A small lahar reached some houses of the town of Santiago Xalitzintla in Puebla State.	Gómez-Vázquez *et al*. 2016 De la Cruz Reyna and Tilling 2017
1995	Gradually, the volcano reaches a state of equilibrium, with frequent exhalations similar to those described in the first stage of activity of the episode 1919-1925. This reduced activity permitted to increase the level of monitoring of the volcano. Geologists of the UNAM (Macías et al. 1995a) produced a first volcanic hazards map for the Popocatépetl, and later (Arana et al., 2016) issued a second version for same volcano, which describe the nature and extent of probable volcanic events. An early warning system is prepared to keep permanently informed the population of the condition that presents the volcano, which is called volcanic Alert Traffic Light (De la Cruz- Reyna 1995, 1996; De la Cruz-Reyna y Tilling 2008; De la Cruz-Reyna et al., 2017).	Macías *et al*. 1995a. Arana *et al*. 2016. (De la Cruz-Reyna 1995, 1996; De la Cruz-Reyna and Tilling 2008; De la Cruz-Reyna *et al*. 2017).
1994	The onset of seismo-volcanic activity causes the development of the Plan Popocatépetl, involving state and federal authorities for Civil Protection and by scientists of the UNAM, the National Center for Disaster Prevention, technical advisory body of the National Civil Protection System of the Ministry of the Interior and other institutions, in order to develop contingency plans initially using the available volcanic maps of Robin and Boudal (Boudal C., Robin, C. 1989) as a basis for the risk assessments. This year it is also installed on the southwest flank of the volcano, about 4 kilometers from the crater, the telemetric station Chipiquixtle (PPX) by the National Center for Disaster Prevention (CENAPRED) and another seismic station telemetric: Colibrí (PPC), about 7 kilometers to the southeast of the crater (Quaas et al. 1995). At 01:31 (local time) on the morning of December 21 1994, a series of larger volcanic earthquakes mark the beginning of a new phase of activity at the volcano. At 01:54 hours (local time), a related to the opening of the volcanic conduit, ejected greater quantities of gas and ash. At dawn, ash falls on Puebla City and other nearby locations cause unrest among people. At 9:00 a.m. (local time) a Scientific Advisory Committee composed of experts from the National Autonomous University of Mexico (UNAM) and the CENAPRED has an emergency meeting requesting a reconnaissance flight; while both the ash emissions as in the seismicity kept on the rise (De la Cruz-Reyna and Tilling 2008; De la Cruz-Reyna et al. 2017). That afternoon and evening, the Response Programs and attention to the population: in Puebla State,	(Boudal C., Robin C. 1989). Quaas *et al*. 1995. (De la Cruz-Reyna and Tilling 2008; De la Cruz-Reyna *et al*. 2017)

was activated and 23 towns with an estimated 25,000 inhabitants were evacuated. A similar number of people auto-evacuated by their own means to homes of relatives and friends. In the State of Morelos 716 people from the village of Tetela del Volcán were evacuated. In the three following days several COSPEC flights showed high output of SO2. More seismic station and three telemetric electronic tilt meters were installed with the support of the United States of Geological Survey (USGS). Some of the evacuated populations gradually returned to their places of origin.

Appendix 2. Evacuation routes for the States of Mexico. Morelos, and Puebla.



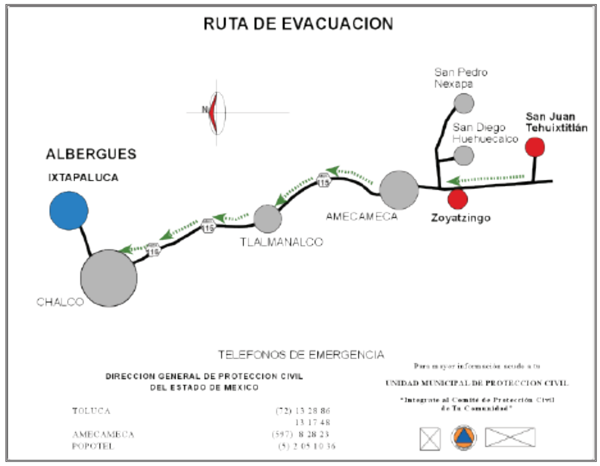
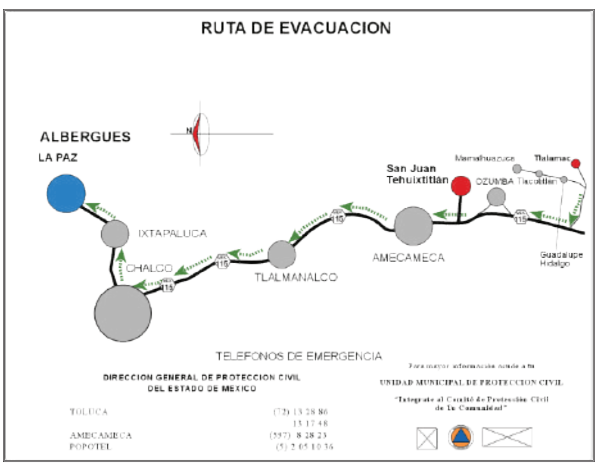


Figure 9. Evacuation routes for San Pedro Nexapa and San Diego Huehuecalco with high risk (red circles) in México State, which have a designated shelter (blue circle) at Chalco, State of México.

Figure 10. Evacuation routes for San Juan Tehuixtitlán and Zoyatzingo with high risk (red circles) in México State, which have a designated shelter (blue circle) at Ixtapaluca, State of México.



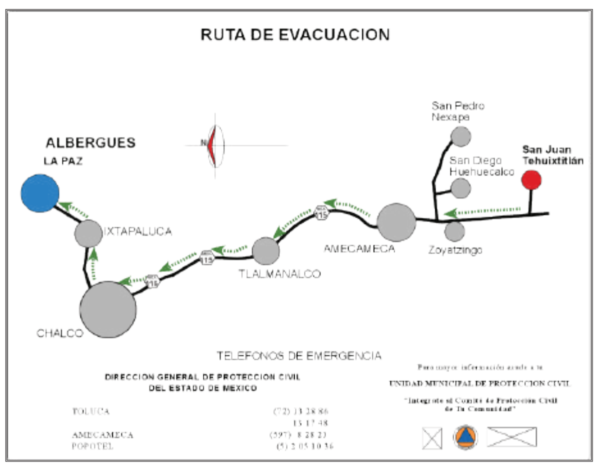


Figure 11. Evacuation routes for Tlalámac and San Juan Tehuixtitlán with high risk (red circles) in México State, which have a designated shelter (blue circle) at La Paz, State of México.

Figure 12. Evacuation route for San Juan Tehuixtitlán with high risk (red circle) in México State, which has a designated shelter (blue circle) at La Paz, State of México.

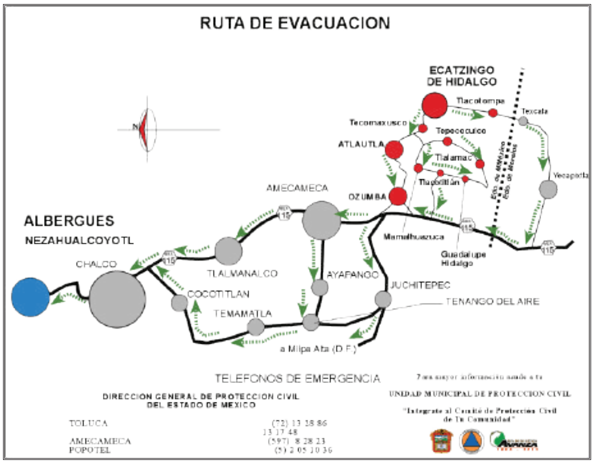


Figure 13. Evacuation routes for Ozumba, Atlautla, Tecomaxusco, Ecatzingo, Tlacotompa, Tepecoculco, Guadalupe Hidalgo, Tlalámac, Mamalhuazuca and Tlacotitlán with high risk (red circles) in México State, which have a designated shelter (blue circle) at Ciudad Nezahualcóyotl, State of México.

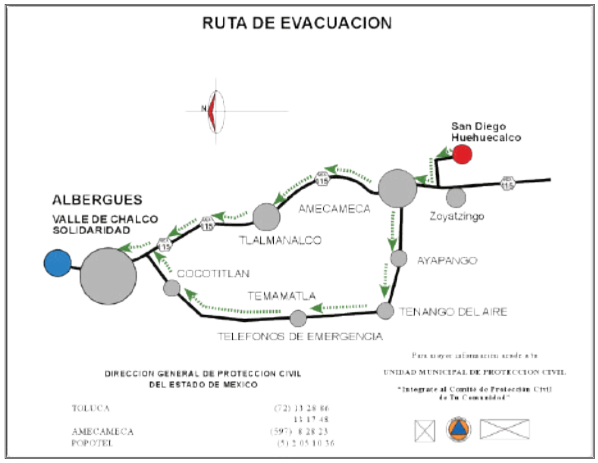


Figure 14. Evacuation route for San Diego Huehuecalco with high risk (red circle) in México State, which has a designated shelter (blue circle) at Valle de Chalco, State of México.

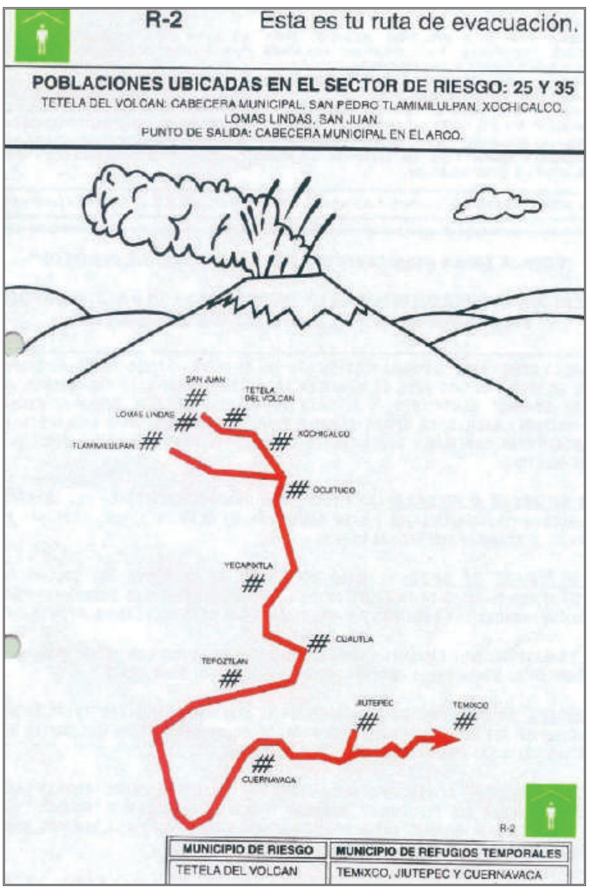


Figure 15. Evacuation route for San Pedro Tlalmimilulpan with high risk in Morelos State, which has designated shelters at Temixco, Jiutepec and Cuernavaca, Morelos.

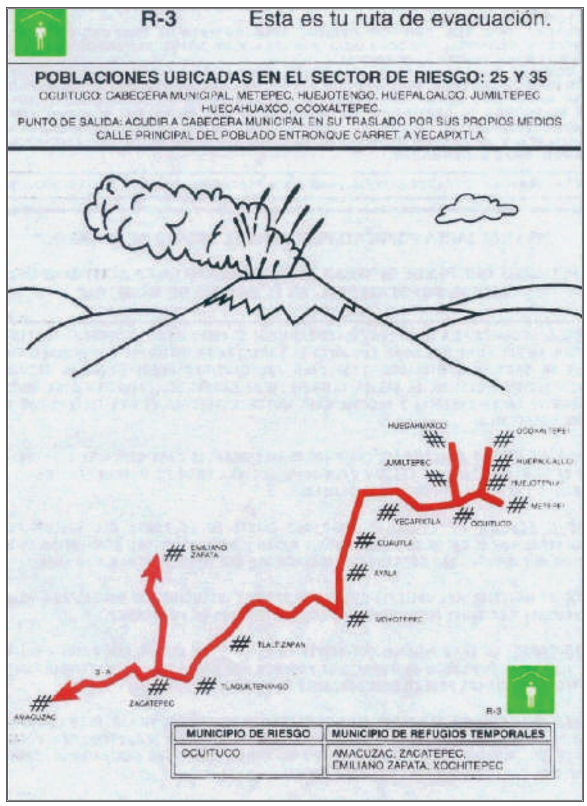


Figure 16. Evacuation route for San Francisco Ocoxaltepec with high risk in Morelos State, which has designated shelters at Amacuzac, Zacatepec, Emiliano Zapata and Xochitepec, Morelos.

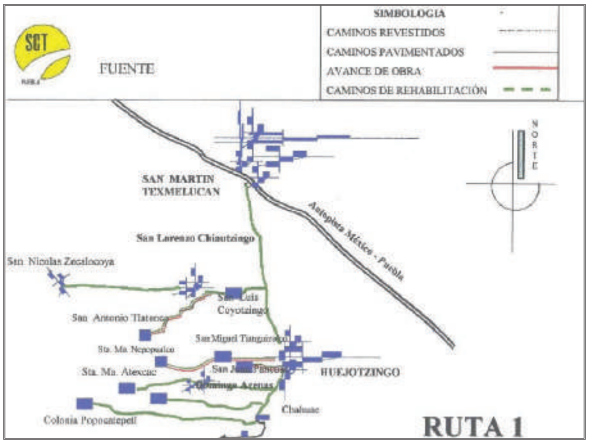


Figure 17. Evacuation routes for settlements with high risk in Puebla State, in which shelters are located at San Martin Texmelucan, Puebla.

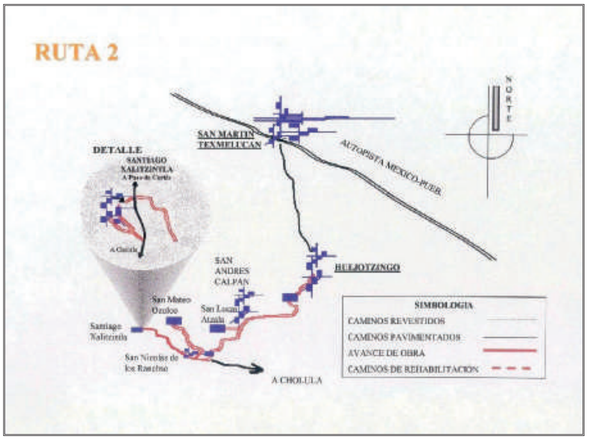


Figure 18. Evacuation routes for Santiago Xalitzintla, San Nicolás de los Ranchos and San Mateo Ozolco with high risk in Puebla State, in which shelters are located at San Pedro Cholula, Puebla.

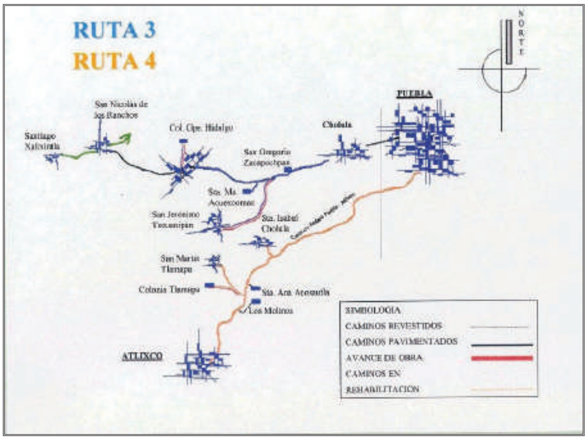


Figure 19. Evacuation routes for Santiago Xalitzintla and San Nicolás de los Ranchos with high risk in Puebla State, in which shelters are located at San Pedro Cholula, Puebla.

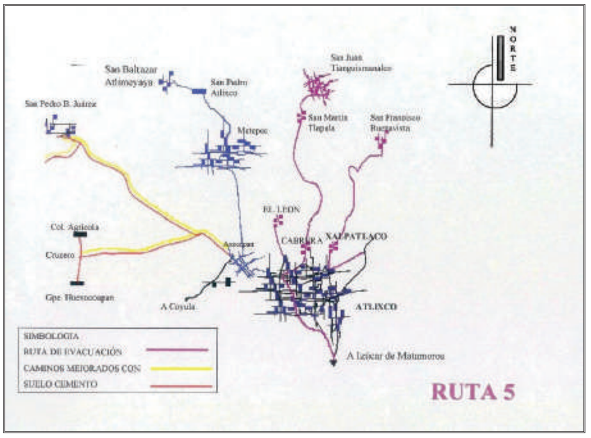


Figure 20. Evacuation routes for San Pedro Benito Juárez, Colonia Agricola and Guadalupe Hexocoapan with high risk in Puebla State, in which shelters are located at Izúcar de Matamoros, Puebla.

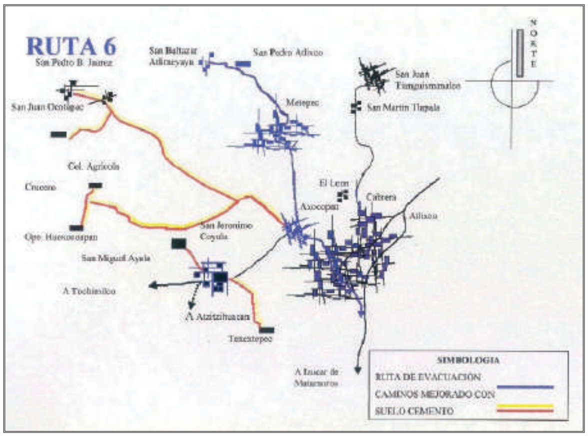


Figure 21. Evacuation routes for San Juan Ocotepec, Colonia Agricola and Guadalupe Hexocoapan with high risk in Puebla State, in which the shelter is located at Izúcar de Matamoros, Puebla.

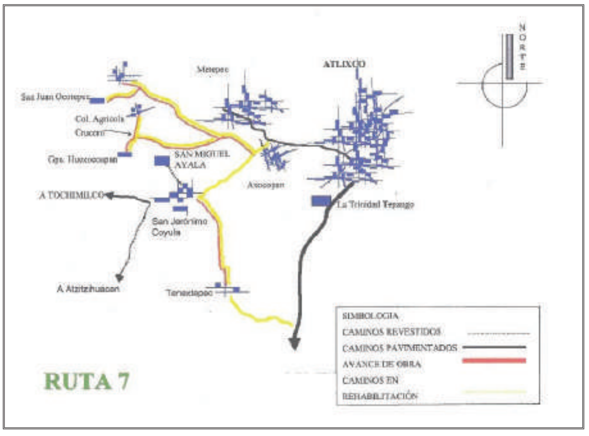


Figure 22. Evacuation routes for San Juan Ocote-pec, Colonia Agricola and Guadalupe Hexocoapan with high risk in Puebla State, in which shelters are located at Izúcar de Matamoros, Puebla.

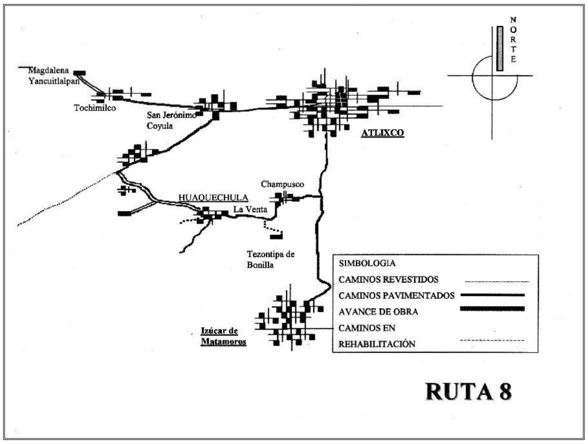


Figure 23. Evacuation routes for La Magdalena Yancuitlalpan, Tochimilco and San Jerónimo Coyula with high risk in Puebla State, in which shelters are located at Izúcar de Matamoros, Puebla.

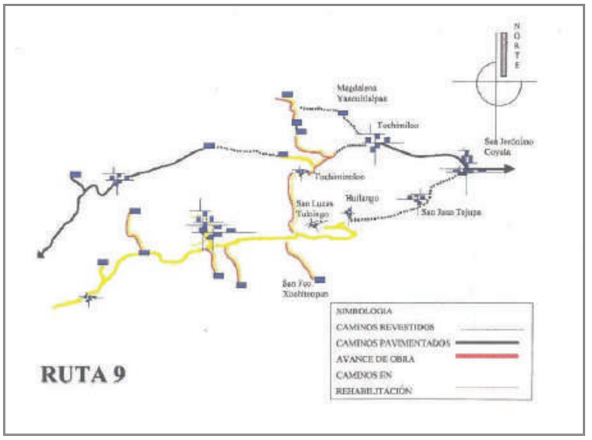


Figure 24. Evacuation route for Tochimizolco with high risk in Puebla State, in which the shelter is located at Tepexco, Puebla.

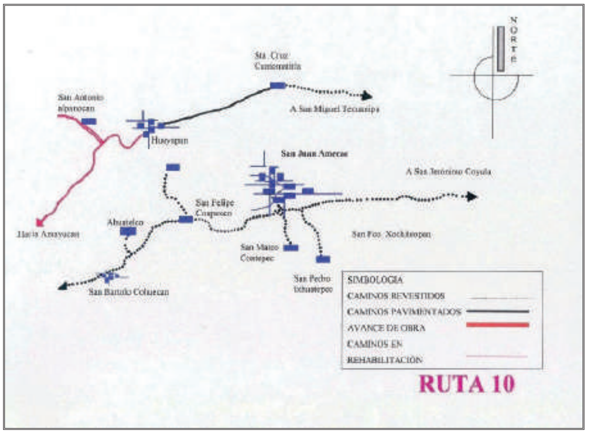


Figure 25. Evacuation routes for San Antonio Alpanocan, Santa Cruz Cuautomatitla and San Miguel Tecuanipan with high risk in Puebla State, in which shelters are located at Izúcar de Matamoros, Puebla.

Appendix 2. Tables containing times and distances from each village (origin) to temporary shelter respective (destination).

Table 7. Times and distances from San Pedro Nexapa to temporary shelters at Chalco, State of México (See Fig. 26).

San Pedro Nexapa (origin)		Chalco (destination)
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Pedro Nexapa	0	0
Amecameca	11	8
Tlalmanalco	31	18
Cocotitlán	41	26
Chalco (temporary shelters 10, 11, 12, 13 and 14).	50	34

Note: Maximum time and distance are up to the temporary shelter 11 of San Marcos Huixtoco.

Table 8. Times and distances from San Diego Huehuecalco to temporary shelters at Chalco, State of México (See Fig. 27).

San Diego Huehuecalco (origin)		Chalco (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Diego Huehuecalco	0	0
Amecameca	9	5
Ayapango	18	10
Tenango del Aire	31	18
Temamatla	43	23
Cocotitlán	52	28
Chalco (temporary shelters 1, 2, 3, 4, 8, 9, 15 and 16).	67	36

Note: Maximum time and distance are up to the temporary shelter 1 of Chalco.

Table 9. Times and distances from San Juan Grande to temporary shelters at Chalco, State of México (See Fig. 28).

San Juan Grande (origin)		Chalco (destination)
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Juan Grande	0	0
San Pedro Nexapa	5	2
Amecameca	16	10
Ayapango	24	15
Tenango del Aire	37	23
Temamatla	49	28
Cocotitlán	58	33
Chalco (temporary shelters 5 and 6).	71	39

Note: Maximum time and distance are up to the temporary shelter 5 of Chalco.

Table 10. Times and distances from San Marcos Tecomaxusco to temporary shelter at Chalco, State of México (See Fig. 29).

San Marcos Tecomaxusco (origin)		Chalco (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Marcos Tecomaxusco	0	0
Atlautla	19	8
Popo Park	24	11
Zoyatzingo	30	15
Amecameca	36	20
Ayapango	44	25
Tenango del Aire	57	33
Temamatla	69	38
Cocotitlán	78	43
Chalco (temporary shelter 7).	91	49

Note: Maximum time and distance are up to the temporary shelter 7 of Chalco.

Table 11. Times and distances from Ocoxaltepec to temporary shelters at Jiutepec, Morelos (See Fig. 30).

Ocoxaltepec (origin)		Jiutepec, Mor. (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
Ocoxaltepec	0	0
Tlalmimilulpan	8	3
Huepalcalco	16	6
Huejotengo	22	7
Ocuituco	32	11
Yecapixtla	50	21
Cuautla	71	35
Cocoyoc	84	41
Yautepec	103	52
Jiutepec (temporary shelters: no. 34, Esc. Primaria Emilio Rivapalacio Morales; 35, Esc. Primaria Jaime Torres Bodet; 36, Esc. Primaria Benito Juárez; 37, Esc. Primaria Mariano Matamoros; 38, Jardín de Niños Tolteca; 39, Jardín de Niños Tepehuanes; 40, Jardín de Niños Miguel Ángel Buonarroti; y 41, Jardín de Niños Cometa Halley).	148	72

Note: Maximum time and distance are up to the temporary shelter 34, Esc. Prim. Emilio Rivapalacio Morales at Jiutepec, Mor.

Table 12. Times and distances from Tlalmimilulpan to temporary shelters at Cuernavaca, Morelos (See Fig. 31).

Tlalmimilulpan (origin)		Cuernavaca, Mor. (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
Tlalmimilulpan	0	0
Huepalcalco	8	3
Huejotengo	14	4
Ocuituco	24	8
Yecapixtla	42	18
Cuautla	60	30
Oaxtepec	74	37
Tepoztlán	105	55
Cuernavaca (temporary shelters: no. 24, Esc. Primaria Plan de Ayala; 22, Esc. Primaria Fray Bartolomé de las Casas; 23, Esc. Primaria Niños Héroes de 1847 y 25, Esc. Primaria Carmen Serdán).		

Note: Maximum time and distance are up to the temporary shelter 24, Esc. Prim. Plan de Ayala at Cuernavaca, Mor.

Table 13. Times and distances from San Mateo Ozolco to temporary shelter at San Pedro Cholula, Puebla (See Fig. 32).

San Mateo Ozolco (origin)		San Pedro Cholula (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Mateo Ozolco	0	0
San Pedro Yancuitlalpan	7	4
San Andrés Calpan	16	9
San Pedro Cholula (temporary shelter 10, Ex Módulo Ferial).	45	26

Table 14. Times and distances from Santiago Xalitzintla to temporary shelter at San Pedro Cholula, Puebla (See Fig. 33).

Santiago Xalitzintla (origin)		San Pedro Cholula (destination).
Village	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
Santiago Xalitzintla	0	0
San Nicolás de los Ranchos	7	4
San Pedro Yancuitlalpan	11	5
San Andrés Calpan	20	10
San Pedro Cholula (temporary shelter 10, Ex Módulo Ferial).	49	27

Table 15. Times and distances from San Nicolás de los Ranchos to temporary shelter at San Pedro Cholula, Puebla (See Fig. 34).

San Nicolás de los Ranchos (origin)		San Pedro Cholula (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Nicolás de los Ranchos	0	0
San Pedro Yancuitlalpan	4	1
San Andrés Calpan	13	6
San Pedro Cholula (temporary shelter 9, Recinto Ferial).	42	25

Table 16. Times and distances from San Pedro Benito Juárez to temporary shelter at Izúcar de Matamoros, Puebla (See Fig. 35).

San Pedro Benito Juárez (origin)		Izúcar de Matamoros (destination).
VILLAGE	CUMULATIVE TIME (MINUTES)	CUMULATIVE DISTANCE (KM)
San Pedro Benito Juárez	0	0
Lomas de Axocopan	24	11
La Magdalena Axocopan	28	12
San Jerónimo Coyula	34	16
San Juan Los Laureles	47	22
La Trinidad Tepango	53	26
Tepeojuma	75	41
Izúcar de Matamoros (temporary shelter 33, Centro Escolar Lázaro Cárdenas).	98	57

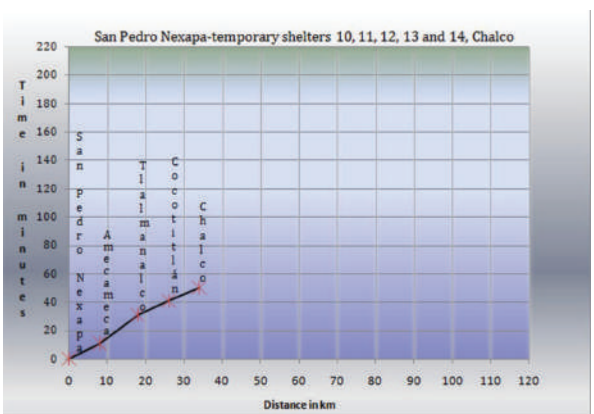


Figure 26. Time and distance diagram among San Pedro Nexapa and their temporary shelters 10, 11, 12 and 13 at Chalco, State of México.

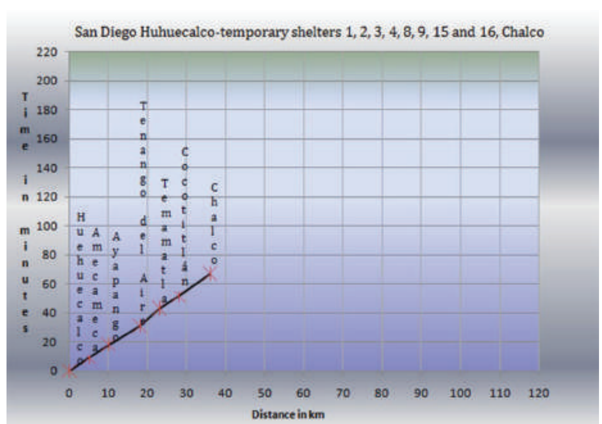


Figure 27. Time and distance diagram among San Diego Huehuecalco and their temporary shelters 1, 2, 3, 4, 8, 9, 15 and 16 at Chalco, State of México.

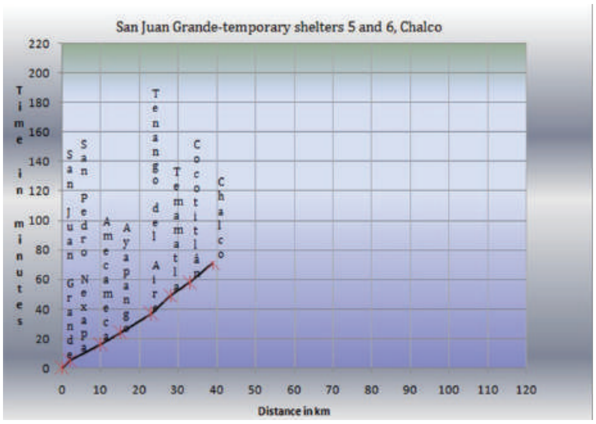


Figure 28. Time and distance diagram among San Juan Grande and their temporary shelters 5 and 6 at Chalco, State of México.

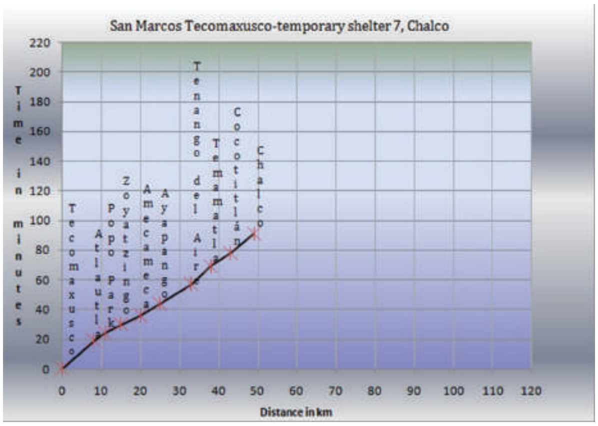


Figure 29. Time and distance diagram among San Marcos Tecomaxusco and its temporary shelter 7 at Chalco, State of México.

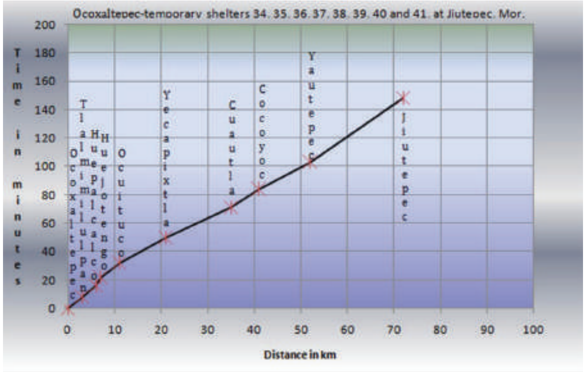


Figure 30. Time and distance diagram among San Francisco Ocoxaltepec and their temporary shelters 34, 35, 36, 37, 38, 39, 40 and 41 at Jiutepec, Morelos.

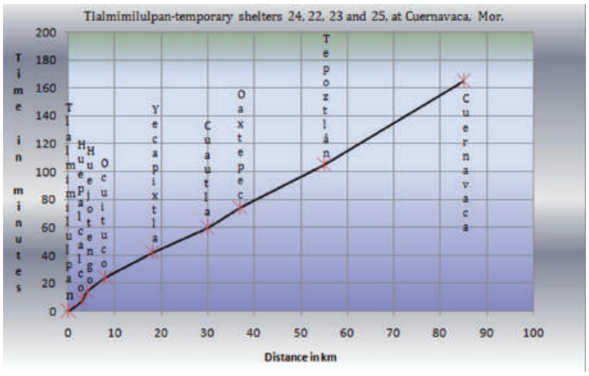


Figure 31. Time and distance diagram among San Pedro Tlalmimilulpan and their temporary shelters 22, 23, 24 and 25 at Cuernavaca, Morelos.

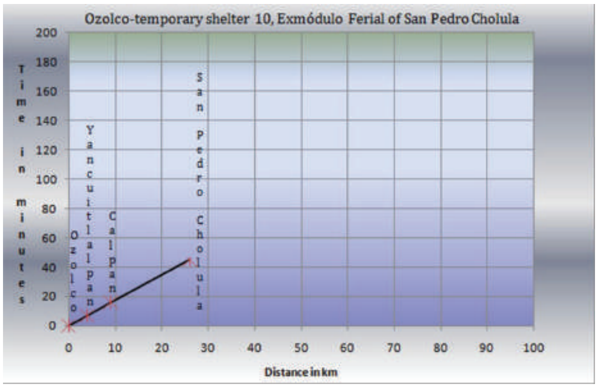


Figure 32. Time and distance diagram among San Mateo Ozolco and its temporary shelter 10 at Ex módulo Ferial of San Pedro Cholula, Puebla.

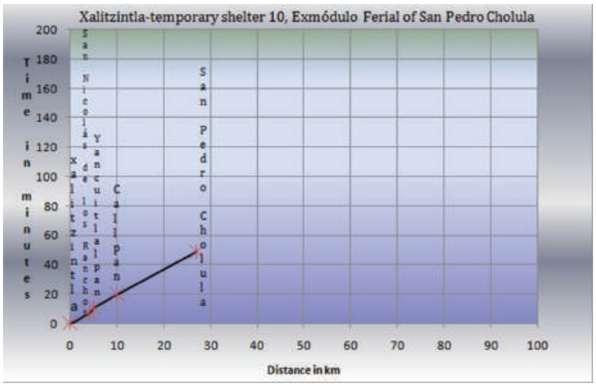
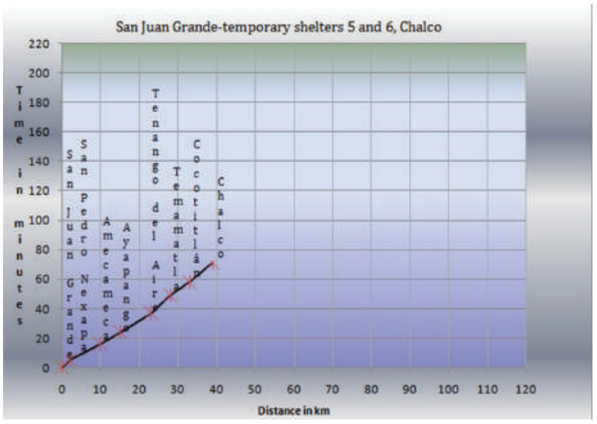


Figure 33. Time and distance diagram among Santiago Xalitzintla and its temporary shelter 10 at Ex módulo Ferial of San Pedro Cholula, Puebla.



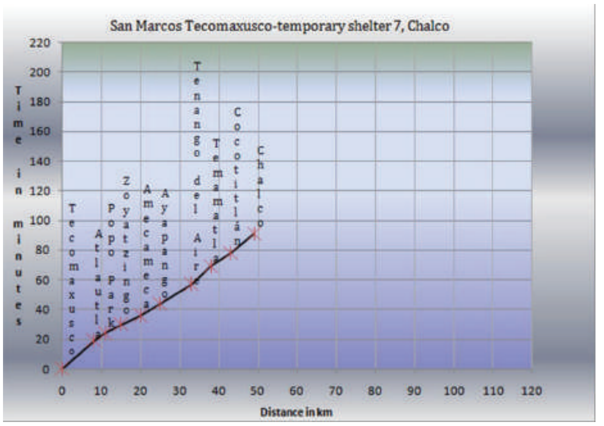


Figure 34. Time and distance diagram among San Nicolás de los Ranchos and its temporary shelter 9 at Recinto Ferial of San Pedro Cholula, Puebla.

Figure 35. Time and distance diagram among San Pedro Benito Juárez and its temporary shelter 33 at Centro Escolar Lázaro Cárdenas of Izúcar de Matamoros, Puebla.