Landslide inventory, Teziutlán municipality, Puebla, México (1942–2015)

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ABSTRACT
This article describes the spatial distribution of landslides in Teziutlán, Puebla, Mexico, which has been historically affected by mass movement processes. The most significant disaster associated with landslides in October 1999. Rainfall-triggered landslides and floods caused more than 100 deaths in Teziutlán and economic losses of US$233 million in Sierra Norte de Puebla. A multi-temporal landslide inventory map (1:25,000) for the period 1942–2015 was constructed by means of field observation and the analysis and interpretation of aerial photographs and satellite images. The inventory map includes 662 landslides and covers 163 km². The total landslide area is in the order of 0.71 km². Taking into account the scarp, channel and depositional area, the mean surface of the landslides is 1075 m². The largest documented area was 17,512 m². The smallest landslide area mapped was 24 m². Most movements can be considered as having been small.

Introduction
Unconsolidated deposits that cover volcanic edifices and surrounding terrains have a great potential for landsliding induced by precipitation or earthquakes (Nocentini, Tofani, Gigli, Fidolini, & Casagli, 2015; Pareschi et al., 2000). In areas where vulnerable people are exposed to such hazards, disasters can occur. This propensity for landsliding can persist for centuries or millennia after a volcanic eruption (Miyabuchi, Maeno, & Nakada, 2015). Heavy rainfall and seismicity can remobilize the volcaniclastic layer and generate slides and debris flows (Nocentini et al., 2015; Smith & Lowe, 1991).

There have been a series of disasters associated with the occurrence of landslides in volcanic terrains. One of the oldest documented events took place on São Miguel Island, Portugal, in 1522, when rainfall-induced landslides on pyroclastic deposits involved 5000 fatalities (Gomes, Gaspar, Goulart, & Queiroz, 2005; Marques & Amaral, 2004). In 1999, in Teziutlán, Puebla, Mexico, hundreds of rainfall-induced landslides affected the Sierra Norte de Puebla; more than 200 fatalities were registered and Teziutlán was the most affected municipality of the region. In just a single event in the La Aurora neighborhood, 109 people died as they were swept away by a complex landslide. There is a clear need to produce an inventory map of landslides of the area to understand their temporal and spatial distribution.

In this study, we present a description of the spatial distribution of landslides that have occurred in Teziutlán during the period 1942–2015. This study involved the construction of a multi-temporal landslide inventory map based on field recognition and identification and the analysis and interpretation of aerial photographs and satellite images.

Study area
Physiographical setting
Teziutlán municipality lies in the Sierra Norte de Puebla mountain system, within the transition of the Sierra Madre Oriental and the Trans-Mexican Volcanic Belt physiographic provinces (Figure 1). Its capital town is also called Teziutlán, and this is situated on a plateau formed by lava flows and pyroclastic materials from Los Humeros caldera. The altitude of the study area ranges from 1221 m a.s.l. in the northeast to 2660 m a.s.l. in the south and west. The climate is warm temperate: temperature varies from 12°C to 22°C (mean 15.5°C) and rainfall occurs all year long and is in the order of 1100–3600 mm (mean precipitation 1658 mm) (INEGI, 2009). The main drainage system has an N–S and NE–SW orientation and is probably controlled by tectonic lineaments (Capra, Lugo-Hubp, & Borselli, 2003). Because of their volcanic origin, soils are predominantly andosols (INEGI, 2009). The north is still covered by pine/oak woodlands but in the rest of the area the original vegetation has been changed to grassland, arable land and urban areas. The extent of the study area is 163 km². Maps
of elevation, slope gradient and stream power index of the study area were added as complementary materials.

Antecedents of instability and the disaster of October 1999

Heavy rainfall events have occurred in historical time. Inhabitants of Teziutlán recall precipitation events of 1999, 1944 and 1955, in that order of importance, and according to the impact of landslides on the population. Records show that those events involved a high accumulation of rain in a short period of time and at least one day with more than 300 mm of rain.

On 5 October 1999, 109 people died in a landslide in the La Aurora neighborhood of Teziutlán city (Alcántara-Ayala, 2004). This was triggered by extraordinarily heavy rains associated with Tropical Depression N°11 in the Gulf of Mexico. This mass movement was not unique; thousands of landslides affected an area of approximately 4000 km² (Lugo-Hubp, Zamorano-Orozco, Capra, Inbar, & Alcántara-Ayala, 2005).

Geological context

The Trans-Mexican Volcanic Belt is characterized by extensive basaltic volcanism and late Tertiary and Quaternary strato-volcanoes, cinder cones, calderas, domes and maars (Alcántara-Ayala, 2004; Alva-Valdivia et al., 2000). It is an E–W oriented volcanic arc produced by the subduction of the Cocos tectonic plate beneath the North American tectonic plate (Alaniz-Alvarez, Nieto-Samaniego, & Ferrari, 1998; Concha-Dimas, Cerca, Rodríguez, & Watters, 2005; Pardo & Suarez, 1995). Its caldera volcanoes include, in its eastern sector, Los Humeros (Figure 1), which rises in central Mexico, 180 km east of Mexico City, and is considered to be one
of the Pleistocene silica centers (Dávila-Harris & Carrasco-Núñez, 2014). The geology of Teziutlán (Figure 2) is directly linked to Los Humeros.

Eruptive products derived from Los Humeros range from basalt to the high-silica rhyolite that covers a Mesozoic section with a thickness of up to 3000 m (Ferriz & Mahood, 1984). Evolution of the volcano center began 1.6 Ma ago. Paleozoic crystalline rocks, folded Mesozoic sedimentary rocks, and Tertiary intrusions and andesites can be found on the surface (Ferriz & Mahood, 1984). This basement of sedimentary rocks was extensively affected by the Laramide Orogeny, with a NE–SW compression, faulting and folding (Dávila-Harris & Carrasco-Núñez, 2014).

The oldest layer that outcrops in the study area is the schist of the Chililis formation (280 Ma.), this is composed of chloritemuscovite and andesite metalava (Salinas-Rodríguez & Castillo-Reynoso, 2011). The Chililis schist is overlaid by the siltstone and polymictic conglomerate of the Cahuasas Formation (170 Ma.), limestone-shale Tepexic, Santiago, Tamán and Pimienta formations (166–140 Ma.) (Salinas-Rodríguez & Castillo-Reynoso, 2011). Likewise, the Teziutlán Massif (Viniegra, 1965) outcrops in the western sector; it is formed by a Paleozoic metamorphic and granite intrusive complex (Ferriz & Mahood, 1984) (Figure 2).

The oldest igneous rocks that can be observed are porphyritic two-pyroxene andesite lavas and breccias, and ferro-basaltic lavas of the Teziutlán Formation (1.55 Ma) (Ferriz & Mahood, 1984), which could be considered as pre-caldera events (Dávila-Harris & Carrasco-Núñez, 2014). The following stage (0.47 Ma), was the accumulation of a 115 km³ magma eruption of the Xaltipan ignimbrite (Ferriz & Mahood, 1984), a type 7 eruption according to the Volcanic Explosivity Index (VEI).

The Xaltipan ignimbrite resulted from the final activity of the first active phase and subsidence of Los Humeros caldera (Dávila-Harris & Carrasco-Núñez, 2014). Most of the ignimbrite deposits found in the study area are non-welded and composed of aphyric high-silica rhyolite material that can be recognized specifically as ash-pumice flow deposits. The pyroclastic flows filled low areas of the rugged preexisting landscape covering 3500 km² (Ferriz & Mahood, 1984).

After another long period of inactivity that allowed further erosive and pedogenetic processes, an eruptive episode gave rise to the Zaragoza ignimbrite (0.06–0.1 Ma.). The Zaragoza ignimbrite is a non-welded ignimbrite covered by a lithic-rich fall deposit (Zaragoza tuff) and can be regarded as a pumice flow.

Numerous deposits of pumice and lapilli falls covered the Zaragoza ignimbrite, including the Xoxoctic member pumice fall, the Tilca lithic-rich layer and finally the pumice fall layer Cuicuiltic member from the Holocene (Dávila-Harris & Carrasco-Núñez, 2014). The final stage of the Los Humeros caldera, ~20,000 years ago (Ferriz & Mahood, 1984), was the eruption of the San Antonio volcano, consisting of rhyodacitic and andesite lava flows, and eruptions of olivine basalt. This has diverse vents and covers the

![Figure 2. Lithology of the studied area.](image-url)
south-center of the study area. General data on the mechanical properties of the deposits of Teziutlán can be found in Alcántara-Ayala (2004).

Methods

**Aerial photographs**

The photographs of 1956 are the best available source to identify the landslides that occurred in the 1955 event. The 1942 oblique photographs were also useful for comparative purposes. Four vertical photographs dated from 1942 were found in the archives of the Geography Institute of UNAM. These photographs were taken on December 13rd, from a height of 9300 m (30,000 ft) (1:20,000 approximate scale) using the trimetrogon system that consisted of three cameras assembled at different angles to take one vertical and two oblique photographs simultaneously. Table 1 summarizes the aerial photograph material used.

**Satellite images**

IKONOS, SPOT 5 and 6, and QuickBird images were used (see Table 2). The principal input set of images for this work was a series of IKONOS images at 1 m resolution in the panchromatic band and 4 m in the multispectral bands. The images were available in mosaic true color and near-infrared composition. Multispectral bands were resampled via a pan-sharpened process to obtain the true color and near-infrared composite images with the resolution of the panchromatic band. The date of the images was December 2000, only one year after the disaster event of 1999; a number of landslides were identified by analyzing this image mosaic. These images and all the satellite images used in this research were only available in the monoscopic display (Table 2).

Besides the use of satellite images, images in Google Earth, Bing Maps and SAS Planet were also used. Specifications for Google Earth images were not available, although some of them can be very high resolution (VHR) or aerial photographs. These tools are free, and landslides can be drawn directly onto the software and exported as a .kmz file extension to then be converted into a shape file. These images were useful as a complement for landslide identification as they provided information for each year, from 2003 to 2015. The SAS Planet program allows geo-referenced images (or maps) to be downloaded from other systems.

**Table 1.** Air photograph material used to generate the landslide inventory.

| Number of photographs | Archive             | Date       | Scale          | Format             | Angle | Smallest recognized landslide (m²) |
|-----------------------|---------------------|------------|----------------|--------------------|-------|-----------------------------------|
| 4                     | ICA foundation      | 1942       | Digital 1200 dpi | Oblique            |       | 282                               |
| 4                     | Geography Institute | Dec 1942   | 1:20,000 Paper Vertical |               |       | 133                               |
| 4                     | ICA foundation      | 1956       | Digital 1200 dpi | Vertical           |       | 59                                |
| 3                     | INEGI Nov. 1974     | 1:50,000   | Vertical       |                    |       | 225                               |
| 4                     | INEGI Nov. 1980     | 1:80,000   | Vertical       |                    |       | 157                               |
| 6                     | INEGI Ago. 1991     | 1:30,000   | Vertical       |                    |       | 96                                |
| 30                    | INEGI Jul. 2007     | 1:20,000   | Digital 1200 dpi | Vertical           |       | 30                                |
| 45                    | CENAPRED Oct 1999   | 1:1,800    | Paper Vertical  |                    |       | 24                                |

**Table 2.** Satellite imagery used to generate the landslide inventory map.

| Image      | Date       | Mode          | Resolution (m) | Smallest recognized landslide (m²) |
|------------|------------|---------------|----------------|-----------------------------------|
| IKONOS     | Dec. 2000  | True composite color | 1              | 33                                |
| SPOT 5     | 27-Dec-2003| Panchromatic   | 2.5            | 879                               |
| From Google Earth | 17-Mar-2003 | True composite color | Unknown        | 682                               |
| From Google Earth | 19-Oct-2004 | True composite color | Unknown        | 84                                |
| SPOT 5     | 12-Nov-2005| Panchromatic   | 2.5            | Unknown                           |
| SPOT 5     | 28-Nov-2006| Panchromatic   | 2.5            | Unknown                           |
| From Google Earth | 17-Apr-2006 | True composite color | Unknown        | –                                 |
| SPOT 5     | 19-Feb-2007 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 26-Oct-2007 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 22-Dec-2007 | Panchromatic   | 2.5            | –                                 |
| QuickBird  | 15-Feb-2008 | True composite color | 0.6            | 24                                |
| SPOT 5     | 26-Dec-2008 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 20-Jan-2010 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 13-Mar-2010 | Panchromatic   | 2.5            | 1752                              |
| SPOT 5     | 08-Jan-2011 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 10-Aug-2011 | Panchromatic   | 2.5            | –                                 |
| SPOT 5     | 21-Oct-2011 | Panchromatic   | 2.5            | –                                 |
| From Google Earth | 10-Aug-2011 | True composite color | Unknown        | –                                 |
| From Google Earth | 14-Nov-2011 | True composite color | Unknown        | –                                 |
| From Google Earth | 04-Jun-2012 | True composite color | Unknown        | –                                 |
| SPOT 5     | 03-Oct-2013 | Panchromatic   | 2.5            | –                                 |
| From Google Earth | 07-Feb-2013 | True composite color | Unknown        | 56                                |
| SPOT 6     | 24-Feb-2014 | Panchromatic   | 2.5            | –                                 |
| From Google Earth | 26-Feb-2015 | True composite color | Unknown        | 379                               |
| From Bing Maps | 2015     | True composite color | Unknown        | –                                 |
| From ESRI   | 2015       | True composite color | Unknown        | 966                               |
(e.g. Google Earth, Bing Maps, ESRI, etc.), but it does not provide detailed information about the type or date of the images. In spite of this, it was possible to use a Bing Map image probably dated in 2015 and also images from ESRI. Analysis of buildings recently constructed in Teziutlán determined that the ESRI images were taken after 2011.

Field surveys

Several field surveys were carried out from 2011 to 2015 to identify landslides, and to validate the interpretation of aerial photographs and the satellite images, in addition to obtaining relevant information about the relation between geology and landslide distribution (Figure 3).

Field surveys allowed the identification of recent landslides. If a landslide is inactive, the vegetation will have completely covered the area in less than a month. Even if the landslide is active, vegetation will have begun to grow soon after the mass movement. Hence, the only landslides that could be recognized by reference to vegetation were those that had occurred in recent time. In addition to direct observation in the field, landslides can also be identified by interviews with the local people, especially for old landslides. Some of the landslides that occurred in 1999 were identified thanks to the information provided by the local inhabitants who pointed out specific locations on which landslide scars were subsequently traced. It also included the case of nine movements in 1955 that were unclear in analyses of the 1956 aerial photographs. This information on landslides associated with the 1955 and 1999 rainfall events was supplied by people from Aire Libre, San Juan Acateno and, in particular, from La Aurora neighborhoods. The Civil Protection office of Puebla State (Protección Civil de Puebla) provided landslide reports registered between 2010 and 2015. All the information obtained from field surveys was compared with that derived from the aerial photographs and satellite images. The landslides identified were afterwards digitized. The ortho-mosaic generated from the 2007 aerial photographs of INEGI was taken as the cartographic base.

Software

In order to use the aerial photographs, at least six points of control were identified by using LPS

Figure 3. Examples of landslides identified by field surveys: (1) Small rock and soil fall along the road near the Aire Libre neighborhood; (2) Translational slide that was transformed into a silt flowslide in a road cut near Teziutlán city; (3) Damage caused by a complex landslide that was initiated as a rotational slide and then transformed into a silt flowslide in the Aire Libre neighborhood; (4) Soil fall at the highway that connects Teziutlán with central sector of Mexico.
ERDAS software. The x and y coordinates were collected using the topographic maps, the Google Earth system and field surveys. The z coordinates were obtained from a 15 m spatial resolution digital elevation model (DEM) developed from aerial LiDAR data acquired from INEGI. An ortho-mosaic was generated using the 2007 photographs from INEGI and was used as a base to geo-reference the rest of the photographs. Then the photographs were used to generate stereo-models using the software mentioned above. Tie points were generated automatically and a block file (.blk) was generated for each stereo model and exported into the Stereo Analyst ArcGis extension from ERDAS. This application combined with the adequate hardware, in this case a digital stereo-mirror PLANAR system, created a 3D stereoscopic environment within which the landslides could be identified and mapped directly in a digital display. More details of this procedure can be found in Murillo-García et al. (2015).

Some of the landslides were identified on the VHR images by visual interpretation using Quantum GIS software (QGIS Development Team, 2012). They were recognized by the scarp and deposit zone in addition to changes in vegetation patterns (Figure 4) (Murillo-García et al., 2015). In general, soil exposure produces a color, tone and texture that differ from those of the surrounding area, and this is clear in the type of landslides registered in the study area; this corresponded to silt or debris flowslides. The final landslide inventory map (Main map) was edited using QGIS software.

Results

Statistical data

The inventory is composed of 662 landslides (Figure 5). The total landslide area is 0.71 km² (0.43% of the study area). Taking into account the scarp, channel and deposit area, the mean area of the landslides is 1075 m². The largest documented area (17,512 m²) for the 1999 event corresponds to one deep-seated slide transformed into mud flow that partially destroyed the building of the Technological University of Teziutlán near the Aire Libre neighborhood (Figure 4 and capital letter A in Figure 5 and Main Map). The smallest area of a landslide in 1999 mapped was 24 m² (Table 3).

Visual interpretation of the landslides identified in the aerial images and field surveys indicated that 78 (11.7%) were harmful to people and caused damage to infrastructure, including arable land and roads;
118 fatalities were registered and 29 buildings were affected. Three significant landslides occurred in 1999: La Aurora landslide (B), Huehueymico landslide (C) and Mexicaluautla silt flowslide (D) (Figure 5 and Main Map); these were associated with the greatest damage. According to the official information provided

![Image of landslide inventory map of Teziutlán.](image)

**Figure 5.** Landslide inventory of Teziutlán.

**Table 3.** Basic landslide inventory statistics. Relict landslides were identified by persistent geomorphological evidence, in the Main Map these are indicated as 'Old landslides'.

|                     | General | 1955 event | 1999 event | Seasonal landslides | Relict landslides (before 1942) |
|---------------------|---------|------------|------------|---------------------|--------------------------------|
| Study area          | 163 km²| 0.71 km²   | 0.23 km²   | 0.16 km²            |                                 |
| Total number of landslides | 662     | 61         | 292        | 844 m²              | 5198 m²                        |
| Mean area landslides | 1075 m²| 969 m²     | 849 m²     | 844 m²              | 5198 m²                        |
| Total area landslides | 0.71 km²| 0.08 km²   | 0.24 km²   | 0.23 km²            | 0.16 km²                       |
| Maximum landslide area | 29,586 m²| 6357 m²   | 18,627 m²  | 11,910 m²           | 29,586 m²                      |
| Minimum landslide area | 24 m²   | 58 m²      | 24 m²      | 25 m²               | 163 m²                         |

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Table 4. Number of landslides by year according to visual or field identification classified according to the date of the photographs, satellite image and/or field surveys.

| Year    | Number of landslides | %       |
|---------|-----------------------|---------|
| Before 1942 | 32                     | 4       |
| 1942    | 65                    | 9.8     |
| 1956    | 61                    | 10.2    |
| 1974    | 17                    | 2.5     |
| 1978    | 21                    | 3.1     |
| 1980    | 1                     | 0       |
| 1991    | 31                    | 4.6     |
| 1999    | 292                   | 45      |
| 2003    | 9                     | 1.3     |
| 2004    | 22                    | 3.3     |
| 2006    | 2                     | 0       |
| 2007    | 110                   | 16.6    |
| 2010    | 2                     | 0       |
| 2013    | 11                    | 1.6     |
| 2015    | 5                     | 0.7     |

To Alcántara-Ayala (2004), 109 people died in La Aurora, although neighbors claimed that not all the bodies were recovered after the tragedy. Flores-Lorenzo and Alcántara-Ayala (2002) reported 24 deaths in the Huehueymico landslide, and at least three persons died and six were reported as missing after the Mexcalcuautla silt flowslide.

At the present time, 29 of the documented landslides can be considered as areas of high risk given that they are inhabited. These include the La Aurora landslide, where the area has recently been re-settled even though the people affected by the 1999 disaster were moved elsewhere.

**Landslide type and lithology**

Type of movement is strongly related with the lithology and soil material. Geology was used as one of the variables to interpret slope instability. Several rock types outcropping in the research area and previously described were identified in the field (Capra et al., 2003; Ferriz & Mahood, 1984).

According to Alcántara-Ayala (2004), Xaltipan ignimbrite ‘induced the infiltration and development of perched water table that caused slope instability’. Capra et al. (2003) also identified this process and classified the mass movements on this ignimbrite as ‘shallow landslides with vertical [lateral] walls’. This type of shallow silt slide occurred in 1999 in one of the slopes of the Juárez neighborhood, in the west sector, near the old road from Tetziuatlán to Chignautla. Landslides of the same type have also occurred, to a great extent, in the north of the research area where the San Juan Acateno and San Sebastián neighborhoods are situated.

When the ignimbrite is underlaid by layers of other material, the type of landslide is different. Chililis schist outcrops at the NW part of the studied area; it can be found as a gray or very dark gray schist rock of high resistance, although when exposed to weathering or situated near a spring the schist is highly crumbly and shows a red-orange color and a high content of quartz. Soil cover thickness is in the order of 1–5 m and appears to have a clay-rich content (field survey observation). In this area, the schist is overlaid by the Xaltipan ignimbrite, and the contact is quite visible. Landslides are of rotational or planar types, and six of those landslides were transformed into clay flowslides.

Near the Mexcalcuautla neighborhood, in the foothills of Chignautla Mountain, the Xaltipan ignimbrite overlays a siltstone layer (Jbj-S) showing a contact with the Chililis schist. In this place, a silt flowslide occurred in 1999 involving at least three fatalities (D in Figure 5 and Main Map); the movement initiated at the geological contact and flowed down into the ignimbrite zone (down slope) where more material was added. The runoff of the movement was 275 m.

In the central sector of the study area, the ignimbrite is covered by a succession of interlaid ash-pumice, lapilli fall deposits and paleosols or highly weathered materials (QptAs-Pu in the Main Map). The thickness of the set of volcanic fall deposits and paleosols sequence unit varies from 2 to 7 m and in some areas the QptAs-Pu deposits are not present. The soil (50–100 cm thick) is developed from the pumice; it can be classified as Andosol (silt saturated). Landslides in the QptAs-Pu are commonly silt flowslides which began as silt falls or planar or rotational slides on surfaces with moderate slope angles, but also soil falls occur along road cuts or steep slopes. Quite often, rotational or translational slides are transformed into flows. The La Aurora landslide of 1999 can be regarded as a silt flow slide that began as a rotational slide according to the classification of Hungr, Leroueil, and Picarelli (2014) (Table 5).

**Discussion**

The inventory map presented here can be used as a main input to produce a susceptibility map, and to analyze time-frequency and landslide magnitude. However, there is a lack of data concerning the landslide event of 1944. This historical information is very difficult to obtain as no accurate images were available and local inhabitants do not recall properly the location of the movements that occurred at that time. A more detailed analysis derived from the LiDAR DEM may help to identify large landslides, but information concerning medium-scale or small landslides (those less than 65 m²) is practically impossible to acquire at this point.

Furthermore, the scale and/or quality of some of the remote sensing inputs used for this work were not ideal. For instance, aerial photographs from 1980 (1:80,000 scale) lost quality when scanned. Identification of small landslides in those images was not possible. However, the present results demonstrate that...
remote sensing inputs available from a range of sources can help to overcome the limitations imposed by time and budget constraints.

Additionally, analysis of the past 15 years indicates that in this area landslides have occurred not only during extreme rainfall events such as in 1999, but also on a yearly basis during the rainy season. It is necessary to analyze the temporal development of this relationship to factors in addition to extreme events, and to determine which are the major controls of instability, including human interference as a possible prime agency. Although there are more and better data regarding landslide occurrence available for the period 2000–2015 than for the preceding years, it has not been possible to identify an increase in the number of landslide events in the past 15 years. However, according to the analysis produced for the historical timeframe established for this research, the frequency of landslide events recorded from 1942 to 2015 shows that since 1999 high-magnitude rainfall events like those of 1944 and 1955 have not occurred. One possibility may be to shorten the period of time of data used to prepare the inventory and focus on the years between 1999 and the present time, on which more information and references are available. Nonetheless, a lower number of landslides could be expected because of this lack of extreme rainfall events since 1999. In any case, updating and improving the historical documentation to increase landslide records remains a huge challenge especially in countries such as Mexico and other nations of Latin America where, in contrast to other regions, the number of researchers and projects focused on landslide inventories is rather low.

Conclusions

In Latin America, landslides occur frequently in volcanic deposits but investigations regarding landslide inventories, characterization of materials and specific mechanisms are still scarce. There are also few studies on the understanding of landslide disasters on volcanic terrains.

In this paper, we described the distribution of the landslides in Teziutlán, Puebla, Mexico. The results suggested that the most frequent landslide types are flows and complex movements that generally are initiated as slides and soon after are transformed into silt and debris flowslides. Even though the 1999 disaster identified Teziutlán as an area prone to landslides, this research is the first attempt to generate a multi-temporal landslide inventory for the municipality. Large landslide events are associated with the occurrence of extraordinary rainfall episodes with at least one day with more than 300 mm of rain preceded by a period of cumulative precipitation. Likewise, small and medium-size events take place during the rainy season. Such occurrences need to be further explored not only in terms of precipitation, but also considering the potential and actual impact of human activities on the slopes. Events like those of 1944, 1955 and 1999 are likely to occur again in the Sierra Norte de Puebla region. This inventory map will be useful in future research on landslide susceptibility and hazard mapping, along with risk assessments at municipal and local scales.

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| Table 5. Landslides in the study area according to typology (Hungr et al., 2014), lithology and land cover. |
|--------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| **Class** | **Number of landslides** | **%** | **Total landslide area (m²)** | **Mean landslide area (m²)** |
|--------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Typology                                          | [160] | 24.1 | 66,790 | 417 |
| Silt flowslides                                   | [140] | 21.1 | 49,992 | 357 |
| Debris flowslides                                 | [119] | 17.9 | 58,302 | 490 |
| Silt planar slides                                | [95]  | 14.3 | 112,445| 1183|
| Slides (planar or rotational) or silt falls to flow slides* | [76]  | 11.4 | 66,854 | 879 |
| Silt Rotational slides                            | [65]  | 9.8 | 10,524 | 162 |
| Soil silt falls                                   | [6]   | 0.9 | 1539  | 307 |
| Rock falls                                        | [1]   | 0.1 | 34    | 34  |
| Rock avalanche                                    | [219] | 33.0 | 96,165 | 441 |
| Land cover                                        | [109] | 16.4 | 84,770 | 777 |
| Grasslands                                        | [89]  | 13.4 | 87,749 | 986 |
| Secondary vegetation (arable land or grasslands abandoned) | [62]  | 9.3 | 16,991 | 278 |
| Arable land                                       | [89]  | 13.4 | 36,970 | 415 |
| Urban areas                                       | [57]  | 8.6 | 32,027 | 579 |
| Road Cuts                                         | [18]  | 2.7 | 4713  | 618 |
| Forest                                            | [15]  | 2.2 | 3253  | 215 |
| Material banks                                    | [3]   | 0.4 | 1935  | 645 |
| Without vegetation                                | [47]  | 7.0 | 33,582 | 730 |
| Industrial areas                                  | [41]  | 6.2 | 79,399 | 2205|
| Lithology                                         | [14]  | 2.1 | 15,910 | 1136|
| Basalt                                            | [369] | 55.7 | 385,859| 1034|
| Fall deposits OqtAs-Pu                             | [15]  | 2.3 | 7924  | 528 |
| Pumice flow deposit OqtPu                         | [125] | 18.9 | 118,786| 928 |
| Xaltipan Ignimbrite unwelded OqtIg-uw             | [18]  | 2.7 | 16,958 | 997 |
| Welded tuff TplT-w                                | [25]  | 3.8 | 24,046 | 961 |
| Andesite Teziutlán TplA                           | [8]   | 1.2 | 30,733 | 3841|
| Sedimentary rocks                                 | [47]  | 7.0 | 33,582 | 730 |
| Granite KvGr                                      | [41]  | 6.2 | 79,399 | 2205|
| Chililis schist Pp(?)Sch                          | [14]  | 2.1 | 15,910 | 1136|
| Sedimentary rocks                                 | [369] | 55.7 | 385,859| 1034|
| Welded tuff TplT-w                                | [15]  | 2.3 | 7924  | 528 |
| Andesite Teziutlán TplA                           | [125] | 18.9 | 118,786| 928 |
| Sedimentary rocks                                 | [18]  | 2.7 | 16,958 | 997 |
| Granite KvGr                                      | [25]  | 3.8 | 24,046 | 961 |
| Chililis schist Pp(?)Sch                          | [8]   | 1.2 | 30,733 | 3841|

*Complex movements* in the Varnes (1978) classification.
Disclosure statement

No potential conflict of interest was reported by the authors.

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