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Landslides Rainfall One of the Main Triggering Factors in the Mountainous Regions of Puebla, Mexico

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ABSTRACT

The rains are one of the main triggers of landslide phenomena in the mountainous region of Puebla, which values reach up 4500 mm/year in some places in this area. Rainfalls combined with other factors such as morphology (mountainous topographic relief with strong inclinations), strongly folded sedimentary rocks (conglomerates, sandstones, siltstones, and limestones), rock discontinuities (fissures, cracks, joints, stratigraphic planes, etc.) and human activity (cuts, excavations, overloads, mining, water discharge, deforestation, land use change, etc.), offer a scenario prone to landslide phenomena that cause human casualties, economic and environmental losses. The landslides disasters have affected many social sectors from these communities (housing, education, health, hydraulic infrastructure, electricity, communication, transportation, public services, agriculture, forestry, etc.), observing that in these sites there are communities of ethnic groups Nahuatls, Totonacs, Otomies and Tepehuas who build their houses out of sheet metal, cardboard, plastic and wood where any natural phenomenon represents a true disaster. This article presents the relationship between hurricanes and torrential rains with the disasters caused in communities in the mountainous region of Puebla. From the analysis of the data obtained from the different meteorological stations installed in the region of interest during a period of 20 years (1999 – 2019), an empirical rainfall threshold of 100 mm/day was determined as a trigger for landslides in the region of study. The aforementioned value is very important data for Civil Protection Government Authorities in order to establish actions and strategies for mitigation and risk management due to landslides. From this rain threshold, evacuation actions are put into operation to reduce the vulnerability of exposed and fragile communities which are immediately transferred to protection shelters.

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Introduction

The morphology of the Mexican territory is mountainous type originated by tectonic activity (converging of coconut plate with those of North America and the Caribbean). The main orographic systems are the Eastern Ridge, the Western Ridge, the South Ridge and the Transversal Volcanic System. The latter crosses the center of the country from West to East and belongs to the Pacific Ring of Fire where the most important area of volcanic and seismic activity in the world is located [1].

Rain is one of the main factors that affects the stability of slopes; many landslides occur during or after rainy periods, in addition, areas where greater annual rainfall is recorded present greater stability problems due, among other things, to the existence of underground flow rates and more weathered materials that have an impact on the geomechanical properties of the terrain [2]. The effect of rain depends fundamentally on the intensity, duration and distribution of the storm; indicate that the precipitation threshold for landslides to occur on slopes made up of detrital and colluvial soils depends on the inclination of the slope, filtration and loss of apparent cohesion [3].

In Puebla, landslide disasters have occurred, with rain being one of the main triggering factors of this phenomenon, although human activity has also played an important role [4]. In these mountainous regions, soil flows, rotational and translational landslides, rock falls and overturns, and complex movements have occurred, causing damage to communities including loss of life and property, affecting many social sectors: housing, education, health, agriculture and livestock, road infrastructure, communications, hydraulics, public services, etc.

Description of the Mountainous Region of Puebla

Morphology and Topography

Morphology is mountainous and steep type, with some elevations up to 3200 masl (Teziutlán and Zacapoaxtla Ranges). There are settlements in very steep slopes or in flood zones next to rivers (Zempoala, Apulco, Pantepec and San Marcos Rivers). The aforementioned represent a high risk for the inhabitants whose suffer mud avalanches and floods that every year caused damages at their communities. Because the slopes are very high and steep, the gravitational forces have a great influence in their behavior and stability, affecting a large mass of rocks and soils (Figure 1).

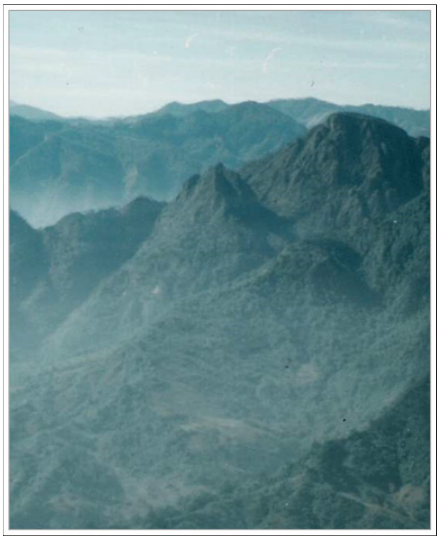

Figure 1: Morphology at the State of Puebla, México

Geology and Superficial Soil Layer

The mountainous ridges at Puebla State are made of sedimentary rocks folded intensely by compression forces during the Cretaceous-Tertiary (Paleocene) periods; this compression lifted layers that gave origin to the Eastern Range. The geologic events produced great failures and intense cracking and inclination of layers. Later, there were volcanic events that covered the sedimentary folded rocks with ashes and pyroclastic materials that are vulnerable to water erosion processes.

The volcanic activity ended up with great collapses of the volcano surroundings and generated another regional failure system where the rivers have formed their channels; the intensely fractured rocks of slopes frequently collapse in blocks, and the volcanic tuff flows or slides suddenly by erosion.

Rainfall and Surface Runoff

In 1999-year, heavy rainfalls over great part of Mexican Territory caused serious damages by landslides and floods in Puebla, Hidalgo, Veracruz, Tabasco, Campeche and Chiapas, among other cities. At the mountainous regions of Puebla State, extraordinary rains of 750 mm in three days of October month were registered (cold fronts 11 and 14); those rains raised the water volume in rivers and streams, dragging sediments and bigger particles of rocks that increasing their erosive force [5].

Besides, important amount of rainfall infiltrated and saturated soils that cover the mountains; these layers are usually several meters thick, increasing its weight per volume unit and causing the collapse or failure slope with plane or circular slip surface, due to gravitational forces (Figure 2).

The landslides disaster risks of mountainous regions of Puebla is presented each year in the rainy season, remember also the torrential rainfall on October 2005 caused by Hurricanes Stan and Wilma that caused serious damage to a large number of locations in the states of Central America and Southeast of Mexico (Puebla, Veracruz, Tabasco, Chiapas, Yucatan and Quintana Roo). In Puebla mountainous regions there were landslides and floods that affecting primarily the housing and infrastructure road, whose damages were estimated at several hundred million pesos [6].

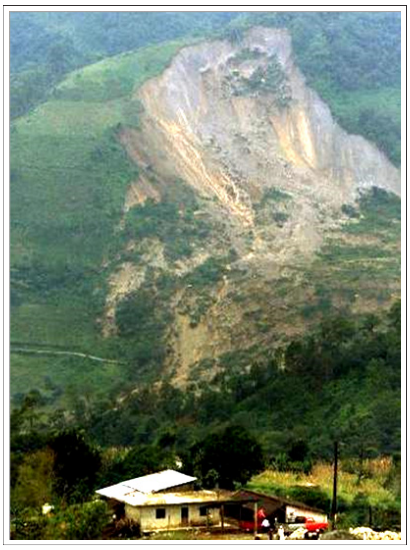

Figure 2: Rotational landslides at Northern Range of Puebla

The rains in the year 2005 reached values above 100 mm/day, which is the characteristic rainfall threshold that triggers landslides in the mountainous regions of Puebla. On October 4, in the community of Acateno, up to 158 mm of rain was measured; in Ahuazotepec 107 mm that day, in Chignahuapan 100 mm on October 5, in Cuetzalan 166, 305, 296 and 101 mm on days 3, 4, 5 and October 6, respectively. 116.5 mm in Huauchinango, in Soledad 250 and 201 on October 5 and 6, in Necaxa 125 and 112 mm, in Oyameles 105 and 160 mm.

In the years 2009 and 2010, there were extraordinary historical precipitations worldwide. In Mexico this rainfall caused damages in Monterrey, Tamaulipas, San Luis Potosi, Michoacan, Mexico State, Veracruz, Hidalgo, Puebla, Oaxaca, Guerrero, Chiapas and Tabasco. In Puebla, Hurricane Karl in September month, left 1500 people homeless, damage to homes, schools and roads, of which highlights the destruction of the bridge in Apapantilla (Northern ridge), also damages in roads Teziultlán-Libres and Hueytamalco, and in the Black Range the roads of Tehuacan, Eloxochitlán and Coxcatlán.

Due to heavy rains from Tropical Depression Mathew at the end of September 2010, two landslides occurred, one in the community of Santa Maria Tlahuiltoltepec in the state of Oaxaca, which is one of poorest regions of the country inhabited by the Mixe ethnic group, and another in the town of Amatlan in the state of Chiapas. In both events, there was a lamentable loss of human lives.

Human Activity at Mountainous Region

The effect of human factor is evident in landslides phenomenon; human activities that most affect the slope stability are as follows [4]:

Changing the Natural Slope Due to Cuts or Excavations

Cuts and excavations cause the following changes on slopes:

a) Increasing the slope angle with direct effect on the gravitational factor.
b) Decompression of the slope material by removing lateral support and pressure.
c) Increase of weathering on slope materials that lost their surface protection (soil and vegetation coverage).
d) Changing the flow of water through the slope.
e) Instability of loose landfills placed to increase the width of cut.

Adding Overloads for Construction of Buildings and Infrastructure Works, Storage of Materials, Etc.

The stress to the soil foundation due to constructions and materials deposited on the slopes, are overloads that have direct impact on the behavior and stability.

Increased Pore Pressure Slopes by the Uncontrolled and Excessive Water

The first effect of this factor is to change the water flow through the materials on slopes, and the second, the increases of pore pressure "u" which reduces the normal stress σ_n that affect the shear strength of the material. It also generates pressure on the tension cracks increasing destabilizing forces and increases the unit weight of the material by saturation.

Removal Of Natural Vegetation (Deforestation)

The vegetation is a main factor that greatly affects the action of other triggers of slope instability. The roots of trees and plants help fixing the soil surface to resistant rock strata located at a greater depth, absorb some of the groundwater, with their foliage mitigate the impact of raindrops and reduce surface erosion to slow water runoff. Other actions related to deforestation include land use change, replacing the forest for cattle pasture, fruit trees and subsistence agriculture. They affect one way or another, the stability of slopes.

Landslides Phenomenon

Rotational and Translational Failures

Fragile sedimentary rocks like shales and siltstones, which weathering into clayey and silty soils (CH and MH, unified soil classification system) suffer translational and rotational landslides due to reduction of strength when increase their water content. The slope failures in Teziutlán, Mexcalcuautla, Necaxaltepetl, Tetela de Ocampo, Pahuatlán, etc., where many lives were lost, belong to this type.

From geotechnical and constructive point of view, these hills have a high risk of landslides due to their slope materials can suffer changes in their mechanical properties (resistance and compressibility), when varying their moisture content or when the rock experiments a reduction in their compression level due to cuts made in slopes [7].

Any construction placed in or adjacent to the slopes made up by these sedimentary rocks (Shales and siltstones), can suffer damages such as cracking (floors, walls, roofs), differential settlements, angular distortion, and they can collapse when landslides coming suddenly [3].

Several rotational and traslational landslides recorded in many slopes, were originated in the zone where a cut had been made previously to build a road or a terrace for building. For the aforementioned is very important to do geotechnical studies before building in this kind of ground, that maybe require construction processes of stabilization such as: geometric rectification, drainage elements, anchoring system and barrier piles, retaining walls and surface protection [8].

Fallen of Rocks

Another common phenomenon in the mountainous regions of Puebla is fallen rocks, which may include limestones, shales, sandstones, conglomerates, tuffs, etc., which have also caused great loss of life and economic losses.

Weather Stations

Table 1 presents the geographical coordinates of main weather stations, and in Figure 3 its location on a map of Puebla.

Table 1: Weather Stations of Puebla

Northeastern Range			
Station name	**Latitude**	**Longitude**	**masl**
Capuluaque (Tetela)	19.79	97.76	2098
Oyameles (Tlatlauqui)	19.71	97.54	2670
Huahuaxtla	19.91	97.60	1486
Ixtacamaxtitlán	19.62	97.81	2472
San Luis Atexcac	19.34	97.45	2414
Zacapoaxtla	19.87	97.58	1828
Francisco I. Madero	19.61	97.50	2585
San José Acateno	20.14	97.21	144
Las Margaritas	19.98	97.28	2422
Ayotoxco de Guerrero	20.09	97.42	237
Northern Range			
Station name	**Latitude**	**Longitude**	**masl**
Chignahuapan	19.83	98.32	2291
Jopala	20.19	97.80	681
Aquixtla	19.79	97.93	2192
Xicotepec	20.29	97.96	1098
Metlaltoyuca	20.74	97.86	131
Ameluca	20.58	97.84	160
Venta Grande	20.11	98.10	2125
Piedras Negras	20.44	97.76	425
Apapantilla	20.40	97.84	278
Venustiano Carranza	20.51	97.66	268
San Nicolas Tetela	19.81	97.86	1760
Universidad de Sierra	20.17	98.06	1555
Tepango Rodríguez	20.00	97.79	1526
Black Range			
Station name	**Latitude**	**Longitude**	**masl**
Zoquitlán	18.35	97.02	2077
Tlacotepec de Díaz	18.46	96.79	91
Telpatlán	18.52	97.14	2212
Tehuacán	18.46	97.39	2416
Bernardino Lagunas	18.60	97.27	1693
Chapulco	18.62	97.41	2115
Calipan	18.29	97.16	1131
Alcomunga	18.43	97.03	2485

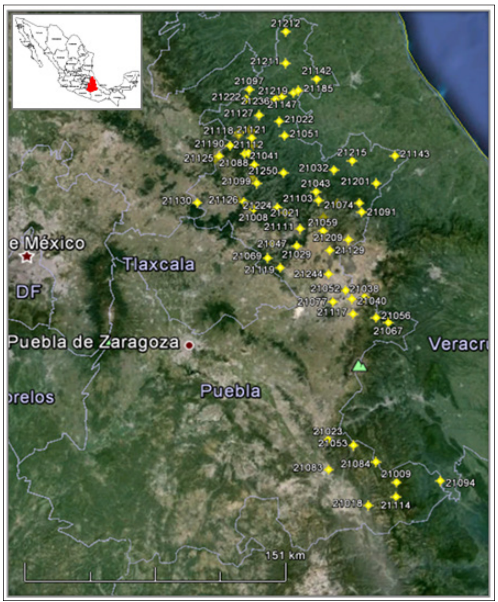

Figure 3: Locations of Weather Stations at mountainous regions of Puebla

Relationship Between Rainfalls and Disasters
In this section is presented the relationship between hurricanes and torrential rains with the disasters caused in different communities in the mountainous region of Puebla: tropical depression eleven (Oct. 1999), hurricanes Stan and Wilma (Oct. 2005), hurricanes Felix and Lorenzo (Aug. 2007), hurricanes Carlota and Ernesto (Jun. and Aug. 2012), hurricanes Manuel and Ingrid (Sep. 2013), hurricanes Franklin and Katia (Sep. 2017) [9].

Tropical Depression Eleven (October 4, 1999)
Eleven Tropical Depression on 1999 Atlantic hurricane season caused torrential rainfall in Mexico for several days, resulting in at least 636 deaths and $1 billion dollars in damages. Table 2 shows the cost of damages in different sectors at the state of Puebla caused by heavy rainfalls of September-October 1999.

Hurricanes Stan and Wilma (October 2005)
As a tropical storm, Stan brought torrential rainfall and gusty winds on October 1, affected several states of Mexico: Chiapas, Hidalgo, Oaxaca, Puebla, and Veracruz. According to Mexican president Vicente Fox, Hurricane Stan wrought roughly 20 billion pesos ($1.9 billion USD) in damage throughout the country. Some areas in the North ridge of Puebla were also flooded. Three people died in a mudslide at Xochiapulco Hill (Northern ridge). After Stan had passed, Wilma surged from tropical storm to Category 5 hurricane in record time at October 21. Winds around the eyewall of the storm were raging at 280 kilometers per hour, making it the most intense hurricane ever observed in the Atlantic basin.

Table 2: Cost of damages in Puebla (1999)

Actions made (1999)	Morales M, 2001	Bitran D. And Reyes C. 2000
1. Emergency Actions Secretary of Health SEDENA IMSS DICONSA	$ 3.29 MD	$ 0.49 MD $ 0.117 MD $ 2.32 MD $ 0.117 MD $ 2.32 MD
2. Housing program	$ 33.12 MD (15,960 houses)	$ 39.58 MD (16,511house)
3. Educational sector	$ 7.44 MD (269 schools) include 27 new buildings	$3.06 MD (570 schools)
4. Health sector		$ 0.243 MD (3 centers of Health)
5. Hydraulic infrastructure program	$ 8.42 MD (404 communities)	$ 8.42 MD (377communities)
6. Electricity		$ 46.89 MD (916 populations) (192,000 people)
7. Highways and bridges	$ 84.69 MD (2,947 Km)	$ 9. 49 MD (2,685.8 Km)
8. Agricultural Sector	$ 4.73 MD (64,854product)	$ 16.33 MD $ 1.5 MD
9. Forest and fishing sector	$ 1.61 MD (7,170 Ha. of forest) (240 Ha. of soil)	$ 3.41 MD $ 0. 76 MD
TOTAL	$ 192.52 MD	$ 218.94 MD
Note: MD: million dollars $1 USD=$10.26 Mexican pesos (December 2000)		

Hurricanes Felix and Lorenzo (August-September 2007)
On August 11, a tropical wave moved off the west coast of Africa, and, encountering favorable conditions, quickly spawned Tropical Depression Four, roughly 520 miles (835 km) west-southwest of Cape Verde. Tropical Depression became Tropical Storm Dean on August 14 and became the first hurricane of the season just two days after. Dean reached a peak intensity as a Category 5 on the Saffir-Simpson Hurricane Scale—the strongest Atlantic hurricane since Hurricane Wilma and was rated the seventh most intense Atlantic storm of all time. The hurricane made landfall on the Yucatán Peninsula on August 21, causing severe damage and at least 44 deaths.

A tropical wave emerged off the coast of Africa on September 11 and traversed the Atlantic, crossing the Yucatán Peninsula on September 21. On September 25 an associated low organized into a tropical depression in the southwest Gulf of Mexico. Further organization took place, and depression become Tropical Storm Lorenzo. Lorenzo peaked with winds of 80 mph a minimal hurricane and made landfall near Tecolutla, Veracruz.

Hurricane Carlotta (June 2012)
Hurricane Carlotta was the strongest eastern Pacific tropical cyclone to make landfall at hurricane strength since 1997. Carlotta, the third tropical cyclone and third named storm of the 2012 Pacific hurricane season, slowly became a tropical depression from a tropical wave southwest of Central America on June 14, 2012. It moved generally to the west-northwest and the next day, it strengthened to tropical storm strength. Thereafter, gradual intensification occurred, and the storm reached hurricane strength on June 15. It intensified further, when Carlotta peaked as a 110 mph (175 km/h) Category 2 hurricane the same day. At 01:00 UTC the next day, Carlotta made landfall near Puerto Escondido after that the storm weakened as it moved towards the southwest coast of Mexico and finally dissipating on June 16.

Hurricane Ingrid and Manuel (September 2013)
On September 15 and 16, Ingrid converged with Hurricane Manuel in the Pacific Ocean, causing heavy rains in 22 of the 32 states of the Mexican Republic. Ingrid and Manuel left more than 200,000 homeless and 157 dead in its path in Mexico. The main states that suffered the effects of Ingrid were Veracruz and Hidalgo. The country's government quickly issued an alert for rainstorm on the beaches of Coatzacoalcos up to the Nautla bar, in addition to data from the hurricane hunter plane showing winds greater than 45 knots (75 km/h) evidenced the formation of the storm tropical Ingrid, while it was located 95 kilometers east-northeast of the city of Veracruz. For this reason, the National Civil Protection System issued an orange alert for the state of Tabasco, and the south of the State of Veracruz. Torrential rains caused by the system combined with the cloudy bands of Tropical Storm Manuel affected the states of Chiapas, Guerrero and Oaxaca on September 14. Ingrid reached category one on the Saffir-Simpson Scale, staying that way all day. The phenomenon known as Ingrid-Manuel hurricanes was the second action in which two phenomena of this type interact and plague Mexico in this way, the phenomenon is among the most costly phenomena in this country and one of the most deadly.

Hurricane Ernesto (August 2012)
Hurricane Ernesto was a devastating tropical cyclone that affected several areas of the Caribbean and Central America during the month of August 2012. As the fifth named storm and the second hurricane of the 2012 season, Ernesto was born from a tropical wave that emerged from the coast Western Africa in late July. Moving westward, the system developed into a tropical depression in the central Atlantic, and before entering the Caribbean, into a Tropical Storm. The system encountered high wind shear south of Jamaica but subsequently peaked at a Category two hurricane, before making landfall on the Yucatán Peninsula. Ernesto emerged into the Bay of Campeche as an intense tropical storm before dissipating over the mountains of central Mexico. Its remnants passed into the Pacific Ocean,

Hurricane Franklin (September 2017)
Hurricane Franklin formed on August 7 was the first hurricane to make landfall in the Mexican state of Veracruz since Hurricane Karl in 2010. The sixth named storm, the first hurricane, and the first of ten consecutive hurricanes of the 2017 Atlantic hurricane season. The storm strengthened in a favorable environment and made landfall on the Yucatán Peninsula as a moderate tropical storm early on August 8 north of Belize. Weakening occurred as it crossed the peninsula, but Franklin reappeared in the Bay of Campeche later that day, quickly regrowing to become the first hurricane of the season. It made landfall near Vega de la Torre, Veracruz, then passed Misantla, Veracruz on August 10 as a Category 1 hurricane, before rapidly weakening over the mountainous terrain of Mexico and dissipating shortly thereafter. On August 12, the remnant of the storm in the mid-level circulation combined with a developing low in the eastern Pacific to form Tropical Storm Jova.

Franklin's main impacts were located in eastern Mexico, specifically in the state of Veracruz, where Franklin made landfall as a hurricane. Strong winds downed trees and power lines, as well as damaging homes and crops. Heavy rains flooded some rivers and caused some landslides. Damage in that area totaled US $15 million. Other areas that Franklin affected, mainly by bringing heavy rains, included the Yucatán Peninsula and Belize. No deaths occurred.

Hurricane Katia (September 2017)
Hurricane Katia was the most intense hurricane in the Bay of Campeche since Hurricane Karl in 2010. The eleventh storm and sixth hurricane of the unusually active 2017 Atlantic hurricane season, Katia originated on September 5 in a wide area of low pressure formed in the Bay of Campeche. Located in an area of weak directional currents, Katia meandered in the region, eventually intensifying into a hurricane on September 6. The nascent storm eventually peaked at a 105 mph (165 km/h) Category 2 hurricane on the Saffir-Simpson Hurricane Scale as it began moving southwest. However, interaction with land began to weaken the hurricane as it neared the Gulf of Mexico coast. At the beginning of September 9, Katia made landfall near Tecolutla at minimal hurricane intensity. The storm quickly dissipated several hours later, though its mid-level circulation remained intact, and it later spawned what would become Hurricane Otis in the eastern Pacific.

At least 53 municipalities in Mexico were damaged by Katia hurricane. Heavy rains left flooding and numerous landslides, with 65 landslides in the city of Xalapa alone. Although damage estimates are unknown, preliminary reports indicated that 370 houses were flooded. Three deaths confirmed to the hurricane, two of them from landslides and one swept away by flooding. Approximately 77,000 people lost power at the height of the storm. Coincidentally, the storm hit Mexico just days after a major earthquake rocked the country, worsening the fallout and recovery. Hurricane Katia marked the first instance of three simultaneously active hurricanes since 2010.

Empirical Rain Threshold
Rainfall is a major concern at the mountainous region of Puebla, every year heavy rain caused serious damages and disasters in communities settled in those zones. Taking into account records of rains in weather stations during the period 1999 to 2019 (20 years), we have estimated an empirical threshold of 100 mm/day that triggers landslides. Figures 4 and 5 present graphs of some weather stations that clearly show when there have been events related to tropical depression and hurricanes which precipitation exceeds of 100 mm/day, landslides had occurred in Puebla.

Figures 4 and 5 were made by the authors of this article from the climatological data records during the period 1999-2019, in the stations located in the mountainous regions of Puebla [10]. The analysis of the information clearly shows the relationship between disasters caused by tropical storms and hurricanes with rainfall greater than 100 mm/day that triggers landslides.

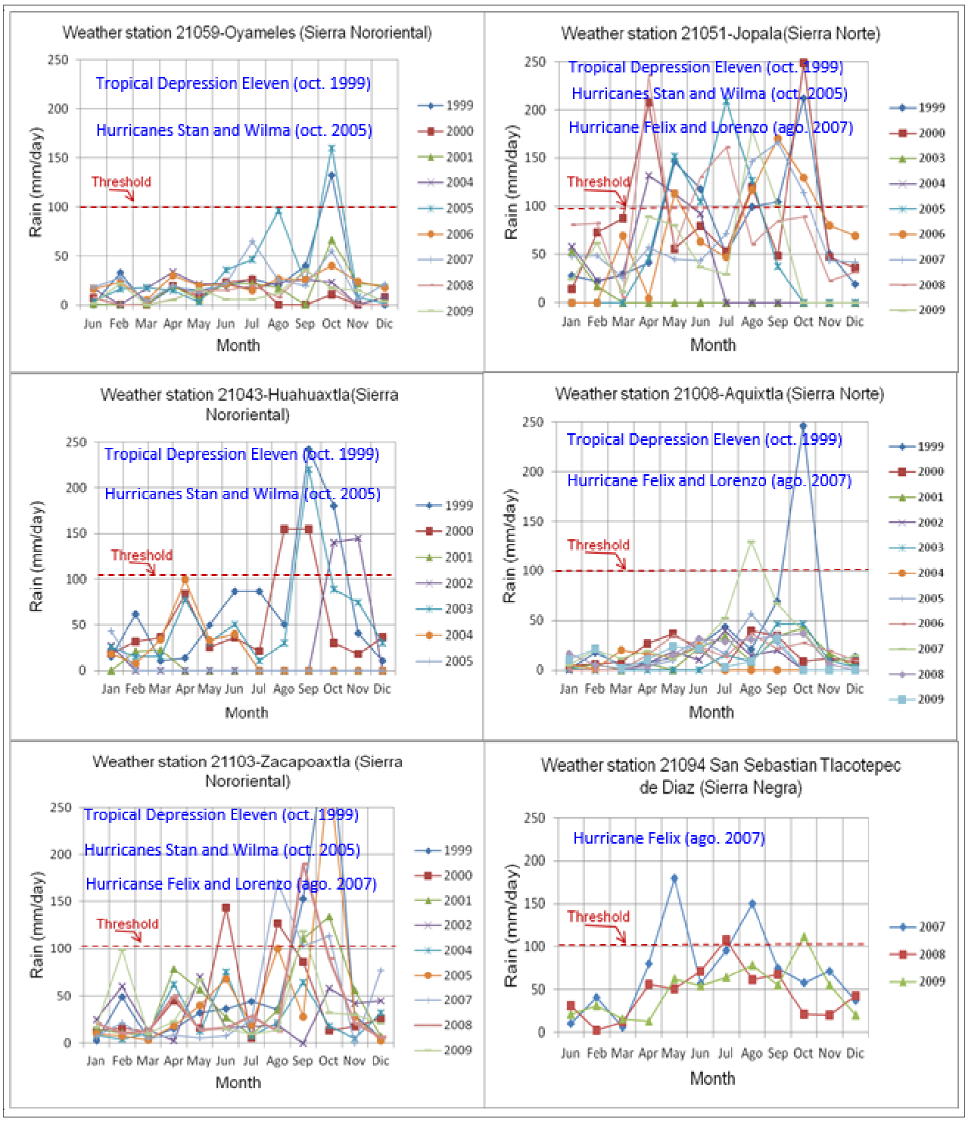

Figure 4: Rainfall recorders at some Weather Stations of Puebla (1999-2009)

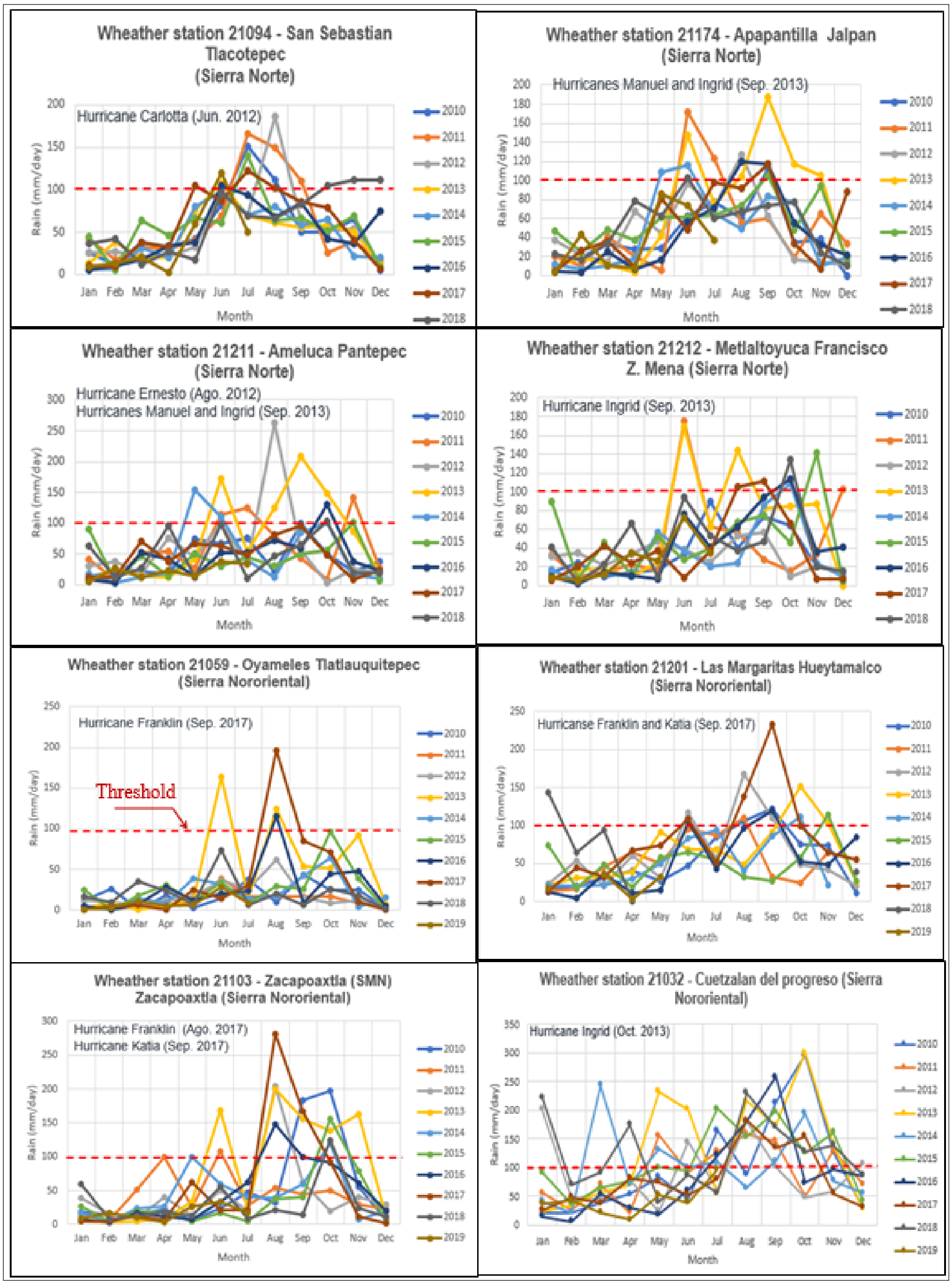

Figure 5: Rainfall recorders at some Weather Stations of Puebla (2010-2019)

Conclusion

Disasters due to landslides have occurred in Puebla, with rain being one of the main triggering factors of this phenomenon; although human activity has also played an important role [11]. Soil flows, rotational and translational landslides, rock falls and overturns, and complex movements have occurred in these mountainous regions, causing damage to communities, including loss of life and property, affecting many social sectors: housing, education, health, agriculture and livestock. road infrastructure, communications, hydraulics, public services, etc.

In general, landslides in Puebla occur during the rainy season when rainfall is close to or greater than 100 mm/day (historical records for rainfall during landslides in the mountainous region). In the months of September and October 1999, rainfall in the northern part of the state (northern and northeastern mountain ranges) was recorded approximately 1240 mm, with accumulated torrential rains of 750 mm between October 5 and 7 (on average 250 mm). mm/day), causing a large number of landslides and numerous losses, whose economic damages amounted to more than 200 million dollars [12].

The threshold rainfall value is very important for Civil Protection Government Authorities in order to establish actions and strategies for mitigation and risk management due to landslides. From this rain threshold of 100 mm/day, evacuation actions are put into operation to reduce the vulnerability of exposed and fragile communities (ethnic groups), which are immediately transferred to protection shelters.

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