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Analysis of the Impact of the Eruptive Process of the Tungurahua Volcano on the Precipitation Patterns of Hydrographic Microbasins Located Inside and Outside the Zone of Influence

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Abstract

The relationship between eruptive processes and precipitation is a topic that lacks research studies, perhaps due to the difficulty that is to have few scenarios, which satisfy conditions for statistical testing. Most of the available literature report a global impact after significant volcanic eruptions. Robock et al. (2008) concluded that the Pinatubo volcano eruption left precipitation consequences in the medium and long term. Kravitz y Robock (2011) suggested considering weather seasons on the estimation of the impact of volcanic eruptions. Allen e Ingram (2002) concluded that volcanic gasses are more important than greenhouse gasses on the climate change at a global level.

In the Ambato river watershed (Ecuador), studies were conducted to evaluate the relationship between eruptive processes of the Tungurahua volcano and the variation in precipitation series. During the main eruptive events between 1999 and 2010, atypical precipitation values were determined during April, May, July, August, and December, with increments within 130.09% and 285.15% with respect to precipitation observations in the studied period (Ríos, 2014).

The results of the present study demonstrate the relationship between rainfall anomalies and volcanic activity. Three watersheds were analyzed: (1) Ambato river watershed, located to the West of the volcano with direct impact of volcanic ash and SO_2; (2) Drenajes Menores of the Pastaza river; and (3) Areas Menores of the Pastaza river. The latter are located to the East of the volcano with no impact from volcanic ash and SO_2 due to the direction of wind flow.

Keywords: Modification, precipitation, volcanic eruption, Tungurahua

1. Antecedents

Knowledge regarding the variability of precipitation patterns and the factors that produce them is one of the challenges for hydraulic and environmental engineering. The world population grows by 80 million people every year and the increase in demand for fresh water is estimated at around 64 thousand million cubic meters of water per year, therefore it is relevant to investigate the internal and external, natural and anthropogenic variables that cause irregularity in the precipitation series (Connor, 2009).

A study on the main impacts on the long-term hydrological cycle (Zurich, 2012), indicates that volcanic eruptions affect the hydrological cycle through its injection of sulfur gases into the stratosphere, which become sulfate aerosols with a residence time of approximately one year. This time of permanence allows the particles to spread worldwide and affect the climate on a global scale (Robock, 2000).

Although most studies of the volcanic effect concentrate on proving that there is an effect on global and regional temperature, some researchers like (Prohom, 2003) establish that a variation of total precipitation during the first year after a large volcanic eruption. The main incidence is detected in the first winter after large tropical volcanic events. Of course the effect depends on the season and the characteristics of the zone of influence.

The analysis of these investigations provided initial premises to support studies on the eruptive process of Tungurahua volcano in Ecuador that has been active since 1993 with continuous ash emissions and from 1999 with eruptive events with explosive volcanic indexes (VEI) between 0 and 3.

During the first research carried out in the Ambato river micro basin, five meteorological stations were selected: Ambato M-066, Cevallos M-128, Pilahuin M-376, Tisaleo M-377 and Urbina M-390. They were located at the northwest at a maximum distance of 100 km from the volcano, within the area affected by volcanic ash. The precipitation series of forty-eight years were studied with the pluviometric data from these stations. They were divided into two subperiods; the first one without eruptive process and the second one directly linked to the volcanic activity. The results obtained show the existence of variations in the seasonal precipitation patterns, with increases up to 131.53% in the subsequent months when a volcanic explosion occurs (Ríos y Solera, 2015).

A second study in the same area establishes the correlation between shape, direction and mainly SO_2 concentration of the tropospheric plumes of the Tungurahua volcano eruption process and the significant changes in the precipitation series with a 95% confidence during the months of December, May, April, July and September. In May 2000, atypical precipitation events were registered in all areas of the Ambato river basin. In the northern part of the micro basin, punctual precipitation increases of 285% in comparison with the period average were registered, in the center and south of the micro-basin there were increases of 170.29% and 249% respectively. The month of December registered changes with increases in rainfall patterns during the second sub-period compared to the first sub-period with values reaching 50.19% (Ríos, 2016).

Although the results of the two studies are conclusive, it is necessary to abstract the variables analyzed from other possible causes that could affect the variability of precipitation, such as climate change or the influence of endogenous and exogenous factors that modify the climate. For this reason a new comparative study that analyzes two different areas near the volcano: a micro watershed affected directly by ash plume and two other equidistant micro-basins, which are not affected by ash plume due to wind orientation is proposed.

2. Description of the Study Area

The study area is part of the zone of influence of the Tungurahua volcano, located in the Mountain Range of the Ecuadorian Andes at latitude 01 º 28` South and longitude 78 º 27` West, 33 km southeast of the city of Ambato, in the province of Tungurahua.

Three hydrographic basins have been selected for this research. The first one is the micro basin of the Ambato River, with an extension of 1 370 km^2 and located to the west of the volcano.This area is affected by ash and SO_2 emissions from the eruptions of the Tungurahua volcano. The monitoring records come from the Tisaleo M-377 weather station, located at latitude 01 °20'54 "S and longitude 78 °40'13" O at an elevation of 3 266 meters above sea level and at a distance of 28.88 km from the Tungurahua volcano.

The second and third micro-watersheds selected are called Minor Drains to the Pastaza River and Minor Areas with extensions of 1 272 Km^2 and 3 348 Km^2 respectively located towards the east of the volcano. Despite of being in the zone of influence, the territories where these watersheds are located do not get affected by emissions of ash and SO_2 expelled by the Tungurahua volcano. The meteorological stations of Río Verde M-378 and Puyo M-008 are located in these micro-watersheds. The first one is situated 18 km from the Tungurahua volcano, latitude 01 º24` 4" S and length 78 º17` 43" O, with an elevation of 1 529 meters. The second one in Latitude 01 º30`27 "S and length 77 º56`38" O, with an elevation of 960 meters above sea level and at a distance of 56 Km from the Tungurahua volcano. (Figure 1).

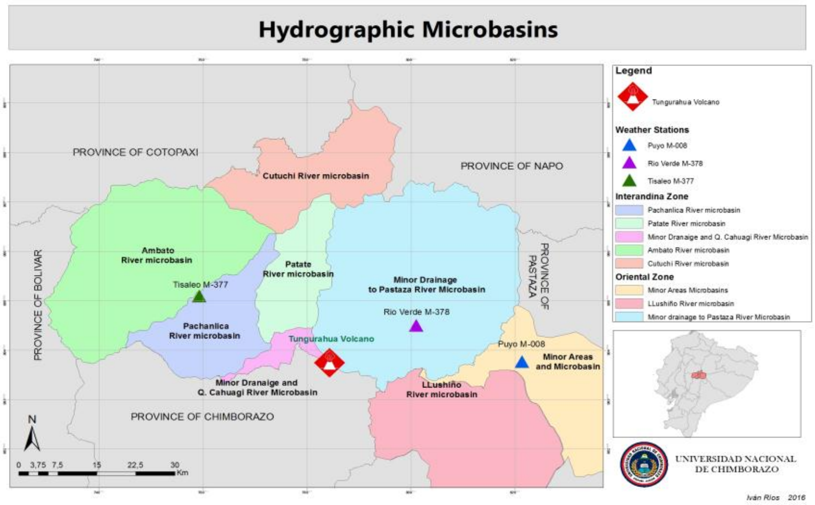

Figure 1. Micro-watersheds: Ambato River- Minor drainage to the Pastaza river - Minor areas.

For the monitoring of the continuous activity of the volcano there are five seismic broadband stations available, five short period seismic stations, five infrasound stations, one video camera, twelve measurement bases with electronic distance meter, 1 electronic inclinometer, a COSPEC correlation spectrometer, a DOAS differential optic spectrometer and a flir temperature measurement camera, used by the Geophysical Institute.

2.1 The Volcanic Activity of Tungurahua

In Ecuador there are 5 active volcanoes, 3 of which are in eruption process. The Tungurahua volcano has had the highest number of eruptions during the last 350 years and a permanent process of ash emission and sporadic explosions since 1993. From this year the reactivation of the volcano has been characterized by the presence of two styles of eruptive activity: a) Explosive events in the upper part of the volcano with bomb falls near the crater and ash in the areas of influence (Figure 2).

b) Larger explosive events with production of pyroclastic flows, accompanied by significant falls of ash and pumice on the region.

Figure 2. Volcan Tungurahua eruption (Medina, 2010)

The main affected area is the micro basin of the Ambato River, where mild and medium intensity eruptions emanate ash mainly affecting the agricultural production of the area, especially from July 1999 to August 2000; May to August 2001; January to March, May to June, August, September to October 2002; March, June to July, August to December 2003; May to July, November to December 2004 and February, July to August 2005 (Figure 3).

The most violent activity of this period occurred in 2006, with two major eruptions, on July 14th and August 16th, where it could be observed that the ash plume extended to the east and center of the micro basin of the Ambato River. With these eruptions, a substantial amount of ash and pyroclastic material was deposited on the northwestern flank of the volcano (Troncoso et al, 2006).

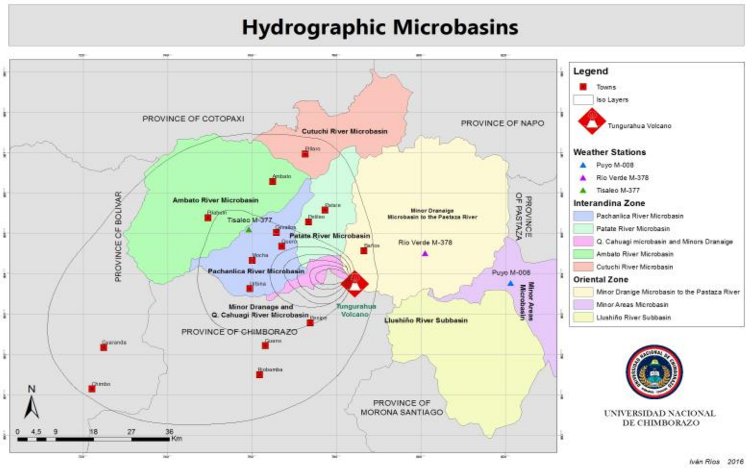

Figure 3. Micro-watersheds affected by ash y SO_2.

3. Methodology

From two previous studies, one of them which is an exploratory analysis that demonstrates the existence of variations in the seasonal precipitation patterns with increases of up to 131.53% in the subsequent months when a volcanic explosion occurs, as well as another study that establishes the correlation between the shape, direction and mainly the SO_2 concentration of the tropospheric plumes of the eruptive process of the Tungurahua volcano and the significant changes in the precipitation series; essential information about the factors that alter climate is obtained and a methodology for the analysis of data, which can be applied in other micro-basins affected by volcanic activity, is developed. The methodology presented below facilitates the analysis of data in three zones where it is possible to clearly establish the damage and impact of ash plume on the precipitation patterns in a micro basin compared to the rainfall behavior in two other micro-basins that, despite being located at a similar distance, are not affected by the presence of SO_2.

This methodology establishes each of the steps that the researcher must follow, as well as the description of tools and statistical tests for data analysis (Figure 4).

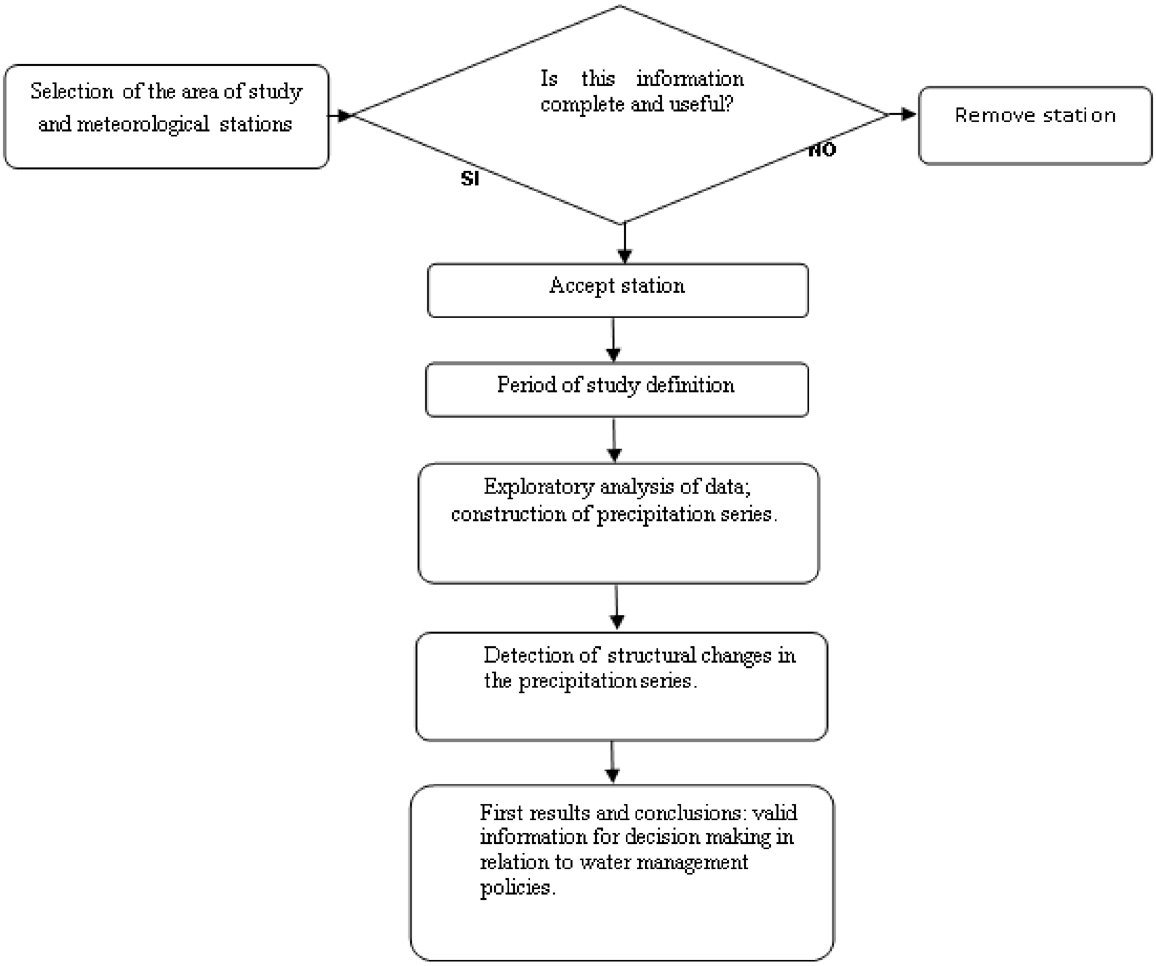

Figure 4. Methodology of variability of precipitation series associated to a volcanic eruption.

3.1 Selection of Area of Study and Meteorological Stations

The initial step is the identification of watersheds located in zones of influence of the eruptive process of a volcano and the selection of meteorological stations located in an area of 100 km of distance from the volcano, with or without damage caused by ash plume and emissions of SO_2. These stations must have precipitation data of at least 40 years. A fundamental criterion for the selection of meteorological stations is the determination of the direction, orientation and coverage of the ash plume that it expelled by the volcano according to the direction and the wind average speed.

3.2 Definition of the Period of Study

The time from 1967 to 2012 is established as the study period and the time from 1967 to 1989 and from 1990 to 2012 as the study sub-periods, in order to compare the variability of the precipitation patterns during periods of time with and without presence of a volcano eruptive process in the selected watersheds.

3.3 Exploratory Analysis of Precipitation Data

The construction of temporary precipitation series and time-series graphs allows basic exploratory analysis, characterizing values, ranges, tendencies, intermittency and the presence of anomalies (Schaefer et al, 2007).

3.4 Detection of Structural Changes in the Precipitation Series

Subsequently, the methodology establishes the implementation of several statistical tests for the detection of changes in the precipitation series, both gradual (tendencies) and abrupt (staggered) (Yue y Pilon, 2004). These changes may affect the average, the variance, the autocorrelation or other aspects of the data.

3.4.1. Detection Tests of Abrupt Changes in the Temporary Precipitation Series

Three statistical tests are performed for the analysis of changes in mean and median precipitation series: The Rank sum test developed by Wilcoxon. In this case it is applied to identify sudden changes in the median and verify if they coincide in time with the main explosive events of the volcano.

Student's t-test is then applied, which is useful and powerful to detect inconsistencies due to abrupt changes in mean precipitation. Finally, the CUSUM statistical test is applied, which analyzes if changes occur in the mean for a set time. In particular, successive observations are compared to the mean of the precipitation series in order to detect sudden changes in the time series.

3.4.2 Change Detection Tests in Tendencies of Temporary Series of Precipitation

The Mann Kendall and Spearman Rho Statistical Test are applied in order to compare the relative magnitudes of data rather than the eigenvalues. One of the advantages of this test is that precipitation series data do not need to confirm a particular distribution, and unreported data can be included by assigning a common value, less than the smallest mean value of the data.

4. Discussion

4.1. Monthly Exploratory Analysis of the Series of Precipitation

With data from the meteorological stations selected in the three hydrographic basins, rainfall series are built for a 46-year study period from 1967 to 2012, in order to have sufficient data to validate the research. Two sub-periods are established, the first one goes from 1967 to 1989 without the eruptive phenomenon of the Tungurahua volcano and the second sub-period from 1990 from 2012 with permanent presence of volcanic activity.

Table 1. Annual precipitation in micro watersheds with and without damage due to the eruptive process of the Tungurahua volcano

Micro watershed	Station	Annual average precipitation	Distance from the volcano	Percentage of area affected by ash emissions and SO_2
MC-1: Ambato River	Tisaleo M-377	717.48 mm	28.88 Km	100%
MC-2: Minor Drainage to the Pastaza River	Río Verde M-378	2 908.67 mm	18.00 Km	0%
MC-3: Minor Areas	Puyo M-008	4 522.43 mm	56.00 Km	0%

Table 1 summarizes data that allow us to compare the impact of volcanic activity on the three micro-basins. In the Ambato River (MC-1), the Tisaleo station M-377 registers an average annual precipitation of 717.48 mm; corresponding to an area called the inter-Andean valley, characterized as dry, with a semi-humid climate with annual average precipitation ranging from 400 mm to 1 000 mm. In the micro watershed Minor Drainage to the Pastaza River (MC-2), the average annual rainfall registered by the Río Verde M-378 station is 2 908.67 mm; corresponding to a very tropical and humid area, which is the transition between the Andean region and the Amazon region, between 500 and 1 500 meters above sea level. In the micro basin called Minor Areas (MC-3), the Puyo M-008 station registers an average annual rainfall of 4 522.43 mm, this zone corresponds to a tropical monsoon climate.

In previous studies it was identified that MC-1 shows variations in precipitation patterns in all months of the year and significant changes in the months of April, July, September and December (Ríos and Solera, 2015). The tests are performed with a confidence level of 90%. For the present study, the methodology is applied precisely in the same months, in two stations located in micro basins without ash affected in order to compare the changes in rainfall amounts in similar periods.

4.2 Month of April

Table 2. April precipitation statistics

			Trend		Media		Mediana
Micro watershed	Station	Period	Mann -Kendall	Spearman ́s rho	Student ́s	Cusum	Rank sum
Ambato River	Tisaleo	1967-2012	*2.803	*2.647	-1.453	7	-1.406
		1967-1989	1.479	1.460	-1.702	5	-1.601
		1990-2012	*2.958	*2.79	*-1.947	*6	*-2.000
Minor Drainages Pastaza River	R ́o Verde	1967-2012	-0.947	-0.161	1.008	7	1.406
		1967-1989	0.739	0.505	-0.803	6	-0.892
		1990-2012	-1.000	0.016	0.042	3	0.277
Minor Areas	Puyo	1967-2012	0.739	0.09	0.095	5	-0.11
		1967-1989	0.687	0.565	-0.291	2	0.031
		1990-2012	1.109	1.085	-1.079	5	-1.446
*Significant							

Table 2 summarizes the main statistical tests applied to detect structural changes in the precipitation series during the month of April. The second sub-period, MC-1, affected by ash emissions and SO_2, presents significant positive changes (confidence level of 90%) in the trend.

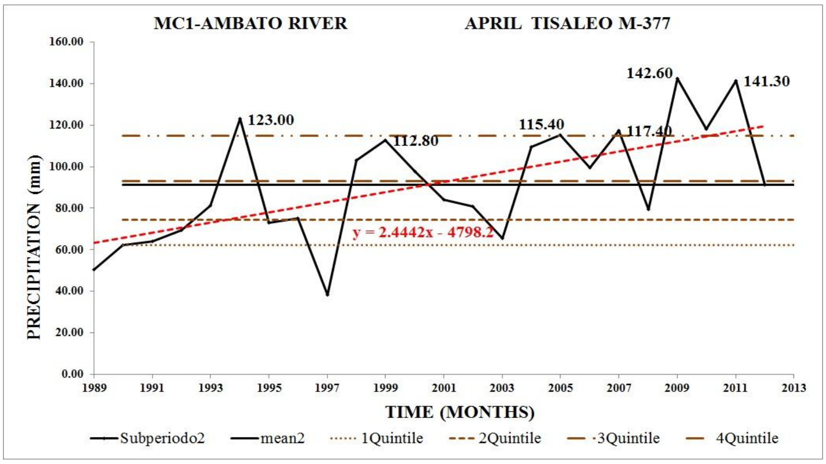

Figure 5. April precipitation MC-1 Ambato River

The average values show a significant jump with confidence level of 90% in 1997. The average rainfall from 2001 to 2012 is higher than the one from 1990 to 2000. The average of the period 2001 to 2012 from is higher than the one of the period from 1990 to 2000. Atypical increases in the precipitation patterns of April were registered following the explosive eruptive process of Tungurahua volcano in September 1999. During the years of 2000, 2009, and 2011 larger eruptive events occurred, which produced atypical precipitation values of 112.80 mm, 142.60 mm, 141.30 mm corresponding to increments of 32.30%, 67.25% and 65.73% respectively with respect to the average of the month of April (Figure 5).

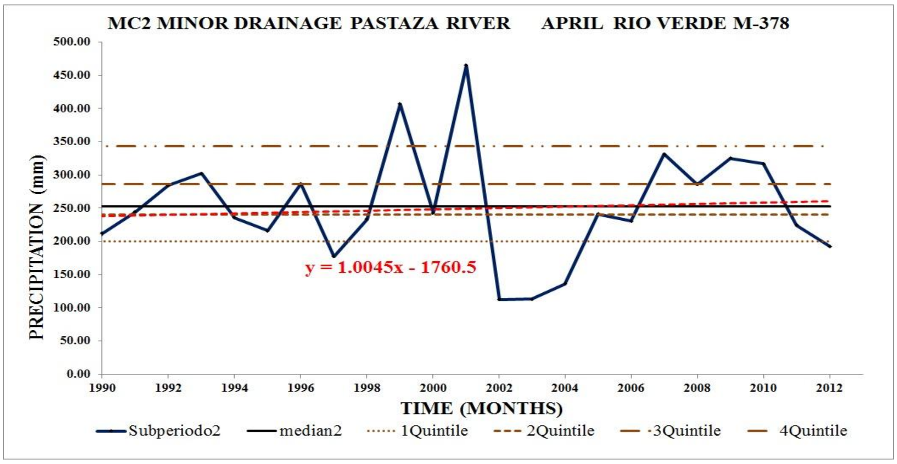

Figure 6. April precipitation MC-2 Minor Drainages Pastaza River

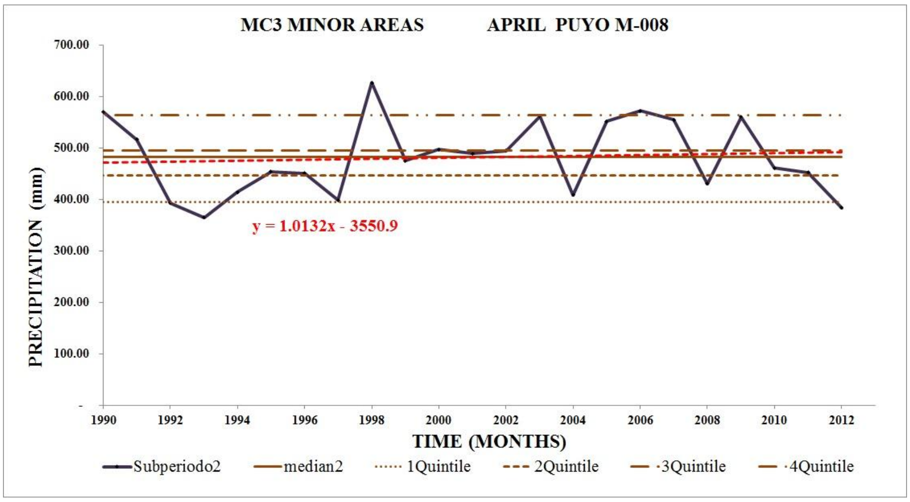

Figure 7. April precipitation MC-3 Minor Areas

When comparing the same period, the stations located in the MC-2 and MC-3, which were not affected by emissions of ash and SO_2, do not detect significant changes in the precipitation series (Figures 6-7). During the month of April a decrease of 8.53% in the precipitation of the second subperiod is detected in comparison to the first in MC-2 and of 0.58% in MC-3, which is not statistically significant.

4.3 Month of July

0995241599

Table 3. July precipitation statistics

			Trend		Media		Mediana
Micro watershed	Station	Period	Mann -Kendall	Spearman ́s rho	Student ́s	Cusum	Rank sum
Ambato River	Tisaleo	1967-2012	-1.591	-1.620	0.945	6	0.945
		1967-1989	-0.902	-0.991	1.693	4	1.633
		1990-2012	-1.364	-1.351	*1.778	4	1.357
Minor Drainages Pastaza River	Río Verde	1967-2012	-1.645	-1.586	1.347	8	1.472
		1967-1989	-0.792	-1.01	1.556	4	1.569
		1990-2012	-1.004	-0.941	0.597	4	0.523
Minor Areas	Puyo	1967-2012	-0.492	-0.587	0.006	6	0.088
		1967-1989	-1.321	-1.418	1.701	5	1.620
		1990-2012	0.158	0.005	-0.102	3	-0.215
* Significant							

From the analysis carried out in July, it can be seen in Table 3 that the MC-2 and MC-3 micro-basins do not present significant changes or atypical values in the rainfall series during any period of study, in the MC-2 and MC-3 precipitation decreases occur during the second period in comparison to the first of 10.92% and 0.04% respectively, which are not statistically significant.

It is interesting to observe that in July the MC-1, which was affected by ash and SO_2, registered a decrease in rainfall during the second sub-period respect to the first, with significant changes in average precipitation with confidence level of 90%, in other words, contrary to what happens in April, the average rainfall from 1990 to 2000 is higher than from 2001 to 2012. However, in spite of the fact that during the second sub-period there is a decrease in average precipitation, in 2007 there are atypical values of 174.90 mm, which are associated with the eruptive event at the end of June of 2007 in which the level of activity of the Tungurahua volcano was high and sustained, with frequent emissions characterized by high ash content, lava fountains and ash columns reaching 4 km above the crater.

4.4 Month of September

Table 4. September precipitation statistics.

			Trend		Media		Mediana
Micro watershed	Station	Period	Mann -Kendall	Spearman ́s rho	Student ́s	Cusum	Rank sum
Ambato River	Tisaleo	1967-2012	-1.136	-0.157	*1.841	3	1.604
		1967-1989	1.004	1.089	0.251	5	0.277
		1990-2012	-0.264	-0.222	*1.721	3	0.892
Minor Drainages Pastaza River	Río Verde	1967-2012	-1.604	-1.569	1.682	8	1.621
		1967-1989	0.053	0.171	0.133	2	0.277
		1990-2012	0.528	-0.552	-0.538	4	-0.339
Minor Areas	Puyo	1967-2012	-1.363	-1.356	1.243	5	0.857
		1967-1989	0.158	0.185	0.099	3	0.154
		1990-2012	-1.546	-1.502	1.173	4	1.139
* Significant							

Table 4 shows the results during the month of September. It can be observed that in the MC-1, which is affected by ash and SO_2, the Tisaleo M-377 station records that from 1998 there are significant changes in the average precipitation with confidence level of 90%, the average precipitation from 2001 to 2012 is less than the one from1990 to 2000. In September, the second sub-period presents a constant dry stage in the MC-1. The decrease of rainfall during the second sub-period with respect to the first one reaches 25.83%. In 1999, however, at the beginning of the explosive eruption process of the Tungurahua volcano a punctual increment in rainfall of 102.89% is produced in the central zone of the MC-1, but immediately after decreasing precipitation tendencies were detected. From the results obtained it can be concluded that the most important effect from the eruptive process of Tungurahua volcano is the modification of the rain patterns in the month of September, which is the driest month in the MC-1.

In September, there were decreases in the rainfall amounts of 27.69% and 10.41% of the second sub-period compared to the first in the MC-2 and MC-3 respectively. However, no significant changes in the precipitation series were detected for any period of study.

4.5 Month of December

Table 5. December precipitation statistics.

			Trend		Media		Mediana
Micro watershed	Station	Period	Mann -Kendall	Spearman ́s rho	Student ́s	Cusum	Rank sum
Ambato River	Tisaleo	1967-2012	0.843	1.015	*-1.780	4	-1.494
		1967-1989	-0.977	-0.751	-0.212	4	0.462
		1990-2012	-0.158	-0.181	*-1.770	2	0.585
Minor Drainages Pastaza River	Río Verde	1967-2012	1.07	1.201	-0.375	6	-0.791
		1967-1989	-0.053	0.171	-0.917	3	-0.462
		1990-2012	1.215	1.242	0.330	4	-0.400
Minor Areas	Puyo	1967-2012	1.386	1.472	-1.682	8	-1.545
		1967-1989	0.449	0.565	-0.300	5	-0.523
		1990-2012	0.739	0.983	-1.579	5	-1.630
* Significant							

In the case of MC-1, affected by ash and SO_2, it is observed that from 1993 significant precipitation changes occur with confidence level of 90% (Table 5).

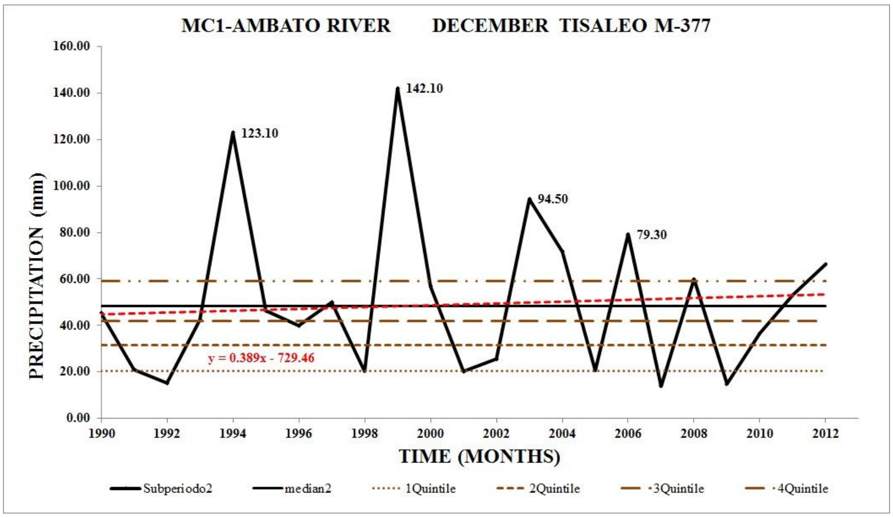

Figure 8. December precipitation MC-1 Ambato River

The average precipitation from 2001 to 2012 is higher than average precipitation from 1990 to 2000. The precipitation increases have a value of 40.40% in the second period, atypical values of rain of 123.10 mm and 142.10 mm in 1993 and 1999 respectively, and which coincide with the dates of the main explosive eruptive events of Tungurahua volcano.

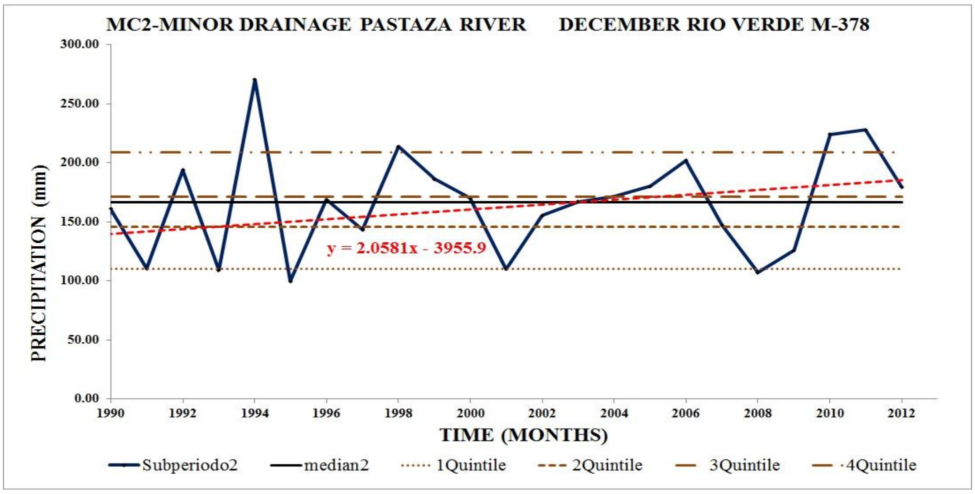

Figure 9. December precipitation MC-2 Minor Drainages Pastaza River

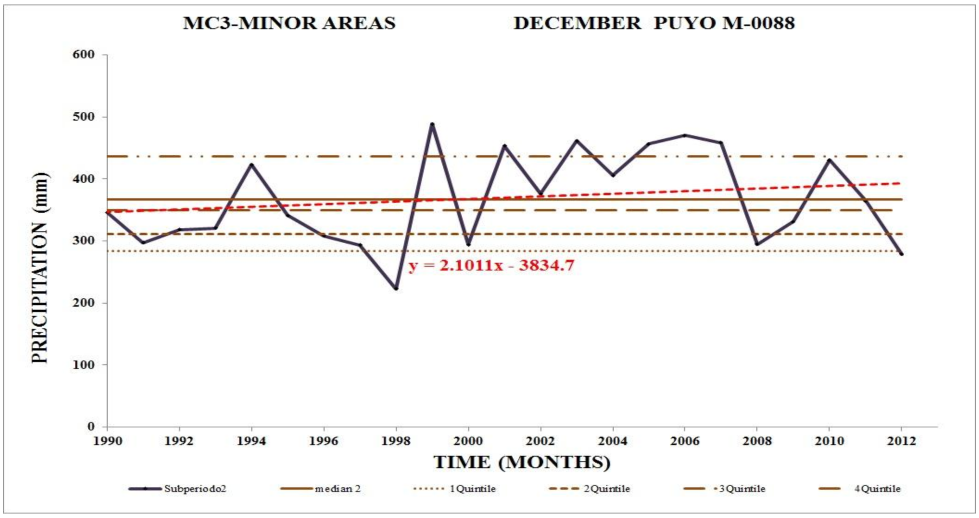

Figure 10. December precipitation MC-3 Minor Areas

Shows that MC-2 (Figure 9) and MC-3 (Figure 10), which are not affected by ash and SO_2, do not record changes in the precipitation series for any selected study period. In December, rainfall increases of 5.01% and 21.84 % are registered of the second sub-period compared to the first in the MC-2 and MC-3 respectively. In general, no significant changes in precipitation series are detected.

5. Conclusions

The results of the present study, as well as previous studies on the variability of precipitation in the Ambato river micro watershed, allow us to conclude that there is a direct connection between the effects of a volcanic eruption and the changes in precipitation series occurred in its zones of influence. In general, a recurrent pattern of increase in precipitation of up to 131.53% is observed in subsequent weeks when an explosive eruption occurs. The impact depends on the intensity of the volcanic activity and of course on other factors such as wind direction and height of ash plume in the affected area.

The greatest effect on precipitation patterns in the Ambato river micro watershed due to the presence of ash and SO_2 from the Tungurahua volcano's explosive eruptive process is recorded between September 1999 and May 2000, the results obtained demonstrate point increases in monthly rainfall amounts, with significant atypical values of precipitation.

The analysis of other zones of influence, in this case two micro watersheds located in the area of influence equidistant to the volcano and that are not affected by ash plume, allows to confirm that the changes in the series of precipitation occur only in the micro-basins affected by the presence of ash and SO_2. Statistical tests, based on data collected for forty-eight years, show significant atypical values in the MC-1 micro watershed that has been affected by ash plume, while the other micro-basins show normal or atypical values which are not significant.

In the present investigation it is confirmed that the ash and SO_2 produced by the eruption come into contact with the clouds that, by wind direction, extend the ash plume over specific areas affecting the micro-basins located in zones of influence. Inside the clouds, the particles ejected by the volcano generate a chemical process that produces precipitation, in some cases with atypical values in the weeks following the eruptive process. This means that there is a redistribution of rain, which in turn causes a further reduction in the level of precipitation during the months of July, August and September, which are generally dry periods.

It is important to take into account that the study area is located in the equinoctial zone, where the four seasons do not exist, but there are dry and rainy seasons that do not have a clearly defined seasonality. This particularity generates difficulties in specifying the impact of volcanic activity on precipitation in the medium and long term. For this reason, the statistical analysis of the meteorological records is carried out monthly in order to identify anomalies and variations that may be related to the activity of the volcano.

The results of the present study and previous research constitute an important contribution in research on the relationship between volcanic activity and natural phenomena such as precipitation and climate in general. The study of the 46-year data records at several stations located near the Tungurahua volcano provide strong evidence that there is a relationship between volcanic activity and variations in precipitation at the local level. Explosive events of the volcano coincide with the presence of atypical rainfall values over the following weeks and it is demonstrated that there is a temporal redistribution of rainfall amounts.

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References

Allen, M., & Ingram, J. (2002). Constraints on future changes in climate and the hydrologic cycle, *Nature, 419*,224-232. https://doi.org/10.1038/nature01092

Connor, R. (2009). Evaluation of water use, water in a changing world. *World Water Development Report, 3,* Accessed June 21.

Hamed, K. (2008). Trend detection in hydrologic data: The Mann-Kendall trend test under the scaling hypothesis. *Journal of Hydrology, 349*(3-4), 350-363. https://doi.org/10.1016/j.jhydrol.2007.11.009

Kravitz, B., & Robock, A. (2011). Climate effects of high-latitude volcanic eruptions Role of the time of year, *Journal of Geophysical Research, 116*, DO1105.

Kundzewicz, Z., & Robson, A. (2004). Change detection in hydrological records a review of the methodology/Revue méthodologique de la detection de changements dans les choniques hydrologiques, *Hydrological Sciences Journal/Journal des Sciences Hydrologiques, 49*(1), 7-19.

Merlos, F., Sánchez, S., & Almanza, J. (2014). Creación de un Sistema de Información Hidrológico para el cálculo de intensidades máximas y gestión de datos meteorológicos, XXIII Congreso Nacional de Hidráulica, México.

Prohom, M. (2003). Incidencia de las grandes erupciones volcánicas en el clima de la Península Ibérica. Universidad de Barcelona, *Departamento de Geografía Física*, 1-36.

Ríos, I. (2014). Análisis exploratorio de la variabilidad de las precipitaciones en la microcuenca del río Ambato asociado a la erupción del volcán Tungurahua en Ecuador, *Universidad Politécnica de Valencia*, 52-104.

Ríos, I. (2016). Incorporación de los efectos de erupciones volcánicas en modelos estocásticos de precipitación en cuencas hidrográficas [Tesis Doctoral]. Universidad Politécnica de Valencia, España, 93-159.

Ríos, I., & Solera, A. (2015). Variations in the patterns of precipitation in the watershed of the Ambato River associated with the eruptive process of the Tungurahua volcano in Ecuador. *Open Journal of Modern Hydrology, 5*, DOI: 10.4236, 121-139.

Robock, A. (2000). Volcanic Erupcions and climate. *Reviews of Geophysics, 38*, 191-219. https://doi.org/10.1029/1998RG000054

Robock, A., Oman, L., & Stenchilov, L. (2008). Regional climate responses to geoengineering with tropical and Artic SO2 injections, *Journal Geophysical Reserch, 113*, 1-15. https://doi.org/10.1029/2008JD010050

Schaefer, M., Barker, B., Taylor, G., & Wallis, J. (2007). Regional precipitation-frequency analysis and spatial mapping for 24 hour and 2 hour durations in eastern Washington. *Oregon. Oregon Climate Service*, 415-442.

Troncoso, L., Pennec, J., Jaya, D., Valle, A., & Mothes, P. (2006). Depósitos de caída de ceniza producidos durante las erupciones del volcán Tungurahua, 14 de julio y 16 de agosto de 2006. 6tas Jornadas en Ciencias de la Tierra. Escuela Politécnica Nacional, Departamento de Geología, Quito, 181-184.

Yue, S., & Pilon, P. (2004). A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection, *en Hydrological Science Journal, 49*(1), 21-37.

https://doi.org/10.1623/hysj.49.1.21.53996

Zurich, E. (2012). Global and European climate response to transient forcings since 1870, as simulated in an atmospheric general circulation model. DISS:ETH No.20360.