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Geostatistical Analysis of the Colorada and Quimichule Canyons Located in Popocatépetl Volcano (Mexico) for the Prevention of Natural Disasters

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Abstract

This paper aims to contribute to the prevention of natural disasters and generate a complement to other similar studies. The Popocatépetl volcano has showed significant and constant activity since 1994. The Colorada and Quimichule canyons are located within its geologic structure; due to their topographic features, ejected volcanic material and torrential rains in the past recent years, they put nearby communities at risk. This work presents a geostatistical analysis to obtain the gravity acceleration, slope by the distance-elevation relation, height-gravity and the fluid force on the canyons. The conversion of UTM to geographical coordinates was made with the use of the program Traninv applying the ITRF2008 epoch 2010.0 Datum and the 14 Zone; the local gravity was calculated with the use of International Organization of Legal Metrology (OIML) and the statistical analysis was obtained with the use of the Geostatistical Environmental Assessment. The structural modeling was performed using *Surfer*, and the spending and force were calculated using hydrological models. The correlation analysis concluded that Quimichule has the greatest gravity and that it would transport lahars faster. Mapping, geomorphological and statistical techniques and models were applied in accordance with the study to obtain the results presented here.

Keywords

Natural Disasters, Geostatistical, Force, Acceleration, Gravity

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1. Introduction

The Popocatépetl volcano is located at 19˚17'N latitude - 98˚38'W longitude from the Greenwich Meridian. Its height is 5520 meters above sea level and it borders with the states of Puebla, Morelos and Mexico. In 1994, the Popocatépetl volcano began an important stage of activity presenting in 1994, an important stage of steam, ash and incandescent rock ejection, as well as seismic events. It has remained active presenting both high and low intensity periods ever since. Its constant activity, atypical torrential rains caused by climate change, existing melting glaciers and topography, favor landslides of mudflows of volcanic ash in the canyons such as Colorada and Quimichule. These are directly related to the gravity, slope, height and expense, which might put the surrounding communities at risk. Furthermore, the pressure changes generated by the activity within the magma chamber cause gravity deformations and variations on the surface of the volcano—which must be quantified periodically. A study named "Possible Mudflow in the possible mudflow on the east side of the Popocatépetl volcano" [1] was carried out after the eruption in 1994. This study built a profile of the El Aguardientero canyon; its slopes were calculated every 100 m of elevation, using topographic maps of the National Institute of Statistics and Geography (INEGI) at a 1:50.000 scale, determining that one of the areas with the highest accumulation of ash is San Pedro Benito Juárez.

This paper aims to contribute to the prevention of natural disasters caused by volcanoes, specifically through the development of geostatistical methodologies. This information will be useful to determine which prevention actions to take in the event of volcanic activity created by thaw when a major volcanic activity exists. Currently, studies continue to be conducted in order to calculate other geomorphologic variables.

Studies on canyon stability have been carried out applying geotechnical methods and finite elements to determine tensions, deformations and shear strength [2]. These methods are based on mathematical models that provide an approach to the solution of the problem; however, they do not take into account geodetic methods to determine the slope and gravity. Geodetic approximate methods provide more realistic results, as the data introduced to the computer programs are obtained from readings on topographic maps with a good approach.

The location of this volcano and its activity in recent years represent a risk structure to the nearby communities (**Figure 1**).

Regarding the work in this paper, there is no information on similar studies or research in the area of Popocatépetl. Still, it is important to know the possible scenarios that would arise in the case of a major eruption.

2. Materials and Methods

The UTM coordinates of the canyons' profile were obtained through digital topographic maps of the volcano readings and are available to users on the website of the NATIONAL INSTITUTE OF STATISTICS AND GEOGRAPHY. Using these maps, we defined the points where the acceleration of gravity, distance-lift slope and gravity-height would be calculated. The UTM coordinates were converted to geographic coordinates using the Traninv program applying the ITRF2008 Datum and Zone 14. Currently, all the mapping and digital products produced by INEGI, subsequent to the date of December 2010 is based on the new Datum ITRF2008, also

Figure 1. Topography of the Popocatépetl volcano in the National Izta-Popo Park, Mexico.

releasing at the same time a software (Traninv) based on the mathematical algorithm for the transformation or conversion of coordinate ITRF92 to ITRF2008, which seeks a smooth transition to a new reference system. The acceleration of local gravity was calculated using the program on the National Metrology Center (Mexico) website, based on the OIML-N. 127 of 1992 newsletter.

The statistical analysis was carried out using the Geostatistical Environmental Assessment, and the structural modeling using the Surfer program. In addition, hydrological models were used to calculate the expense and force of a liquid.

Later, relations between gravity-height and gravity-slope were obtained, as well as their corresponding correlation coefficients. The correlation between the three studied variables is important because it defines the behavior of flows over the canyons, giving an idea location of the area of greatest risk in those geological structures.

2.1. Converting the Coordinates of Recorded Data

For each canyon data, the data was obtained from the E14B42 topographic map, getting the UTM coordinates and then transforming them to geographical coordinates using the Traninv program where X = W and Y = N (**Figure 2**).

The data used for the processing each 500 m in length for both canyons is shown on **Table 1** and **Table 2**.

2.2. Development for the Calculating of the Acceleration of Local Gravity

The acceleration of gravity is the act of universal attraction that propels bodies to the center of the Earth; it is a force that determines the weight of bodies [2]. The acceleration of gravity is by the letter *g* and it is defined as the constant increase of velocity by time unit on a body in free fall, it is inversely proportional to the body massin *kilograms* (kg) $g = F/m$. In order to calculate the local gravity of each canyon, the program recommended by the International Committee of Legal Metrology (OIML) was applied (**Figure 3**).

The Equation (1) was used to confirm the results of gravity in different points of the canyon every 500 meters of distance, which can be calculated accurately in the 0.001% = 100 ppm order. Introduced data includes: altitude (m) and North latitude (˚). This program calculates the acceleration of local gravity by applying the Equation (1) (**Table 3** and **Table 4**).

$$gl = \left[ge * \left(1 + f' * sen^2\phi\right) - \left(F_4 * sen^2 2\phi\right)\right] - \left(Dg * h\right) \quad \text{Model} \quad (1)$$

where:

gl = acceleration of local gravity (m/s^2).

ge = 9.7803185 m/s^2, acceleration of gravity in the Equator ($\varphi = 0$).

Coordinate transformation [NAD27 a ITRF92]			
Geographical coordinates			
NAD27		ITRF92	
Longitude	Latitude	Longitude	Latitude
98°12′56.5 ″W	19°01′12.4 ″N	98°12′57.379 ″W	19°01′14.900 ″N
-98.21569	19.02011	-98.21594	19.02081
Coordinates in UTM projection			
Zone 14			
NAD27		ITRF92	
x	y	x	y
582541.421	2103110.870	582514.154	2103313.555
Diferencia (ITRF92-NAD27)			
x		y	
-27.267		202.685	
Coordinates in CCL projection (12,-102,17.5,29.5,2500000,0)			

Figure 2. Transformation model of the UTM coordinates to geographical coordinates for all the readings of the canyons.

Table 1. The Colorada canyon has a length of 6.5 km, thus 13 readings were carried out (Z = height, N = latitude, W = length, in meters).

Data					
Point	**Latitude**	**Longitude**	**Z**	**W**	**N**
1	19˚1˚46.451˚	98˚37˚23.916˚	4880	539640.388	2104015.758
2	19˚1˚39.899˚	98˚37˚07.464˚	4580	540121.747	2103815.432
3	19˚1˚33.707˚	98˚36˚51.840˚	4280	540578.888	2103626.111
4	19˚1˚26.616˚	98˚36˚36.287˚	4040	540034.0525	2103409.175
5	19˚1˚21.071˚	98˚36˚20.015˚	3820	541510.084	2103239.814
6	19˚1˚14.628˚	98˚36˚03.888˚	3580	541981.976	2103042.855
7	19˚1˚08.400˚	98˚35˚48.119˚	3440	542443.398	2102852.492
8	19˚0˚01.668˚	98˚35˚31.236˚	3280	542937.432	2102646.725
9	19˚0˚54.404˚	98˚35˚15.396˚	3120	543401.024	2102424.549
10	19˚0˚49.14˚	98˚34˚59.628˚	3000	543862.377	2102263.849
11	19˚0˚44.280˚	98˚34˚47.460˚	2960	544218.462	2102115.326

Table 2. The Quimichule canyon has a length of 6.5 km, thus 13 readings were carried out (Z = height, N = latitude, W = length, in meters).

Data					
Point	**Latitude**	**Longitude**	**Z**	**W**	**N**
1	19˚4˚25.824˚	98˚36˚11.16˚	3400	541756.3216	2108918.483
2	19˚4˚14.087˚	98˚36˚21.995˚	3500	541440.2879	2108557.144
3	19˚4˚3.9˚	98˚36˚35.244˚	3587.872	541054.0718	2108243.504
4	19˚3˚52.055˚	98˚36˚46.835˚	3651.994	540715.6962	2107878.453
5	19˚3˚39.996˚	98˚36˚55.512˚	3738.675	540463.5108	2107507.299
6	19˚3˚24.66˚	98˚37˚0.804˚	3820.266	540309.7976	2107035.544
7	19˚3˚11.087˚	98˚37˚8.4˚	3881.08	540088.629	2106617.608
8	19˚2˚56.759˚	98˚37˚15.348˚	3978.361	539885.7634	2106177.386
9	19˚2˚41.64˚	98˚37˚17.436˚	4149.287	539826.3458	2105712.186
10	19˚2˚27.42˚	98˚37˚14.52˚	4291.082	539912.5866	2105275.253
11	19˚2˚11.327˚	98˚37˚14.808˚	4491.679	539904.7367	2104780.647
12	19˚1˚56.567˚	98˚37˚21.576˚	4760.342	539708.4806	2104326.534
13	19˚1˚46.74˚	98˚37˚22.835˚	4962.988	539672.0045	2104024.676

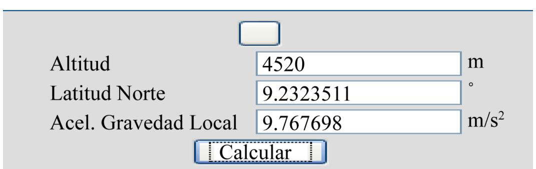


Figure 3. Example of the calculation of the acceleration of local gravity.

Table 3. Colorada canyon. Gravity was calculated every 500 meters, resulting an average of 9.774308 m/s^2.

CALCULATION OF PARTIAL ACCELERATION OF GRAVITY												
Pnt.	COORDINATES		Altitude (Z)	Latitude °			(Decimal)	sen^2	Sen^{2}2	Local gravity acceleration (*gl*)	Constants to calculate the acceleration of gravity of a point with latitude different Ecuador (*ge*)
	W	N		°	'	"					
1	539640.388	2104015.758	4880	19	01	46.451	19.02956972	0.10631257	0.380041	9.770750	*ge* = 9.7803185 m/s²
2	540121.747	2103815.432	4580	19	01	39.899	19.02774972	0.10629299	0.379979	9.771675	*f′* 0.0053024
3	540578.888	2103626.111	4280	19	01	33.707	19.02602972	0.10627448	0.379921	9.772600	f_4 = 0.0000059
4	540034.0525	2103409.175	4040	19	01	26.616	19.02406	0.10625329	0.379854	9.773339	*Dg* 0.000003086
5	541510.084	2103239.814	3820	19	01	21.071	19.02251972	0.10623673	0.379802	9.774017	
6	541981.976	2103042.855	3580	19	01	14.628	19.02073	0.10621748	0.379741	9.774757	*h* = (altitude)
7	542443.398	2102852.492	3440	19	01	8.400	19.019	0.10619887	0.379683	9.775188	f XX"
8	542937.432	2102646.725	3280	19	01	1.668	19.01713	0.10617876	0.379619	9.775681	(latitude)
9	543401.024	2102424.549	3120	19	00	54.404	19.01511222	0.10615706	0.379551	9.776173	Local Gravity Acceleration (*gl*)
10	543862.377	2102263.849	3000	19	00	49.140	19.01365	0.10614134	0.379501	9.776543	
11	544218.462	2102115.326	2960	19	00	44.280	19.0123	0.10612683	0.379456	9.776666	$gl = [ge*(1+(f'*sen^2 j)-(f_4*sen^2 2j))]-(Dg*h)$
											$\sum gl$ = 107.517389928 Data 11
											Average Gravity Canyon: 9.774308

Table 4. Quimichule canyon. Gravity was calculated every 500 meters resulting an average of 9.776018 m/s^2.

CALCULATION OF PARTIAL ACCELERATION OF GRAVITY												
Pnt.	COORDINATES		Altitude (Z)	Latitude °			(Decimal)	sen^2	Sen^{2}2	Local gravity acceleration (*gl*)	Constants to calculate the acceleration of gravity of a point with latitude different Ecuador (*ge*)
	W	N		°	'	"					
1	541756.3216	2108918.483	3400	19	4	25.824	19.07384	0.10678937	0.381542	9.775342	*ge* = 9.7803185 m/s²
2	541440.2879	2108557.144	3500	19	4	14.087	19.07057972	0.10675422	0.381431	9.775032	*f′* 0.0053024
3	541054.0718	2108243.504	3587.872	19	4	3.900	19.06775	0.10672372	0.381335	9.774759	f_4 = 0.0000059
4	540715.6962	2107878.453	3651.994	19	3	52.055	19.06445972	0.10668826	0.381224	9.774559	*Dg* 0.000003086
5	540463.5108	2107507.299	3738.675	19	3	39.990	19.06110833	0.10665215	0.38111	9.774290	
6	540309.7976	2107035.544	3820.266	19	3	24.660	19.05685	0.10660627	0.380965	9.774036	*h* = (altitude)
7	540088.629	2106617.608	3881.08	19	3	11.087	19.05307972	0.10656566	0.380838	9.773846	f XX"
8	539885.7634	2106177.386	3978.361	19	2	56.759	19.04909972	0.10652279	0.380703	9.773543	(latitude)
9	539826.3458	2105712.186	4149.287	19	2	41.640	19.0449	0.10647757	0.38056	9.773014	Local Gravity Acceleration (*gl*)
10	539912.5866	2105275.253	4291.082	19	2	27.420	19.04095	0.10643505	0.380427	9.772574	
11	539904.7367	2104780.647	4491.679	19	2	11.327	19.03647972	0.10638693	0.380275	9.771952	$gl = [ge*(1+(f'*sen^2 j)-(f_4*sen^2 2j))]-(Dg*h)$
12	539708.4806	2104326.534	4760.342	19	1	56.567	19.03237972	0.10634281	0.380136	9.771121	
13	539672.0045	2104024.676	4962.988	19	1	46.740	19.02965	0.10631343	0.380044	9.770494	$\sum gl$ = 127.054561911 Data 13
											Average Gravity Canyon: 9.773427839

f' = 0.0053024 (gravitational collapse)
ϕ = Latitude, in degrees, minutes, seconds (00˚00'00")
h = Height above mean sea level (m)
F_4 = 0.0000059
Dg = 0.000003086

2.3. Calculating the Slope

The slope is the existing relation between the elevation and horizontal distance on a plane, which is equal to the tangent of the angle that forms the line to measure with the X axis. See Equation (2)

$$m = \frac{y_2 - y_1}{x_2 - x_1} \quad \text{Model} \tag{2}$$

Using the contour lines on the topographic map and applying the interpolation method, the slope of the canyons was determined taking readings every 500 meters along the channel. The arithmetic average was also calculated for the points in each canyon [3] (**Table 5** and **Table 6**).

3. Results

3.1. Geostatistical Analysis Using the Geoeas Program

Through the use of the *Geoeas* program, which creates weighted normal probability graphics of the forcing variables (gravity and height), the statistical behavior of dispersion was obtained with the linear regression model of the matrix of the analyzed variables, which coefficient for each processed canyon is close to −1 (**Figure 4**).

Table 5. Colorada canyon.

Slope of the Canyon						
Pnt.	COORDINATES		**Altitude**	Distance	$m = \frac{N_2 - N_1}{W_2 - W_1}$	
	W	**N**				
1	539640.388	2104015.758	4880			$\sum m_1 + m_2 =$ −3.840000000
2	540121.747	2103815.432	4580	500	−0.60000	
3	540578.888	2103626.111	4280	500	−0.60000	
4	540034.0525	2103409.175	4040	500	−0.48000	Average slope
5	541510.084	2103239.814	3820	500	−0.44000	
6	541981.976	2103042.855	3580	500	−0.48000	−0.349090909
7	542443.398	2102852.492	3440	500	−0.28000	
8	5422937.432	2102646.725	3280	500	−0.32000	High point
9	543401.024	2102424.549	3120	500	−0.32000	4880
10	543862.377	2102263.849	3000	500	−0.24000	Low point
11	544218.462	2102115.326	2960	500	−0.08000	2960
						Distance
						5000
						Slope between points
						−0.384000000

Table 6. Quimichule canyon.

Slope of the canyon						
Pnt.	COORDINATES		**Altitude**	Distance	$m=\frac{N_2-N_1}{W_2-W_1}$	
	W	**N**				
1	541756.3216	2108918.483	3400			$\sum m_1 + m_2 =$ 3.125976000
2	541440.2879	2108557.144	3500	500	0.20000	
3	541054.0718	2108243.504	3587.872	500	0.17574	
4	540715.6962	2107878.453	3651.994	500	0.12824	Average slope
5	540463.5108	2107507.299	3738.675	500	0.17336	
6	540309.7976	2107035.544	3820.266	500	0.16318	0.240459692
7	540088.629	2106617.608	3881.08	500	0.12163	
8	539885.7634	2106177.386	3978.361	500	0.19456	
9	539826.3458	2105712.186	4149.287	500	0.34185	High point
10	539912.5866	2105275.253	4291.082	500	0.28359	4963
11	539904.7367	2104780.647	4491.679	500	0.40119	Low point
12	539708.4806	2104326.534	4760.342	500	0.53733	3400
13	539672.0045	2104024.676	4962.988	500	0.40529	Distance
						500
						Slope between points
						−3.125976000

With an overlay of the surfer model and the statistical representation deployed, the match between the processed and modeled data can be observed. There were also graphics created to show the behavior of each one of the considered variables [4].

Geostatistical analysis of the canyons was carried out, calculating the standard deviation for determining the arithmetic average of fluctuation of data from its mean or center point and the covariance, a joint dispersion measure of two statistics variables for each of the canyons [5]. The previous measures were used to obtain the correlation coefficient, which general result for each canyon is close to −1. For statistics purposes, an analysis is presented in order to determine the covariance and correlation coefficient for each of the channels and to obtain their respective graphics, as shown in **Table 7** and **Table 8**.

3.2. Geostatistical Analysis Using SURFER

The analysis of the statistical variables between height and gravity was obtained by applying the *Surfer* program [6]. By comparing the results of this analysis with the *Geoeas* graphics, it may be observed that the gravity process tends to approach the calculated value even as the altitude reduces (**Table 9** and **Table 10**).

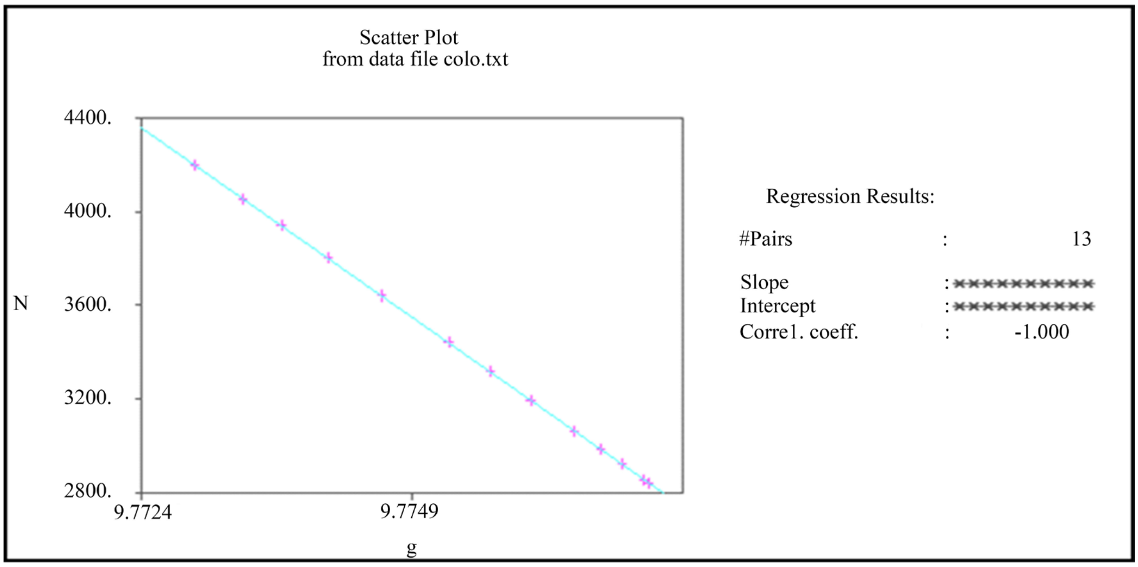
3.3. Structural Modeling Applying SURFER

The 2D and 3D structural modeling was made using *Surfer*, which was useful to identify the canyons of study and their vector behavior [7] (**Figure 5** and **Figure 6**).

The variogram is a tool that allows analysis of the spatial behavior of a variable over a defined area [8].

In the case of the canyons, the variogram of the height was created against the local calculated gravity (**Figure 7**).

Colorada Canyon



Quimichule Canyon

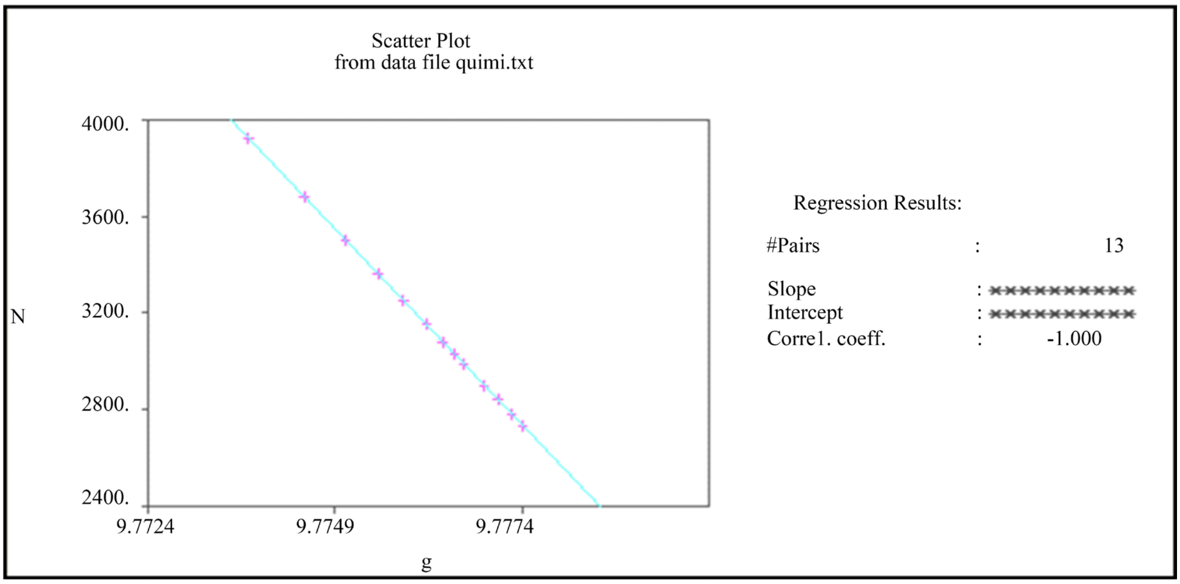


Figure 4. Correlation coefficient on the Colorada and Quimichule canyons.

3.4. Calculating the Force of Water

The force of water is the amount of thrust that this liquid exerts on the slope direction; the water density is 1 gr/cm^3 or 1000 Kg/m^3. The calculations done using the mathematical model or Equation (3) showed that the force increases proportionally to the inclination of the slope.

$$F_1 = (d * cosm)(gl) \qquad \text{Model} \qquad (3)$$

The water channel was subdivided in an equidistance of 500 m [9]; the calculations are shown in **Table 11** and **Table 12**.

3.5. Calculating the Waste

The waste is the volume of a substance, which passes per unit of time. In this case, the waste of each of the can-

Table 7. Colorada canyon.

Pto.	Altitude (m)		$\left(X_i - \bar{X}\right)^2$		Local gravity acceleration (m/s²)		$\left(Y_i - \bar{Y}\right)^2$		
1	4200	796.1538	633860.947		9.772851	−0.002458	6.0394E−06		−1.956560877
2	4055	651.1538	424001.331		9.773300	−0.002009	4.0373E−06		−1.308367578
3	3940	536.1538	287460.947		9.773655	−0.00165	2.736E−06		−0.886845767
4	3800	396.1538	156937.870		9.774088	−0.001221	1.4916E−06		−0.48382825
5	3640	236.1538	55768.639		9.774582	−0.000727	5.2901E−07		−0.171762177
6	3440	36.1538	1307.101		9.775199	−0.000110	1.2057E−08		−0.003969814
7	3315	−88.8462	7893.639		9.775585	0.000276	7.6147E−08		−0.024516798
8	3195	−208.8462	43616.716		9.775954	0.000645	4.1625E−07		−0.134741456
9	3065	−338.8462	114816.716		9.776355	0.001046	1.0945E−06		−0.354493546
10	2985	−418.8462	175432.101		9.776601	0.001292	1.6699E−06		−0.541259438
11	2920	−483.8462	234107.101		9.776801	0.001492	2.2259E−06		−0.721869941
12	2855	−548.8462	301232.101		9.777000	0.001691	2.8591E−06		−0.928044829
13	2840	−563.8462	317922.485	Standard deviation	9.777046	0.001737	3.017E−06	Standard deviation	−0.979377112
	3403.846154		211873.669	460.2973698	9.775309		2.0157E−06	0.001419758	−0.653510583
						Correlation coefficient			Covariance
						−0.999999554			

Table 8. Quimichule canyon.

Pto.	Altitude (m)		$\left(X_i - \bar{X}\right)^2$		Local gravity acceleration		$\left(Y_i - \bar{Y}\right)^2$		
1	3920	750	562500.0000		9.773706	−0.002312	5.3435E−06		−1.733698657
2	3680	510	260100.0000		9.774448	−0.001570	2.4656E−06		−0.800811723
3	3500	330	108900.0000		9.775002	−0.001016	1.0323E−06		−0.335282639
4	3360	190	36100.0000		9.775434	−0.000584	3.414E−07		−0.111015158
5	3250	80	6400.0000		9.775773	−0.000245	6.0108E−08		−0.019613542
6	3150	−20	400.0000		9.776081	0.000063	3.9834E−09		−0.00126228
7	3080	−90	8100.0000		9.776297	0.000279	7.7683E−08		−0.025084539
8	3030	−140	19600.0000		9.776451	0.000433	1.8754E−07		−0.060628639
9	2990	−180	32400.0000		9.776574	0.000556	3.0938E−07		−0.100119271
10	2900	−270	72900.0000		9.776850	0.000832	6.9193E−07		−0.224592674
11	2840	−330	108900.0000		9.777033	0.001015	1.0307E−06		−0.335033064
12	2780	−390	152100.0000		9.777216	0.001198	1.4359E−06		−0.467330943
13	2730	−440	193600.0000	Standard deviation	9.777369	0.001351	1.8247E−06	Standard deviation	−0.594357709
	3170		120153.8462	346.6321482	9.776018		1.1388E−06	0.001067156	−0.369910064
						Correlation coefficient			Covariance
						−0.999998549			

Table 9. Colorada canyon.

Univariate Statistics			
	X	Y	Z
Minimum:	2840	9.772851392	9.772851392
25%-tile:	2985	9.774087594	9.774087594
Median:	3315	9.775584855	9.775584855
75%-tile:	3800	9.776601172	9.776601172
Maximum:	4200	9.777045867	9.777045867
Midrange:	3520	9.7749486295	9.7749486295
Range:	1360	0.0041944750000003	0.0041944750000003
Interquartile Range:	815	0.0025135780000003	0.0025135780000003
Median Abs. Deviation	395	0.0012159950000008	0.0012159950000008
Mean:	3403.8461538462	9.7753089084615	9.7753089084615
Trim Mean (10%):	3382.7272727273	9.7753744137273	9.7753744137273
Standard Deviation:	460.29736979376	0.0014197582068528	0.0014197582068528
Variance:	211873.66863905	2.015713365926E−006	2.015713365926E−006
Coef. of Variation			0.00014523921649411
Coef. of Skewness			−0.34133729589633

Table 10. Quimichule canyon.

Univariate Statistics			
	X	Y	Z
Minimum:	2730	9.773706207	9.773706207
25%-tile:	2900	9.775433515	9.775433515
Median:	3080	9.776296522	9.776296522
75%-tile:	3360	9.77684963	9.77684963
Maximum:	3920	9.777638618	9.777368618
Midrange:	3325	9.7755374125	9.7755374125
Range:	1190	0.0036624110000005	0.0036624110000005
Interquartile Range:	460	0.0014161149999996	0.0014161149999996
Median Abs. Deviation	240	0.00073653499999971	0.00073653499999971
Mean:	3170	9.7760178050769	9.7760178050769
Trim Mean (10%):	3141.8181818182	9.7761051491818	9.7761051491818
Standard Deviation:	346.63214818283	0.0010671560113215	0.0010671560113215
Variance:	120153.84615385	1.1388219524997E−006	1.1388219524997E−006
Coef. of Variation			0.00010916060430734
Coef. of Skewness			−0.72181350474623

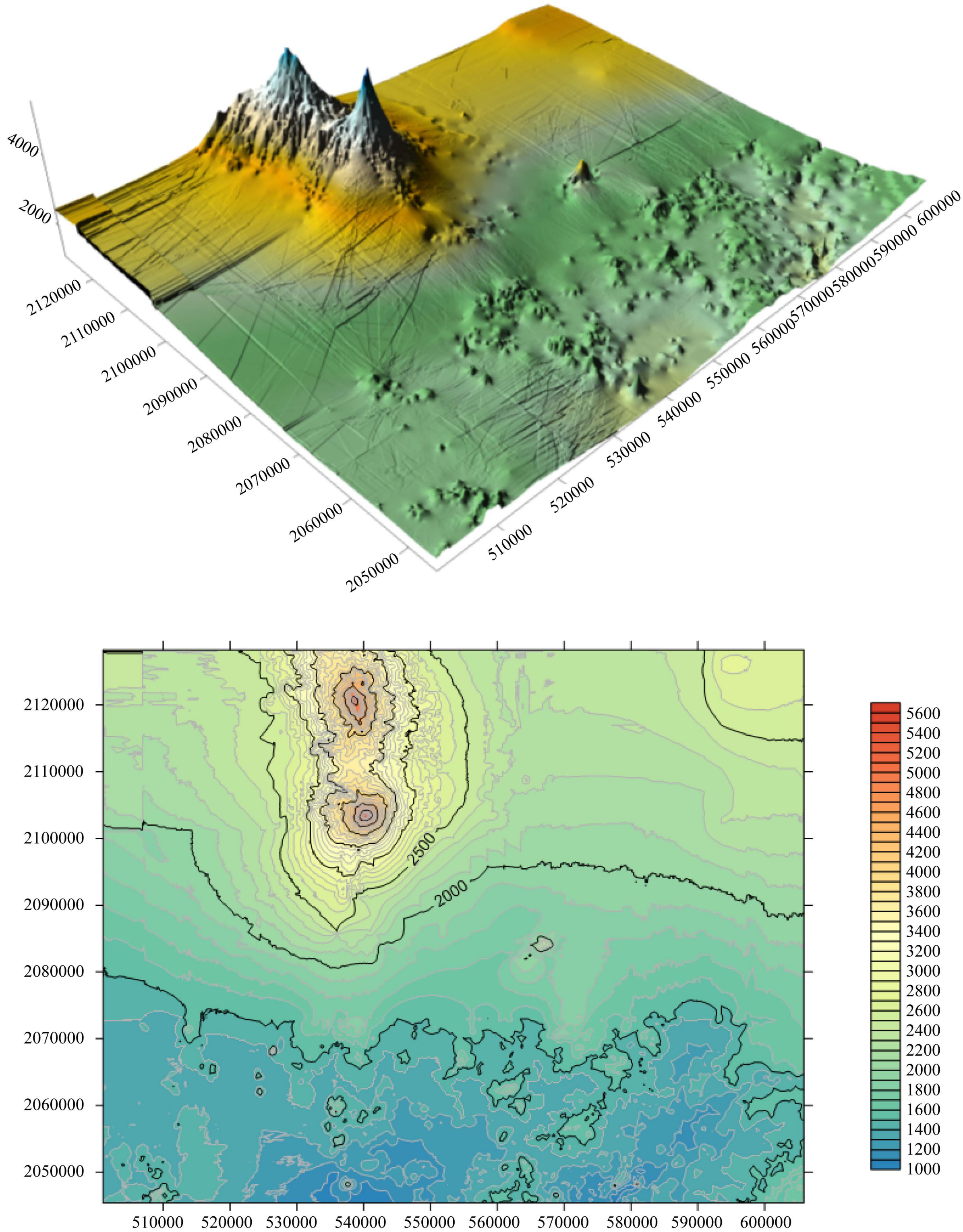


Figure 5. Identification of the canyons of study in the base map of the Popocatépetl volcano area.

yons was obtained by applying the equation of the rational method (4) (**Table 13** and **Table 14**).

$$Q = 0.278 * k * i * A \qquad \text{Model} \tag{4}$$

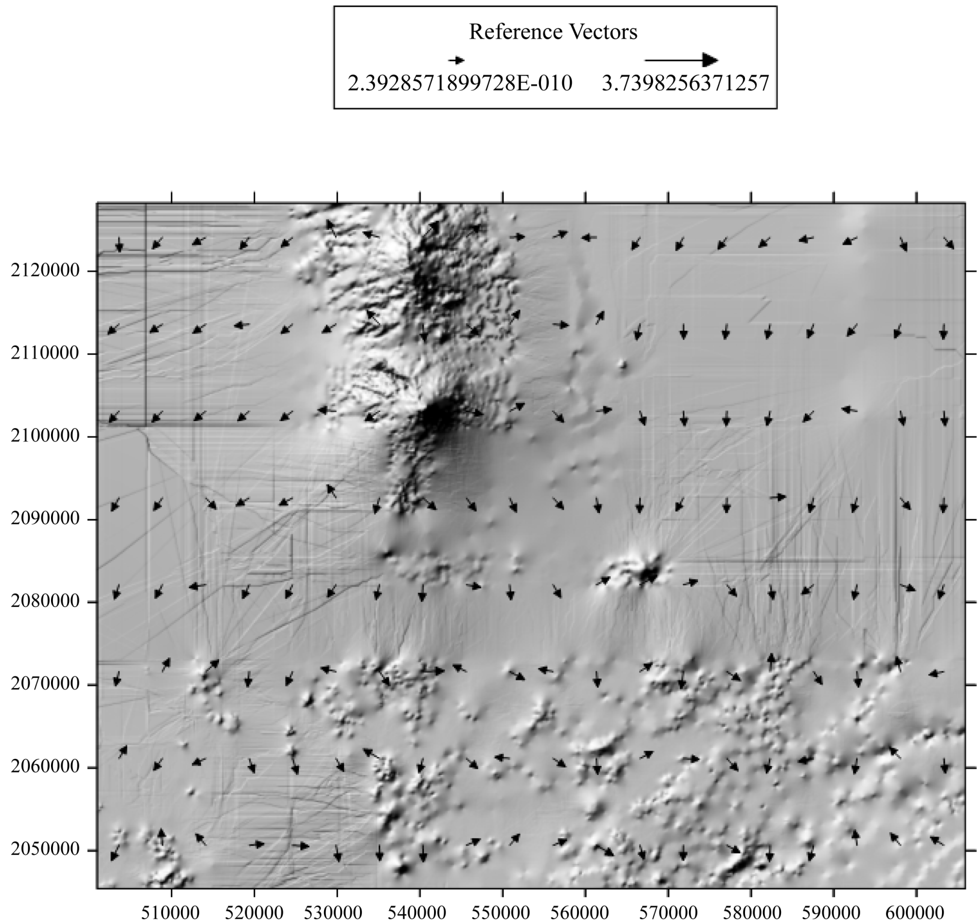


Figure 6. Vector direction of the canyons with respect of gravity.

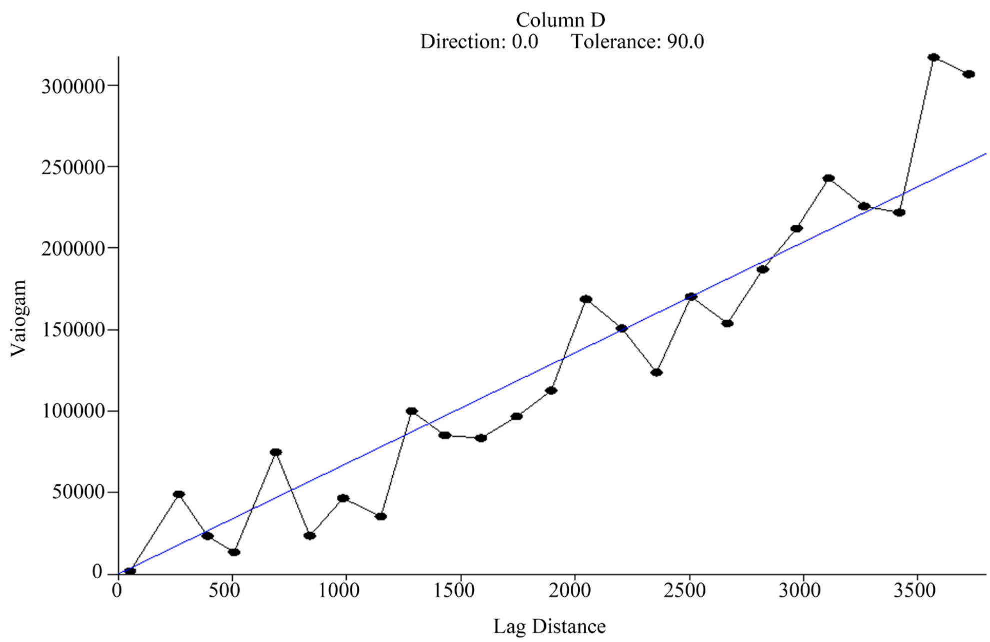


Figure 7. Variogram of the height with respect of gravity.

Table 11. Colorada canyon.

Strength calculation of water							
Pto.	Altitude	Density of water	$m = \frac{N_2 - N_1}{W_2 - W_1}$	Cosine of the slope (Cos m)	Acceleration gravity local (gl)	Partial forces	F_i = (d*cosm) (*gl*)
			Channel slope				
1	4200						$\sum F_i$ = 1173.00206330
2	4055	1000	−0.416168	0.999974	9.773300	97.730418	
3	3940	1000	−0.414141	0.999974	9.773655	97.733995	
4	3800	1000	0.398168	0.999976	9.774088	97.738516	Data
5	3640	1000	−0.114741	0.999998	9.774582	97.745620	
6	3440	1000	−0.417382	0.999973	9.775199	97.749397	12
7	3315	1000	−0.412557	0.999974	9.775585	97.753314	
8	3195	1000	−0.000042	1.000000	9.775954	97.759541	
9	3065	1000	0.000046	1.000000	9.776355	97.763551	
10	2985	1000	−0.348323	0.999982	9.776601	97.764205	$F = \sum_{i=1}^{n} F_i$
11	2920	1000	−0.417100	0.999974	9.776801	97.765418	
12	2855	1000	0.582900	0.999948	9.777000	97.764936	97.75017194 N
13	2840	1000	1.582900	0.999618	9.777046	97.733150	

Table 12. Quimichule canyon.

Strength calculation of water							
Pto.	Altitude	Density of water	$m = \frac{N_2 - N_1}{W_2 - W_1}$	Cosine of the slope (Cos m)	Acceleration gravity local (gl)	Partial forces	F_i = (d*cosm) (*gl*)
			Channel slope				
1	3920						$\sum F_i$ = 1173.08566882
2	3680	1000	−0.416168	0.999974	9.774448	97.741897	
3	3500	1000	−0.414141	0.999974	9.775002	97.747464	
4	3360	1000	0.398168	0.999976	9.775434	97.751975	Data
5	3250	1000	−0.114741	0.999998	9.775773	97.757530	
6	3150	1000	−0.417382	0.999973	9.776081	97.768215	12
7	3080	1000	−0.412557	0.999974	9.776297	97.760431	
8	3030	1000	−0.000042	1.000000	9.776451	97.764509	
9	2990	1000	0.000046	1.000000	9.776574	97.765740	
10	2900	1000	−0.348323	0.999982	9.776850	97.766690	$F = \sum_{i=1}^{n} F_i$
11	2840	1000	−0.417100	0.999974	9.777033	97.767740	
12	2780	1000	0.582900	0.999948	9.777216	97.767101	97.75713907 N
13	2730	1000	1.582900	0.999618	9.777369	97.736376	

Table 13. Colorada canyon.

Calculation of the waste		
Area of drainage basin	2835645.45	m^2
Channel length	5500	m
Permeability coefficient (*c*)	0.05	cm/s
Rainfall rate (*i*)	0.000000	m
Waste	0.000000	m^3/s

Table 14. Quimichule canyon.

Calculation of the waste		
Area of drainage basin	2990700	m^2
Channel length	6500	m
Permeability coefficient (*c*)	0.05	cm/s
Rainfall rate (*i*)	0.000000	m
Waste	0.000000	m^3/s

where:
Q = Waste in m^3/s
k = permeability coefficient
i = Hydraulic gradient
A = Capture area
0.278 = Conversion factor

4. Conclusions

First of all, it is worth mentioning that no similar analysis has been found within the literature related with research studies on the Popocatépetl volcano. This paper presents the results obtained through the processing of the cartographic data and by applying the Geoeas and Surfer programs to calculate the relation between the acceleration of local gravity, height, slope, waste and force of a substance that runs over a profile of the Colorada and Quimichule canyons.

Gravity, slope, force and waste are lower in the Colorada canyon, results validating the methods applied. The correlation coefficient between gravity and height shows that there is a perfect negative correlation, *i.e.* the higher the height, the lower the gravity.

It is given that the absolute value of the flow rate obtained in each canyon is not comparable, since the surface of the Barranca Colorada is only 54.5% of the Barranca Quimichule, and to compare it is necessary to obtain the specific flow of each (dividing its surface, which is usually given in $m^3/s*km^2$ or $l/s*km^2$).

The specific flows of each canyon would then be:

Colorada (68.528454 m^3/2.3563 s km^2) = 0.2908311 $m^3/s\ km^2$ or 290.8311 l/s km^2

Quimichule (110.050759 m^3/4.324587 s km^2) = 0.254477 $m^3/s\ km^2$ or 254.477 l/s km^2

Therefore, Quimichule canyon produces per km^2 87.5% of water that runs off the Colorada canyon, the latter being the one that would be able to produce a greater runoff. This result can be compared to the acceleration of local gravity of 9.7760 m/s^2 in Quimichule and 9.7753 m/s^2 in Colorada with the values of force of water of 97.76131777 N in Quimichule and 97.75423653 N in Colorado, with the average values of the slope of −0.166153846 in Quimichule and −0.196923077 in Colorada, revealing that the few differences of local gravity (0.0007% greater in Quimichule) have an equivalent influence over the force of water, which suggests that this is due primarily to differences in altitude that show both canyons.

However, these variables do not intervene in the calculation of the flows (Q) where the difference of the average slope or hydraulic gradient (i) determines the theoretical calculating of the flows. This same difference observed between the values of (i) is present in the values of (Q) (87.5% between Quimichule and Colorada).

The application of geostatistical models highlights the importance of applying mathematics in geomorphological analysis, presenting different graphs and comparative data analysis and structural modeling studies in geomorphological and hydrological processes that are useful to get an idea of the behavior of the water flow, mud or magma, caused by rain or activity of Popocatépetl, which could affect the communities near the canyons.

This study aims to contribute to the existing work, and its results obtained by using technological tools applied in the analysis are considered as a valuable contribution to the natural disaster prevention field. We put special emphasis on the fact that the application of different models would certainly lead to similar results.

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