MORPHOMETRIC ANALYSIS OF MICRO-WATERSHEDS IN ACHUPALLAS PARISH, SANGAY NATIONAL PARK, ECUADOR USING GIS TECHNIQUES

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Resumen

El objetivo del trabajo fue determinar los parámetros morfométricos de cuatro microcuencas de los ríos: Zula, Ozogoche, Jubal y Pulpito, en la parroquia Achupallas, Parque Nacional Sangay, Ecuador. Se utilizaron métodos cuantitativos en un Sistemas de Información Geográfica permitiendo obtener distintos parámetros morfométricos los mismos que establecen la vulnerabilidad a fenómenos como las inundaciones, erosión entre otros. Los resultados demuestran altos valores de la densidad de drenaje, tiempos de concentración de masas de agua muy reducidos, formas accidentadas de las microcuencas y curvas hipsométricas que determinaron una tendencia a ciclos erosivos inestables. En general las características morfométricas atenúan los efectos de las inundaciones. Únicamente la forma circular de las microcuencas de los ríos Zula y Ozogoche aumenta el riesgo de inundación.

Palabras claves: análisis morfométrico, curva hipsométrica, microcuencas alto andinas, inundaciones, SIG

Abstract

The research objective was to determine the morphometric parameters of four micro watersheds of Zula, Ozogoche, Jubal and Pulpito rivers in the Achupallas parish, Sangay National Park, Ecuador. Quantitative methods were used in a Geographic Information Systems allowing to obtain different morphometric parameters the same as establish the vulnerability to events such as floods, erosion among others. The results show high values of density drain, time of water mass concentration very low, accidental forms of the micro watersheds and hypsometric curves that determined a tendency to unstable erosion cycles. In general morphometric characteristics attenuate the effects of flooding. Only the circular shape of the micro watersheds of Ozogoche and Zula rivers increase the risk of flooding.

Keywords: morphometric analysis, hypsometric curve, micro-watersheds high andean, floods, GIS

Introduction

In Geology, relief and climate are the primary determinants of running water ecosystems functioning at the watershed scale (1, 2). Different workers define watershed differently. Watershed is a natural hydrological entity which allows surface run-off to a defined channel, drain, stream or river at a particular point (3). Also it represents run-off and infiltration areas where rainfall tends to be drained into rivers, lakes or into sea. The structure model of the earth is strongly influenced by watershed as the preferred directions of surface flows define the erosion mechanisms and sedimentation (4). These processes are the result of the interaction of land use, climate, geology, soil type, topography and vegetation cover (4).

Morphometric analysis provides quantitative description of the watershed geometry to understand initial slope or irregularities in the rock hardness, structural controls, recent diastrophism, geological and geomorphic history of drainage watershed (5). The evaluated parameters are classified as geometric, relief and drainage (6), the same that have wide application as indicators of vulnerability of the watershed events such as floods, erosion among others (7). Also, the characterization of a watershed is an important step towards sustainable management policies, as it currently does not have studies on the behavior of water flow and morphometric (8).

Geographical Information System (GIS) techniques are widely useful in morphometric analysis of watersheds, as they provide a powerful tool for the manipulation and analysis of spatial information particularly for the feature identification and the extraction of information for better understanding (9). In the present study, a morphometric analysis was carried out in the Achupallas micro-watersheds, Sangay National Park using GIS techniques. The objective was to analyze the influence of morphometric properties in the behavior of both the flow and flood, as these parameters can attenuate or intensify floods (10).

Study area

Achupallas is located in the southwestern part of the Sangay National Park, Chimborazo province, Ecuador (Figure 1). The study area covers an area of 1016 km^2 and it lies on Nudo de Tarqui that joins the western and eastern mountain ranges, the maximum elevation ranges from 4440 m in the Soroche Mountain to 2000 m in the Guangra zone. A statistical summary of meteorological data related to Achupallas for the period 2012-2014 indicates that the average annual temperature in the northern part of study area is 9.5°C with daily temperatures ranging between 3 - 18°C, the relative humidity is 74% and average annual rainfall is 1050.59 mm, finding diverse ecological levels from paramo to mountain cloud forests. In the southern part of the study area the average annual temperature is 8.3°C with daily temperatures ranging between 0 - 17°C, the relative humidity is 83.6% and average annual rainfall is 1762.51 mm, presenting several montane and high Andean ecosystems continuous, interrupted only by some grasses and few crops.

This area is the most isolated floristically in relation to anthropogenic activities. The climate data were taken for the northern part of the M5140 weather station and for the southern part were taken of the EMA_Jubal weather station. Paramo ecosystems have been developed essentially on pyroclastic deposits resulting from numerous volcanic eruptions, generating andosol soils with morphology and properties that vary according to the pedogenesis, such as age, chemical composition of the materials and conditions weather (11).

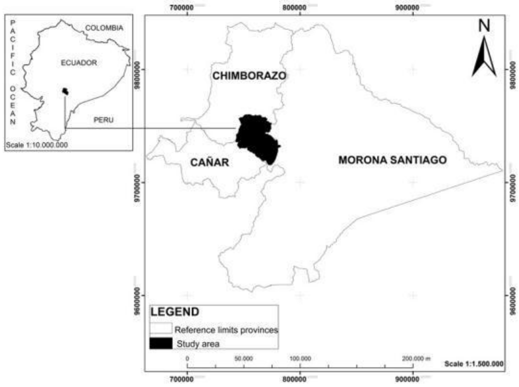

Figure 1. Study area

Methodology

Digital elevation model (DEM) with a resolution of 30 m was used to define the micro-watersheds and delineate the drainage network. The work scale was 1:50,000. The micro-watersheds boundaries were demarcated using the Hydrology tool of ArcGIS Ver. 10.1 software, on the basis of contour value, slope, relief, and drainage flow directions. The morphometric parameters considered for the analysis are summarized in detail in Tables 1 to 3. The input parameters for morphological study such as area, perimeter, elevation, stream length and others, were obtained directly in ArcGIS software. Others morphological parameters were calculated using standard methods with input values (12-15). The drainage network of the micro-watersheds was analyzed per Horton´s laws (16) and the stream ordering was made after with Strahler method (5). The drainage network of each micro-watershed was derived from DEM and it was delineated with the Stream Order tool. The hypsometric curve of the micro-watersheds was made and analyzed per Strahler method (17) and with Reclassify tool were determined the areas between the curves.

Parameter	Formula	Reference
Area (A)	Geometric calculation ArcGIS 10.1	-
Perimeter (P)	Geometric calculation ArcGIS 10.1	-
Watershed length (L)	Geometric calculation ArcGIS 10.1	-
Watershed width (W)	$W = \frac{A}{L}$	-
Form factor (Ff)	$Ff = \frac{A}{L^2}$	(Horton, 1932)
Compactness coefficient (Cc)	$Cc = \frac{P}{2\sqrt{\pi * A}}$	(Gravelius, 1914)
Circularity index (Ci)	$Ci = \frac{4 * \pi * A}{P^2}$	(Miller, 1953)
Elongation ratio (Er)	$Er = 1.128\frac{\sqrt{A}}{L}$	(Schumm, 1956)

Table 1. Geometric parameters.

Parameter	Formula	Reference
Mean height ($\hat{H}$)	$\hat{H} = \frac{\Sigma(Hi * Ai)}{A}$	-
Basin relief (Br)	H-h	-
Hypsometric integral (Hi)	$Hi = \frac{\hat{H} - h}{H - h}$	(Pike and Wilson, 1971)

H: maximum height; h: minimum height.

Table 2. Relief parameters.

Parameter	Formula	Reference
Length of main river (L_r)	Geometric calculation in ArcGIS 10.1	-
Drainage density (Dd)	$Dd = \frac{L_t}{A}$	(Horton, 1945)
Area density (Ad)	$Ad = \frac{N}{A}$	(Horton, 1945)
Sinuosity (S)	$S = \frac{L_r}{L_r'}$	(Schumm, 1963)

Lr´: Longest dimension parallel to the principal drainage line; L_t: total length of the stream segment of all orders; N: total number of stream segments of all orders.

Table 3. Drainage network parameters.

Results and Discussion

The total drainage area of Achupallas was divided into four micro-watersheds for the analysis: Zula (A), Ozogoche (B), Jubal (C) and Pulpito (D) (Figure 2.). The drainage networks of the four micro-watersheds feed three of the most important watersheds in the country. The micro-watershed of Zula River forms part of the upper area of Guayas River watershed and subsequently flows into the Pacific Ocean.

The micro-watershed of Ozogoche River, form part of the upper area of Pastaza River watershed and the micro-watersheds of Jubal and Pulpito Rivers are part of the upper area of Santiago River watershed. The last three micro-watersheds flow into Amazonas River. Jubal, Ozogoche and Pulpito micro-watersheds are within the limits of Sangay National Park, in a transition zone, where the warm and moisture currents of the Amazon converge with cold and dry currents of the Andean mountains, reason why this zone have a high level of rainfall, while Zula micro-watershed is far from this site convergence. It is characterized by the presence of cold and dry currents with low rainfall (18). The results of morphometric study are summarized in

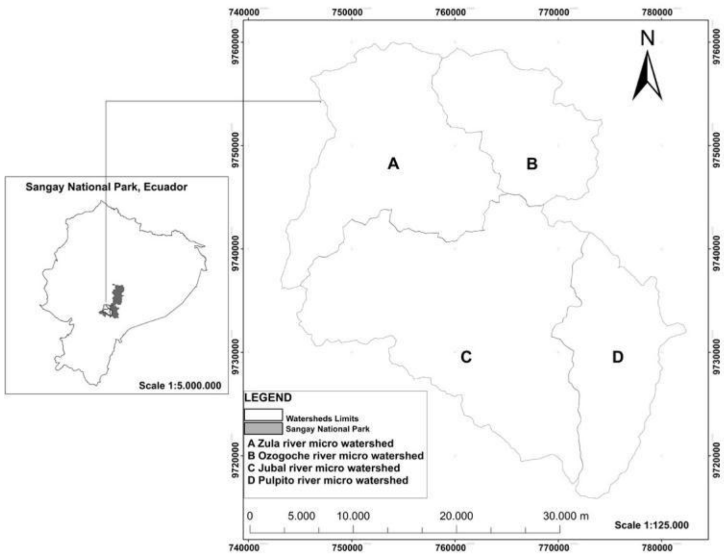

Figure 2. Ozogoche, Zula, Jubal and Pulpito Micro-watersheds inside the Sangay National Park

1 Area

The watershed area is perfectly defined by its contour and it is drained area from the division line of water or divisorium aquarium to the agreed point or mouth. The areas of each micro-watershed are shown in Table 4. Ozogoche is the smaller micro-watershed (A<150 km^2) and Jubal is bigger (A>400 km^2) than the others.

2 Perimeter

Watershed perimeter is the outer boundary of the watershed that enclosed its area (19). The perimeter of the four micro-watersheds is shown in Table 4. Jubal has the higher value (P>115 km) and coincides with the higher value of area, while the perimeter of Ozogoche is less (P<60 km) than the other micro-watersheds.

3 Basin length

The basin length corresponds to the maximum length of the watershed measured parallel to the main drainage line (20). The basin length values are shown in Table 4. Jubal and Pulpito are the longer micro-watersheds (L>20 km) while Ozogoche has the minimum value of length (L=15 km).

4 Form factor

Form factor was proposed by Horton (16) to predict the flow intensity of a watershed of a defined area. The Ff of a drainage watershed is expressed as the ratio between the area of the watershed and the squared of the basin length. The value of form factor must be always less than 0.754 for a perfectly circular watershed (19). In our case Jubal and Pulpito micro-watersheds have values of 0.39 and 0.35 respectively these are lower than 0.754 indicating them to be elongated in shape and suggesting flatter peak flow for longer duration. The Ozogoche and Zula micro-watersheds are similar to the circular shape. Flood flows in elongated watersheds are easier to manage than in the circular watersheds (10).

5 Compactness Coefficient

According to Gravelius (21), compactness coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed. When the index is closets to the unit, the watersheds has a circular shape and therefore is more compact (10). Cc increases when decreasing compactness. In our case the compactness coefficient of the four micro-watersheds is greater than 1.37 indicating that the micro-watersheds are a somewhat oval, and compactness is not high. Considering that in a circular watershed the flood wave takes more time to reach the mouth and the peak flow is more pronounced (10), Cc in our case does not intensify the flood effects, at least in the mouth.

6 Elongation Ratio

Elongation ratio was defined by Schumm (20) as the ratio between the diameter of a circle of the same area as the watershed and watershed length. The value of elongation ratio generally varies from 0.6 to 1.0 associated with a wide variety of climate and geology (3). These values can be grouped into three categories, namely circular (>0.9), oval (09-0.8) and elongated (<0.7) (19). Er values indicate that Ozogoche and Zula have circular shape while Jubal and Pulpito have elongate shape. The high elongated of micro-watersheds does not intensify the river floods (10).

7 Circularity index

The circularity index (5, 13) is expressed as the ratio of the watershed area and the area of a circle with the same perimeter as that of the watershed. Circularity index range from 0.4 to 0.5 indicates watersheds strongly elongated with homogenous geologic materials highly permeable (13). In this case, circularity index values vary between 0.38 to 0.53, indicating that the area is characterized by high relief and the drainage system is structurally controlled.

8 Mean height

The mean height is referred to sea level. This value can be found using the

Parameters	Ozogoche	Zula	Jubal	Pulpito
Area (km^2)	149.97	268.16	429.66	168.46
Perimeter (km) Watershed	59.43	93.67	119.48	71.12
length (km) Watershed	15	17.60	33.25	22
width (km) Length of	10.00	15.24	12.92	7.66
main river (km) Form	20.60	25	46.8	29.7
factor	0.67	0.87	0.39	0.35
Compactness coefficient	1.37	1.61	1.63	1.55
Circularity index	0.53	0.38	0.38	0.42
Elongation Ratio	0.92	1.05	0.70	0.67
Maximum height (km)	4.585	4.431	4.635	4.637
Minimum height (km)	3.521	2.482	1.930	1.930
Mean height (km)	4.119	3.764	3.760	3.575
Watershed Relief (km)	1.064	1.949	2.705	2.707
Coefficient of massiveness	30.64	15.68	6.30	23.19
Hypsometric integral (%)	56	66	68	61
Stream order	V	V	IV	V
Stream lenght (km)	92.94	233.18	161.27	392.91
Length of main river (km)	20.59	24.96	46.81	29.74
Drainage density (km^{-1})	0.62	0.87	0.91	0.96
Stream frecuency (km^{-2})	1.66	1.93	2.66	2.67
Sinuosity	2.18	1.89	1.32	1.40

Table 4. Results of morphometric analysis.

hypsometric curve calculating the area under the curve and dividing by the total area of the watershed (Table 2). The Ĥ of the four micro-watersheds is shown in Table 4. Ozogoche micro-watershed presents the highest value of mean height (4119 m).

9 *Basin Relief*

Basin relief is the difference in the elevation between the highest point of a watershed and the lowest point on the valley floor (22). In this study, Jubal and Pulpito micro-watersheds present values above to 2700 m of watershed relief. These values confirm the variety of altitudinal levels and the many ecosystems in the area. Since by each 500 m of basin relief is evident a variation of ecological systems presenting important variations in precipitation and temperature (23).

10 *Hypsometric curve*

Hypsometric analysis, or the relation of horizontal cross-sectional drainage watershed area to elevation, was developed in its modern dimensionless form by Langbein (24). This curve determines how the mass is distributed within a watershed from base to top (13, 20, 25). The shape of the hypsometric curve varies in early geologic stages of development of the drainage watershed, but once having attained an equilibrium, or mature stage, tends to vary little thereafter (15). Generally the curve properties tend to be stable in homogeneous rock masses and to adhere generally to the same curve family for a given geologic and climatic combination (17).

The hypsometric curves of Jubal, Pulpito and Zula micro-watersheds have convex shape (Figure 3) indicating that its territory is composed of a set of geologically young landscapes characterized by mountainous and rugged areas. Also these curves indicate that the rivers are in constant erosion of their channels, with the subsequent transport of solid material. While Ozogoche watershed is formed by less high mountains and vast plains also this micro-watershed is characterized by the presence of wetlands and marshes, being Ozogoche the most important lake system. Its rivers are in a transitory state between the young and equilibrium so the erosion is less.

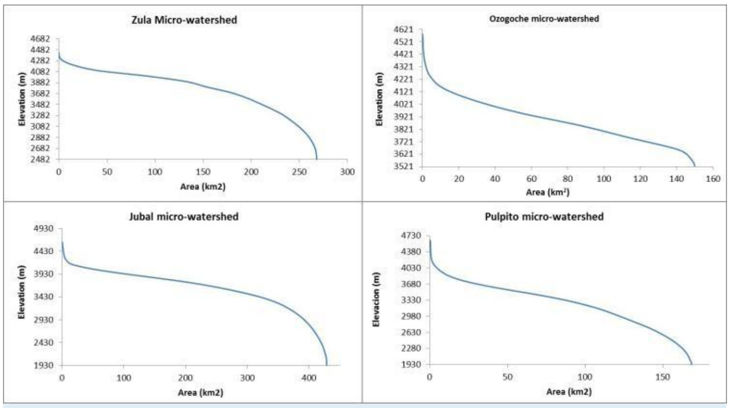

Figure 3. Hypsometric curves.

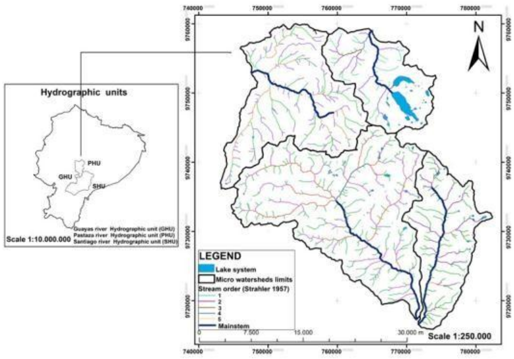

Figure 4. Hydrometric classification according the Strahler (1957) method.

11 Hypsometric integral

The hypsometric integral is a geomorphological parameter classified under the geologic stages of watershed development (26). The hypsometric integral is also an indication of the cycle of erosion (25, 27). The erosion cycle can be divided into three stages monadnock (old) (Hi ≤ 0.3), in which the watershed is fully stabilized; equilibrium or mature stage (0.3 ≤ Hi ≤ 0.6); and inequilibrium or young stage (Hi ≥ 0.6), in which the watershed is highly susceptible to erosion (25, 26, 28). In this case Zula, Jubal and Pulpito micro-watersheds present values of Hi above 60% indicating that these micro-watersheds are in inequilibrium stage and the erosion process is very high. While Ozogoche micro-watershed is finishing the young stage and approaches equilibrium because the Hi is equal to 56%. Hi values confirm the observed in the hypsometric curves.

12 Stream Order

The designation of stream order is based on hierarchic ranking of streams proposed by Strahler (5). The first order streams have no tributaries. The second order streams have only first order streams as tributaries. Similarly, third order streams have first and second order streams as tributaries and so on (3). The stream order dates (Table 5) indicate that Ozogoche, Zula and Jubal are designated as fifth order micro-watersheds having a total of 249, 517 and 1145 stream segments of different orders respectively (Figure 4). These values of stream order indicate that each micro-watershed possess a structured drainage network with perennial rivers that empty quickly the water of the constant rainfall originated in the transition zone between the paramo and Andean forest.

13 Stream Length

Stream length is the total length of streams in a particular order (3). The number of streams of various orders in the micro-watersheds were counted and their lengths measured based on the Horton´s law. Generally, the total length of stream segments is maximum in first order streams and decreases as the stream order increases (29). Deviation from its general behavior indicates that the terrain is characterized by high relief and/or moderately steep slopes, underlain by varying lithology and probable uplift across the watershed (30). In the present study only the Zula micro-watershed confirms Horton‟s second law (1945) showing a linear relationship between the stream order and the stream length (Table 5). The others three micro-watersheds present a small deviation of a straight line in superior orders.

14 Drainage Density

Drainage density is the measure of the total length of the stream segments of all orders per unit area (31). Dd is influenced by numerous factors, among which resistance to erosion of rocks, infiltration capacity of the land and climatic conditions high rank (32). The drainage density of the micro-watersheds varies between 0.62 to 0.96 km/km^2 indicating a very low drainage density. This suggests that micro-watershed soils are highly permeable and covered by thick vegetation (33).

15 Stream Frequency

Stream frequency is the total number of stream segments of all orders per unit area (12). For the present study stream frequency is low varying between 1.66 and 2.67. This indicates a relatively low run-off. Table 4 shows close correlation with the drainage density values of four micro-watersheds indicating the increase in streams population with respect to increase in drainage density.

16 Sinuosity

Sinuosity has been defined as the ratio of channel length to down valley distance (34). In general, its value varies from 1 to 4 or more. Rivers with a sinuosity of 1.5 are called sinuous, and above 1.5 are called meandering (35). Values of Ozogoche and Zula micro-watersheds are above to 1.5 indicating that these rivers are meandering and other two are sinuous because the values are less 1.5.

Micro-watersheds	Stream Order						Stream length (km)					
	I	II	III	IV	V	Total	I	II	III	IV	V	Total
Ozogoche	135	49	13	48	4	249	42.6	29.4	7.79	12.4	0.78	92.94
Zula	282	107	93	31	4	517	101	73.2	39	16.5	4.05	233.18
Jubal	555	282	200	24	84	1145	190	99.8	68.7	9.08	25.02	392.91
Pulpito	225	126	21	77	-	449	85.3	47.5	5.69	22.8	-	161.27

Table 5. Stream order and stream length.

Conclusions

Fluvial morphometric analysis using geospatial tools derives quantitative information on the geometry of the watersheds in less time and cost, this information can be correlated with hydrological data for appropriate management of them.

The relief parameters and hypsometric curves of Zula, Jubal and Pulpito micro-watersheds defined mountainous areas with high altitudinal gradient and rivers in continued erosion by natural or anthropogenic effects. Also these micro-watersheds have landscapes geologically young that after long time they will reach equilibrium increasing the inter-Andean plains.

While hypsometric curve of the Ozogoche watershed indicates that its territory is in a transitory state between the young stage and the equilibrium. Its relief is formed by less high mountains and vast plains, also, this micro-watershed is characterized by the presence of wetlands and marshes, being Ozogoche the most important lake system. The shape parameters also reveal the elongation of the Jubal and Pulpito micro-watersheds and the almost circular shape of the Zula and Ozogoche micro-watersheds. Due to this characteristic, the two first micro-watersheds will have flows flood longer lasting but smaller peak flows compared to Zula and Ozogoche micro-watersheds that present higher risk of flood by the most pronounced peak flows.

The drainage density indicates a wide vegetation cover and hard lithology, also high infiltration rates that feed the underground flow favoring the increase of concentration time and peak flow decrease.

In general we can conclude that the morphometric characteristics not increase rather attenuate the effects and vigor of floods. Only the circular shape of Zula and Ozogoche micro-watersheds can increase the flood risk.

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