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Morphometric analysis of basins located in the piedmont of central western Argentina

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Abstract

Morphometric characteristics are quantitative indicators of basin elements, which influence the magnitude and variability of hydrological processes. The main objective of this work is to determine morphometric parameters related to the geometry, relief and drainage network of 34 subbasins located in the WEST of Mendoza capital city (Argentina), between parallels 32° 55' and 32° 58' S and meridians 68° 53' and 69° 05' W. This information will allow understanding and characterize the hydrological processes in the eastern slope of the Precordillera, Piedmont and Mogotes low hills range.

Based on previous cartography, a base map was made, where basins were delimited, riverbed and level curves were digitized and the dimensions of basins and hypsometric bands were subsequently determined. In this way, the basic information was obtained from the calculation of the shape indexes, hypsometric curve, height and mean slope, network parameters and Horton's laws. A Geographical Information System (GIS) has been used for the delineation and calculation of the morphometric parameters of the basins, using free software GvSIG.

Keywords: morphometric parameters; basins; piedmont; geographic information system (GIS)

Resumen

Análisis morfométrico de las cuencas localizadas en el piedemonte del centro occidental de Argentina

Las características morfométricas son indicadores cuantitativos de los elementos de la cuenca que, de una manera u otra, influyen en la magnitud y variabilidad de los procesos hidrológicos. El objetivo principal de este trabajo es determinar los parámetros morfométricos relacionados con la geometría, relieve y red de drenaje de 34 subcuencas localizadas al oeste de la ciudad de Mendoza, entre los paralelos 32° 55' y 32° 58' S y los meridianos 68° 53' y 69° 05' W. Esta información permitirá comprender y caracterizar los procesos hidrológicos en el faldeo oriental de la Precordillera, el piedemonte y la Cerrillada de Mogotes.

En base a la cartografía existente se elaboró un mapa base, donde se delimitaron cuencas, luego se digitalizaron cauces y curvas de nivel y posteriormente se determinaron las dimensiones de las cuencas y fajas hipsométricas, obteniendo así la información básica para el cálculo de los índices de forma, curva hipsométrica, altura y pendiente media, parámetros de la red y leyes de Horton.

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Todo este proceso fue realizado en base a un sistema de información geográfica (SIG) generado mediante software libre, GvSIG, programa de origen valenciano desarrollado a través de la Consejería de Infraestructuras y Transporte.

Palabras claves: parámetros morfométricos; cuencas; piedemonte; sistema de información geográfica (SIG)

1. Introduction

The Metropolitan Area known as "Gran Mendoza" is located in the central west of the Mendoza province, in the area of contact with the non-irrigated foothills of the Precordillera (Vich & Pedrani, 1993a). The watersheds situated west of "Gran Mendoza" provide a range of ecological goods and services, among which the regulation of the surface water flows. The nearby urban settlement, with more than one million inhabitants, submits this environment to a process of accelerated deterioration, caused by different activities or uses.

Human pressure, on the natural environment, manifests itself in various ways such as: open dumps with imprecise boundaries, aggregate quarries, unplanned human settlements, clearing of bush species; overgrazing, wildfires, and recreational activities (Vich et al., 2012).

The lack of knowledge of hydro-environmental relations and the high demand for land for urbanization has led to the use of new marginal lands, accelerating the process of degradation and increasing the risk of flash flooding in the metropolitan area. As occurred in the 1970s when heavy rains in the piedmont area originated flash floods that caused countless socioeconomic damages (Vich et al., 2014).

The assessment of the physical and morphometric characteristics is important in studying the water regime of a basin (Gregory & Walling, 1973; 1979). Morphometric characterization of the watershed, located on the west of Gran Mendoza, is the first step in finding the relations between them and the climatic and geological conditions that determine their evolution. In this work, authors estimated the morphometric parameters related to the geometry, relief and drainage network. To analyze, compare and characterize 34 sub-basins of the San Isidro, Papagayos, Frías, Maure and minor basins of the arid piedmont of Precordillera, located west of the city of Mendoza (Argentina).

A Geographical Information System (GIS) has been used for the delineation and calculation of the morphometric parameters of the basins, using free software GvSIG. GIS techniques provide a powerful proven tool for manipulation and analysis of spatial information and morphometric analysis of drainage basin, particularly for the future identification and extraction of the information for better understanding (Vijith & Satheesh 2006).

Our results will provide useful information to policy makers, managers and environmentalists of the territory in the design of their programs and activities, to mitigate flooding and risks that may affect the population.

2. Study Area

2.1. Location

The basins under study extend between the mountain ranges (Cordón de la Peñas and Cordón de los Manantiales) to the north, and the Mendoza river to the south. To the west, they border with the watershed of the Precordillera (Uspallata hills), and to the east with the urbanized area of Greater Mendoza and crops of the eastern plain.

The total area is approximately 800 km^2 and develops between parallels 32° 55' S and 32° 58' S and meridians 68° 53' W and 69° 05' W. It is constituted by the eastern slope of the Precordillera Piedmont and Mogotes hills range, where the main channels drain in west-east direction depression.

The Piedmont topographically connects the mountainous area with the plain. The heights vary from 1300-1600 (masl) to 800 (masl), reaching the urbanized area. Moreover, hill Mogotes is a mountain range of low height, 1200 m of average height (1550 m maximum height) separates the torrential alluvial basins of the peri-urban and urban area. The eastern slope of the mountain range is an inclined plane covered with debris, alluvial cones and landslides that intersect the urbanized area (Vich & Pedrani, 1993). The main channels are generally intercepted by dikes and surpluses are driven by means of natural and artificial channels through the urbanized zone until its main collector, the Cacique Guaymallén channel.

Basins that integrate the alluvial area upstream of the protection works (Figure 1) are, from north to south:

San Isidro basin (SIS). The largest of the alluvial basins: 145.7 km^2. Its main streams, rivers San Isidro and Casa de Piedra, flow into the homonymous dam. Its relief is very steep: its maximum height is in the Chimenea Mountain (approximately 3100 masl) and the minimum height is around 1100 masl.

Papagayos basin (PAP). Its area is about 56.8 km^2. Its maximum height is reached in the Pajarito Mountain (2795 masl) and the minimum height is around the 980 masl. The main channel drains into the homonymous dam. When arriving at the urban area, the channel changes its denomination to Los Ciruelos, until its arrival to the Cacique Guaymallén channel.

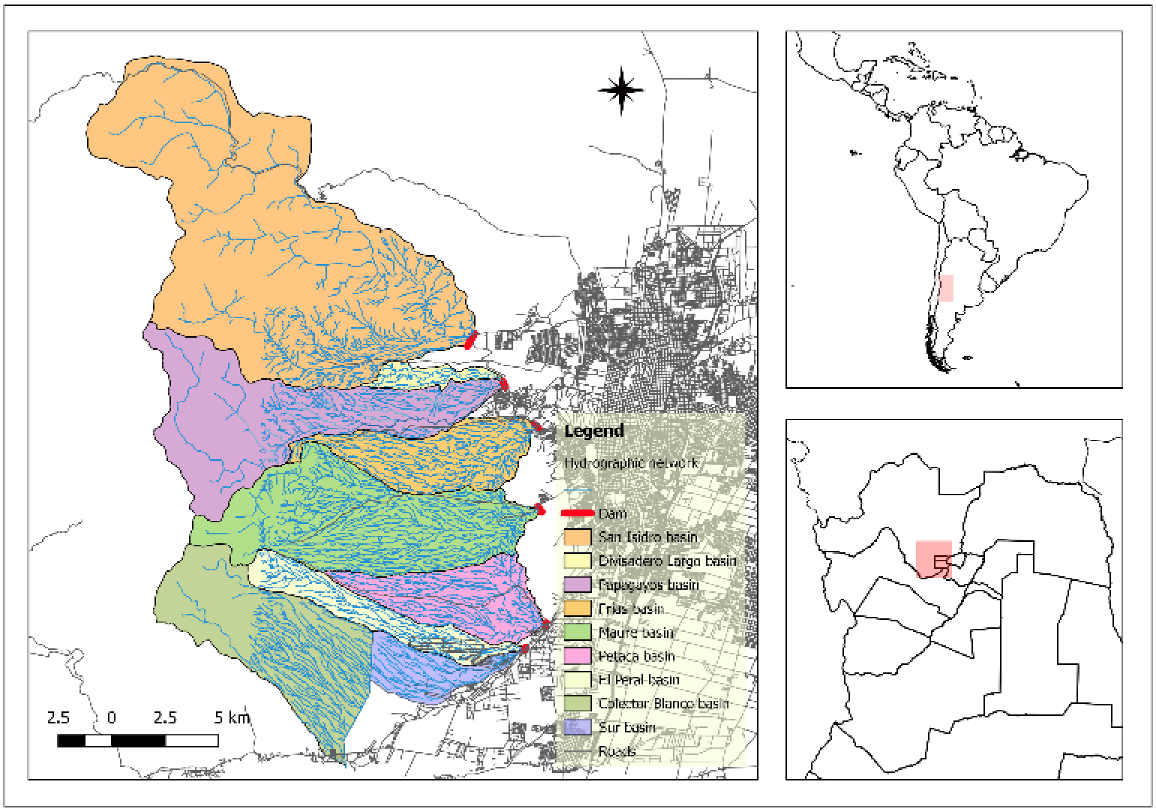
Frías basin (FRI). Its area is 24.5 km^2. Its maximum height is the Bayo Mountain (1527 masl) while the minimum is around the 930 masl. The main stream flows into the Frías dam; from this point it flows through the city of Mendoza and flows into the Cacique Guaymallén channel.

Maure basin (MAU). The basin area is 56.0 km^2 and its height ranges are between 1900 and 950 masl. The main channel drains into the homonymous dam, where the Maure channel begins. The channel runs through the city of Godoy Cruz (Mendoza) and flows into the Cacique Guaymallén channel.

Cerro Petaca basin (PET). It has an area of 22.9 km^2 and does not have a defined main channel. Water surpluses are concentrated in the Tejo collector. The maximum height is in the Cerrillada Pedemontana hills, at the Puntudo Mountain (1477 masl); the minimum height is about 1000 meters.

El Peral basin (EPE). It drains into the Sosa collector and its basin presents an extension of 17.2 km^2. Its heights range are between 2600 and 900 masl.

Figure 1: Main basins and sub-basins of order 5 in the alluvial area of Gran Mendoza, Argentina.



Source: compiled from official maps of the National Geographic Institute.

South basin. In the southern sector of the alluvial area the drainage network is sub parallel and often divergent, which makes it very difficult to identify a well- defined main channel. In the southwest sector, the streams flow directly into the Mendoza River. In the remaining area, the collector construction modified the surface runoff and determined the formation of two sub-basins: to the east, the runoff is concentrated in the Chacras de Coria (CA) collectors (12.9 km^2); to the west (46.1 km^2), water surpluses are intercepted by the Escudo collector and taken to the Mendoza River (CBE).

Papagayos (PAP), Frías (FRI) and Maure (MAU) basins are those of greatest socio-economic importance since they affect areas with the highest population density and commercial and/or industrial concentration.

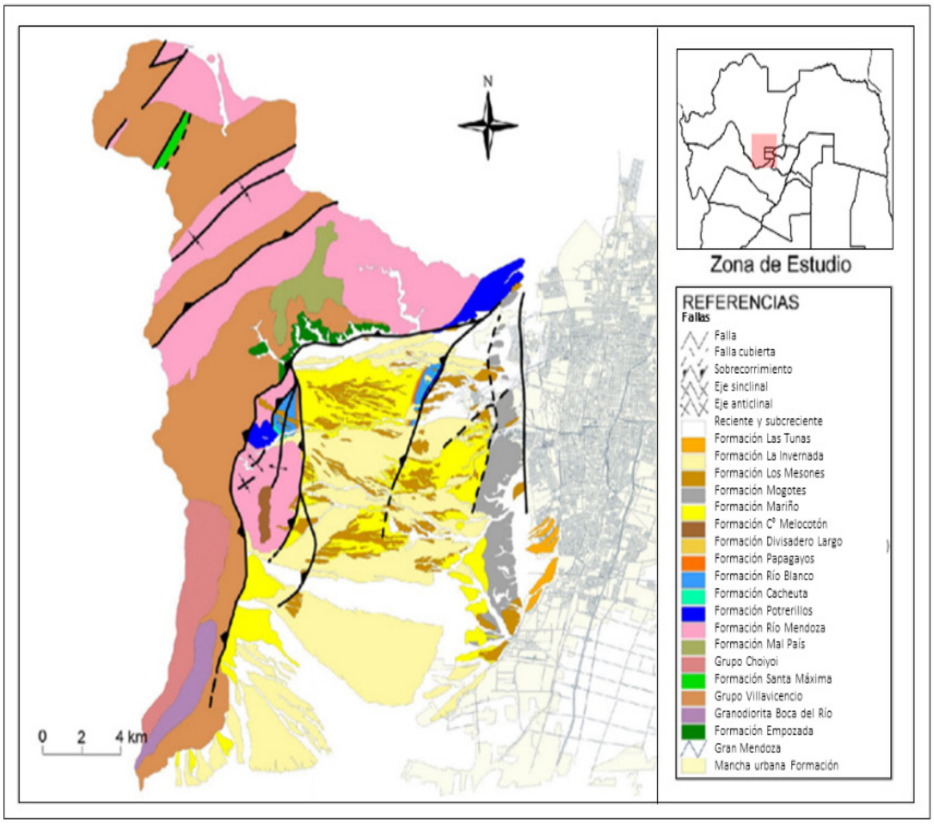
2.2. Regional geological outline

The Mendoza piedmont is located within the northern sector of the morph-structural domain called Cerrilladas Pedemontanas (Polanski, 1963). This domain is located to the east of the Precordillera, consisting of hills below 2000 masl in height, separated by depressions. To the east these hills lower their altitude to elevations near 1000 masl, west of the city of Mendoza (Moreiras, 2010). The Mariño Formation is the oldest geological unit outcrops in the area, consisting of levels of sandstones and fluvial conglomerates of Miocene age. The Invernada and Los Mesones Formations overlie it (Polanski, 1963).

Los Mesones formation consists on a coarse of clastic sediments deposited in piedmont slopes during the Early Pleistocene, between 0.7 and 2 million years ago (Inpres, 1995). The Invernada formation consists on alluvial levels of middle to late Pleistocene age. The most modern Quaternary deposits (alluvial systems) with clasts derived exclusively from Precordillera, have remained to date associated with debris flows. The outcropping formations in the area are shown in Figure 2 (Sepúlveda, 2010).

The geographic conditions of the city of Mendoza, determine its high vulnerability to violent and sudden natural geological processes which have triggered natural disasters causing great economic losses for the region. Natural processes with the greatest impact in the city of Mendoza are debris flows from the foothills, known as aluviones, and medium to high magnitude earthquakes, whose epicenters are associated with active quaternary faults (Ramos, 1996).

Figure 2: Geologic figure of the study area.



Source: Vich et al. Sepúlveda E. Chapter: Geology of the Mendoza piedmont.

2.3. Climate

The highest precipitation period is during the summer. This area receives air masses with enough moisture to generate important precipitations, in the form of isolated thunderstorms from the Atlantic Ocean only. Occasionally, under very particular conditions, a system from the Pacific Ocean can cause major rainfall in winter (Marzo & Inchauspe, 1967).

At this time of year, they generally occur in the form of drizzles and are generated by maritime advection of the southeast from the Atlantic Ocean. Rainfall decreases towards SW to NE, from 400 mm to 130 mm annually (Fernández, 2010). There is no definite trend in precipitation during the last three decades of the twentieth century, while the average number of p recipitation days seems to have declined over the decades (Norte & Simonelli, 2010).

According to the Köppen-Geiger climate classification system, the two meteorological stations in the study area (Mendoza Aero -32.50° S, 68.47° W- and Mendoza Observatory -32.53° S y 68.51° W-) have a BWakw climate type, i.e., dry (B), desert (BW), mean temperature of the warmest month above 22° C (a), mean annual temperature below 18°C, temperature of the warmest month above 18° C (k) and dry winter: precipitation during the driest month is less than a third of the rainfall in the wettest month (w) (Norte & Simonelli, 2010).

2.4. Vegetation

The study area extends over two large landscape units: Sierra de Uspallata and Piedmont, each with its own communities and plant associations. The Sierra de Uspallata hills encounter the grass associations of the *Stipa genus*, the saxic vegetation of *Hyalis argentea var. argentea* and the riparian thickets. In the Piedmonts communities of *Larrea divaricata*; scrubs with *Larrea cuneifolia* and *Zuccagnia punctata* in solanas, riparian thickets of *Acacia furcatispina*, communities of springs with *Cortaderia rudiuscula* and lithomorphic vegetation with *Cercidium praecox* exist. From a phyto-geographical approach, vegetation corresponds to the Monte Province, the Andean Piedmont district, with two sub-districts: *Fabiana denudata* and *Larrea divaricata* sub-district and *Larrea cuneifolia* and *Lycium tenuispinosum* sub-district (Roig, 1976). The average plant cover is 50%. It reaches its best expression on quaternary deposits or on sites with accumulation of eroded material, with greater depth of soil.

3. Methodology

3.1. Base map

A Geographical Information System (GIS) has been used for the delineation and calculation of the morphometric parameters of the basins, using free software GvSIG.

Based on previous cartography, a digital base map of the study area was elaborated. Topographical charts at 1:50,000 scale produced by Instituto Geográfico Militar (IGM) in 1950 and updated in 1970 were used, as well as charts derived from aerial photogrammetric restitution, developed in 1970 by Spartan Air Service, which cover more than two-thirds of the area.

Geo-referencing and assembling of the various scales and topographical charts were performed. Subsequently, the different basins were delimited with a closing point in the existing alluvial defense dams, and researchers proceeded to the contour lines vectorization every 25 m.

3.2. Morphometric characteristics. Elementary concepts

Morphometric characteristics are quantitative indicators of basin elements that influence the magnitude and variability of hydrological processes in different ways. They are a quantitative basis for predicting basin response based on some easily calculated parameters.

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The basins named above and their sub-basins of order 5 were delimited, resulting in a sample of 34 sub-basins. In each of them, the parameters, grouped into three categories, were calculated: a) parameters related to the geometry of the basin, such as extent, dimensions and shape indexes; b) parameters related to the distribution of elevations and slopes; and c) parameters linked to the drainage network, among which are: stream length, stream order, drainage density. The determined morphometric parameters are shown in Table 1.

Table 1: Morphometric parameters

PARAMETERS	METHODS	REFERENCES / COMPONENTS	UNITS
Area (Au)	Direct measurement	--	km^2
Perimeter (Pu)	Direct measurement	--	Km
Axial length (L)	Direct measurement	--	Km
Mean width (W)	$W = A_u/L$	--	Km
Compactness factor (KC)	$K_C = 0.28\, P_u/\sqrt{A_u}$	Gravelius, 1914	Dimensionless
Circularity ratio (C)	$C = (4\pi A_u)/P_u^2$	Miller, 1953	Dimensionless
Elongation ratio (E)	$E = \sqrt{1.27\, A_u}/L$	Schumm, 1956	Dimensionless
Form factor (Ff)	$F_f = W/L$	Horton, 1945	Dimensionless
Maximum elevation (CM)	Direct measurement	--	Masl
Minimum elevation (Cm)	Direct measurement	--	Masl
Basin relief (ΔH)	$\Delta H = CM - Cm$	--	M
Mean elevation (Hm)	$Hm = \sum_{i=1}^{N}(hm_i \cdot A_i)/A$	N is number of hypsometric bands; hmi is mean height of i-th band; Ai is extent of i-th band; Au is total area of basin.	M
Mean slope (Ic)	$Ic = \sum_{i=1}^{N}(h_i \cdot l_i)/A_u$	N is number of hypsometric bands; hi is elevation difference of i-th band; li is mean length of contour lines that limit the i-th band; Au is total area of basin.	%
Massivity coefficient (CMa)	$CMa = Hm/A_u$	--	m·km^{-2}
Orographic coefficient (CO)	$CO = CMa \cdot Hm$	--	Dimensionless
Stralher set (N_k^S)	$N_k^S\,(N_1, \ldots, N_u, \ldots, N_k)$	Nu Number of stream segments of order u; k highest stream order in the basin.	Dimensionless
Bifurcation ratio (RB)	$R_B = N_{u-1}/N_u$		Dimensionless
Length ratio (RL)	$R_L = \bar{L}_u/\bar{L}_{u-1}$	$\bar{L}_u$ is mean length of u order streams.	Dimensionless
Drainage density (Dd)	$D_d = L_t/A_u$	Lt is total stream-segment lengths cumulated for all orders, u=1 to u=k.	km·km^{-2}
Constant of Channel Maintenance (Ck)	$C_k = 1/D_d$	--	km^2·km^{-1}
Average length of overland flow (LES)	$L_{ES} = 1/(2D_d)$	--	M
Stream frequency (F)	$F = No/A_u$	No is the total number of stream segments of all orders, u=1 to u=k.	No*m^{-2}

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3.3. Basin shape and geometry

The basin geometry is characterized by variables measured directly from the digital base map and others elaborated from the previous ones.

In the first group are: total Au of basin, Pu and L. L is expressed as the distance from the outlet to the most remote point on the basin. In the second group are: mean width (W) and shape indexes, such as: KC, C, E and Ff. In general, the defined indexes (except for the Ff), measure the degree of analogy between the shape of the basin and a hypothetical basin of circular configuration.

3.4. Relief parameters

Analysis of relief in a river basin (height and slope) is a key aspect in hydrological studies due to its strong influence on surface runoff, infiltration and water erosion phenomena; the topographical configuration is closely related to the phenomena that occur on its surface. Many parameters describing the relief of a river basin have been developed. Some of the most useful are: extreme heights, hypsometric curve, mean height, mean slope and relief coefficients.

The difference between the CM and the Cm (closing point) of the basin is the power of the relief or Basin relief ΔH. The hypsometric curve or area-elevation curve relates the area of the basin, measured in the projection on a horizontal plane, and the height above a reference level defined by the height of the closing point of the basin. It is generally expressed in dimensionless terms to allow comparison with other basins. For its construction hypsometric bands are delimited, which are portions of the basin bounded by two consecutive contour lines. Subsequently, the accumulated area of the bands (abscissa) and the elevation of each of the bands (ordinates) are taken to a coordinate system. For this study bands of 25m and 100m in elevation difference were used, depending on the available information, with a number always greater than 6.

Based on the hypsometric analysis, the erosion cycle and the geologic stage of development of the basin can be determined. It allows for classification of the relief, into three types: no equilibrium (young) stage, when the relative area lying below the dimensionless hypsometric curve, which represents the volume of relief, is greater than 60%; equilibrium (mature) stage, if this area is between 35% and 50% and a residual relief with an area less than 35% (Strahler, 1957, as cited in Eagleson, 1974; as cited in Hilton, 1979); and monadnock phase. If the curve has a steep slope at the origin, it indicates plains or pen plains to lower levels and risk of flooding in large areas of the lower part of the basin. A steep slope in the middle of the curve indicates a large plateau (López-Cadena de Llano & Pérez-Soba, 1983).

Other parameters analyzed in this study, which allow characterizing the relief and comparing water erosion and degradation phenomena of basins are: Mean elevation Hm, obtained from the ratio between the relief volume and the extent of the basin, measured in relation to a horizontal plane passing through the closing point (Gutiérrez-Hernández & Gonzales-Piedra, 1986); Mean slope Ic, weighted average of the slopes of the elemental surfaces that make up the basin (Heras, 1972; 1976); CMa and Co (Martonne, 1940), which result from combining the mean elevation of the basin and its extent.

The CMa is an indicator of the slope of the hypsometric curve, which in turn is a kind of longitudinal profile of the basin. It varies between 11 and 256; it has high values for watersheds with large slopes and small values for low relief basins.

It also allows differentiating those basins with similar mean elevation Hm. Co, dimensionless, measures the relationship between the forces forming the geoforms and effectively characterizes the relief. If Co is greater than 6, the relief is rugged. Whereas, if Co is less than 6 the relief is slightly rugged. This coefficient has been widely used to define relief as a factor of water erosion and in studies of basin degradation (Fournier, 1960), since it establishes conditions of dynamic similarity between hydrographic systems.

3.5. Drainage network parameters

The different runoff (surface, subsurface and underground) tends to achieve an orderly spatial association, reflected in a set of channels where water drains periodically or continuously. This is the so-called drainage network. On it, each part is related to another with a certain degree of integration and hierarchy (Popolizio, 1975). I.e. a drainage network is a dynamic structure, capable of connecting the different subareas that make up a water basin to each other. In order to determine the characteristics of the drainage network, it is necessary to define a hierarchy or ordering of its different channels.

Later, the well-known Horton's laws (Horton, 1945) of composition of the drainage are established: Law of stream numbers and Law of stream lengths. They state that the number and mean lengths of stream segments of each of the successive orders of a basin tend to approximate a direct geometric sequence; they allow establishing interrelations between the drainage network and the hydrological response of the basin. The RB will not be precisely the same from one order to the next, because of chance variations in watershed geometry, but will tend to be a constant throughout the series; length ratio RL tends to be constant throughout the successive orders of a watershed (Strahler, 1975).

Finally, the attributes are determined, such as: Dd, index that quantifies the degree of development of a hydrographic network and F. Dd is simply the ratio of total channel-segment lengths (intermittent and permanent) cumulated for all orders within a basin to the basin area (Horton, 1945). It tends to be minimal in arid environments of flat relief and permeable soils; it is highest in humid regions with steep slopes, fine-grained soils with rocky outcrops. Also high Dd values generally reflect easily erodible or relatively impermeable soils with steep slopes and low plant cover. The higher Dd, the faster the basin responds to a storm, evacuating excess runoff in less time. The classification considered is: coarse Dd<5.0 km·km-2; medium 5.0<Dd<10.0 km·km-2; fine 10.0<Dd<15.0 km·km-2; ultrafine Dd>15.0 km·km-2 (Smith, 1950; Strahler, 1957; as cited in Gregory & Walling, 1973).

Forming a channel depends on the combination of numerous climatic, topographical, biological, geological and hydrodynamic factors. From Dd it is possible to find the minimum area required to sustain one length unit of channel, called Constant of Channel Maintenance Ck (Schumm, 1956, as cited in Strahler, 1964). Ck value also indicates the distance needed to reach critical erosion velocity, from which the formation of a channel begins.

LES is defined as the average maximum distance from locations in the watershed to the nearest flow concentration. F is another parameter indicative of the degree of drainage of the basin and is defined as the number of stream segments of any order per unit area. The following classification is considered: coarse F<30 nº·km-2; medium 31<F<60 nº·km-2; fine 61<F<90 nº·km-2; ultrafine F>91 nº·km-2 (Smith, 1950; Strahler, 1957; as cited in Gregory & Walling, 1973). This parameter is independent of Dd since a high number of channels do not imply that they have a greater or lesser length (Melton, 1958).

The scheme proposed by Strahler (1952, as cited in Strahler, 1964) is the most used currently for the hierarchy of the channels that make up the drainage network, due to its simplicity and because it does not consider subjective aspects. Its major limitation is that the order of the basin and its streams depends on the scale of the map used. The Strahler stream-order system is a topological characterization, so a change in the order of a channel does not imply changes in physical or hydrodynamic characteristics (such as width and shape) at that point.

All indexes used to characterize the drainage network are very sensitive to the base map scale used.

4. Results and discussion

4.1. Basin shape and geometry

Seventy-one percent of the 34 basins analyzed had an area of less than 9.0 km^2, with their minimum and maximum values being 1.59 km^2 and 88.37 km^2, respectively. Their perimeters vary between 7.2 km and 49.5 km. While the correlation coefficient between area and perimeter is high (0.818), the linear functional relationship is non-existent from the physical point of view.

The basin can be geometrically represented by a rectangle of major side, equivalent to the axial length L and minor side equal to mean width W, with closing point at the right end of the minor side. The Ff represents the number of times that W is contained in L and is a measure of its elongation. 89% of basins have an Ff greater than 3 and 21% greater than 10, indicating a significant elongation in the direction of runoff. This situation has an important effect on the crushing and delay of the peaks of the flood hydrographs. These results are shown in Table 2.

Table 2: Geometry and basin shape parameters.

Basin	Area A_u [km^2]	Perimeter P_u [km]	Basin length L [km]	Mean width W [km]	Shape parameters (dimensionless)			
					K_C	C	E	F_f
SIS1	88.37	49.5	17.4	5.1	1.48	0.45	0.79	0.29
SIS2	3.58	9.4	3.6	1.0	1.4	0.51	0.65	0.28
SIS3	25.05	27.3	9.8	2.5	1.53	0.42	0.61	0.26
SIS4	6.12	11.8	4.9	1.3	1.33	0.55	0.61	0.26
SIS5	4.71	11.5	4.9	1.0	1.48	0.45	0.61	0.19
SIS6	2.04	7.9	3.3	0.6	1.55	0.41	0.61	0.18
SIS7	1.59	7.2	3.0	0.5	1.59	0.39	0.59	0.17
SIS8	21.16	14.9	6.6	3.2	0.91	1.19	0.57	0.49
PAP1	40.55	35.0	11	3.7	1.54	0.41	0.57	0.33
PAP2	2.89	11.1	4.7	0.6	1.83	0.29	0.56	0.13
PAP3	6.07	15.7	6.8	0.9	1.78	0.31	0.54	0.13
DL	4.97	16.3	6.8	0.7	2.05	0.23	0.51	0.11

Basin	Area A_u [km^2]	Perimeter P_u [km]	Basin length L [km]	Mean width W [km]	Shape parameters (dimensionless)			
					K_C	C	E	F_f
FRI1	4.97	11.6	5.0	1.0	1.46	0.46	0.5	0.20
FRI2	3.78	18.9	8.9	0.4	2.72	0.13	0.5	0.05
FRI3	7.12	23.0	9.7	0.7	2.41	0.17	0.48	0.08
FRI4	6.44	23.7	9.5	0.7	2.61	0.14	0.47	0.07
MAU1	7.72	21.0	9.4	0.8	2.11	0.22	0.47	0.09
MAU2	8.23	16.4	6.4	1.3	1.60	0.39	0.46	0.20
MAU3	4.75	11.4	4.6	1.0	1.46	0.46	0.42	0.23
MAU4	13.39	30.0	12.0	5.1	1.48	0.45	0.42	0.29
MAU5	9.1	24.8	10.7	5.1	1.48	0.45	0.41	0.29
MAU6	3.19	11.8	5.1	0.6	1.85	0.29	0.41	0.12
MAU7	1.77	7.6	3.5	5.1	1.48	0.45	0.39	0.29
PET1	3.12	11.9	4.2	0.7	1.88	0.28	0.37	0.17
PET2	9.24	22.8	9.3	1.0	2.10	0.22	0.37	0.11
PET3	7.51	21.0	9.4	0.8	2.14	0.21	0.36	0.08
PET4	1.61	7.5	3.1	0.5	1.65	0.36	0.36	0.17
ELP1	10.75	26.6	8.7	1.2	2.27	0.19	0.33	0.14
ELP2	4.3	18.6	8.7	0.5	2.51	0.16	0.33	0.06
CBE1	16.78	29.0	11.1	1.5	1.98	0.25	0.33	0.14
CBE2	6.33	18.0	7.8	0.8	2.01	0.24	0.31	0.10
CBE3	5.16	16.7	7.7	0.7	2.06	0.23	0.3	0.09
CBE4	2.96	11.6	5.3	0.6	1.89	0.27	0.27	0.10
CA1	11.84	18.4	7.0	1.7	1.50	0.44	0.25	0.24
Max.	88.37	49.5	17.4	5.1	2.72	1.19	0.79	0.49
min	1.59	7.2	3.0	0.4	0.91	0.13	0.25	0.05
Average	10.5	18.2	7.4	1.6	1.80	0.36	0.46	0.18

The shape of the basin is largely responsible for the characteristics of flood spikes. For basins where the extension, relief and factors governing the phenomenon are similar rainfall-runoff, hydrographs may differ significantly due to the shape of the contour of each basin. According to the classification of López-Cadena de Llano & Pérez-Soba (1983), calculated KC indicate that 65% of the basins analyzed are oval-oblong to rectangular-oblong and only 32% are oval-round to oval-oblong basins. Despite its widespread use, the KC does not consider the position of the closing point of the basin (Horton, as cited in Linsley et al., 1977). Basins of identical shape but with different location of the closing points have the same value of KC. However, these basins have different hygrograms for the same rainfall event, due to the different distribution of contribution sub-areas and flows upstream the closing point.

Circularity ratio indicates that all basins analyzed, with the exception of one of them, are elongated to very elongated (C <0.6), typical of rugged terrain with sub parallel drainage.

Form factor indicates that basins under study are elongated to very elongate. The mean value of Ff is 0.18, with maximum and minimum values of 0.49 and 0.05, far from the reference value of 0.78 for the circle. 73% of basins under study have 0.1> Ff> 0.3. Elongation ratio confirms that the basins are elongated to very deformed (65% of basins analyzed with 0.4<E<0.8 and the rest with E<0.40). Senciales and Ferre (1999) suggest that the lowest E occur in areas with relief and steep slopes, in coincidence with the physiographic features of the Piedmont area. Shuh Shiaw Lo (1992) states that basins with E values close to 1.0 occur in lowland areas; values 0.6 <E <0.9 are found in regions of marked relief. E values range from 0.6 to 1.0 for a wide variety of climate regimes and geological conditions.

As discussed above, the different calculated indices present similar results. These indicate that in the area under study the surface runoff could be moderately delayed, with increased time between precipitation and flood in the mouth. However, the rainfall-runoff phenomenon is a complex process, with many specific attributes which makes it difficult to characterize with a single numerical parameter.

4.2. Relief parameters

The four largest sub-basins (12% of the total area) have their headwaters at the high summits of the Precordillera range, above 3000 masl; the remaining sub-basins have their headwaters at the foot of the eastern slope, Piedmont area, between 3000 and 1500 masl. The closing points are located upstream or in the Piedmont low hills range, between 1300 and 850 masl. The Basin relief ΔH has a very wide range, between 2180 and 87 m, with an average value (770 m) that gives an idea of the accentuated relief and the magnitude of the alluvial risk.

The study area corresponds to ancient geological formations, covered largely by modern erosion products, which in turn were affected by neotectonism. According to Stralher's scheme (1952, as cited in Stralher, 1964) the area is in intermediate stage, between the steady state and mature stage. This is corroborated by the mean value of the hypsometric integral HI of 41 and extreme values between 64 and 22. Only three sub-basins are in the in equilibrium (young) stage, while 13 of them in the equilibrium (mature) stage.

The mean elevation Hm of the basins under study varies between 1001 m and 2721 m, with an average value of 1441 m. The altitude above the closing point ||m is 352 m, varying in a wide range between 1621 and 44 m. It is very common that Hm <1500 m and altitude H'm <500 m.

The average value of the mean slope Ic for the region is 34% and indicates that it is a heavily rugged terrain. This value ranges from 74% in basins whose headwaters are located on the eastern slope of the Precordillera system and 4% when the basins are developed on a glacis. It predominates the heavily rugged relief to steep relief.

4.3. Massivity coefficient CMa

Orographic coefficient Co values indicate that 68% of the studied basins have rugged relief (Co> 6.0).

In summary, the relief parameters indicate that the alluvial basins under study have characteristics of mountainous areas, with high average altitudes, rugged relief and very steep slopes. Parameter values for the different sub-basins are shown in Table 3.

Table 3: Relief parameters.

Basin	Maximum elevation CM [masl]	Minimum elevation Cm [masl]	Basin relief ΔH [m]	Mean elevation Hm [masl]	Mean slope IC [%]	Massivity coefficient CMa[m.km-2]	Orographic Coefficient [dimensionless]
SIS1	3450	1270	2180	2426.2	40.36	13	15
SIS2	2000	1200	800	1571.3	54.17	104	39
SIS3	2800	1300	1500	2242.3	56.63	38	35
SIS4	2400	1300	1100	1797.3	59.57	81	40
SIS5	2100	1100	1000	1539.1	68.78	93	41
SIS6	2020	1370	650	1580.2	36.39	103	22
SIS7	1800	1300	500	1487.6	33.22	118	22
SIS8	1500	1064	436	1326.1	3.77	12	3
PAP1	2800	1317	1483	2132.8	45.90	20	16
PAP2	2200	1317	883	1511.7	45.71	67	13
PAP3	1475	975	500	1185.1	38.49	35	7
DL	1424	945	479	1172.1	35.41	46	10
FRI1	1200	889	311	1037.1	26.20	30	4
FRI2	1537	975	562	1217.3	22.20	64	16
FRI3	1836	975	861	1242.9	27.70	37	10
FRI4	1516	937	579	1167.9	25.00	35	8
MAU1	1813	1010	803	1324.5	24.25	41	13
MAU2	2363	1282	1081	1699.8	54.15	51	21
MAU3	2090	1275	815	1599.4	51.33	68	22
MAU4	2690	1070	1620	1623.5	40.32	41	23
MAU5	1620	980	640	1184.0	17.23	22	5
MAU6	1200	920	280	1032.2	23.05	35	4
MAU7	1090	940	150	1019.3	20.97	45	4
PET1	1114	980	134	1024.2	12.42	14	1
PET2	1440	980	460	1133.8	11.68	17	3
PET3	1355	945	410	1075.4	9.64	17	2
PET4	1032	945	87	1000.6	45.35	35	2
ELP1	2142	987	1155	1412.2	25.60	40	17
ELP2	1463	988	475	1151.2	74.23	38	6
CBE1	2710	1165	1545	1591.5	32.10	25	11
CBE2	2100	1100	1000	2721.4	30.21	256	415
CBE3	2100	1141	959	1430.7	28.13	56	16
CBE4	1500	1127	373	1252.3	25.68	42	5
CA1	1230	955	275	1080.0	8.45	11	1
Max.	3450	1370	2180	2721.4	74.23	256	415
Min.	1032	889	87	1000.6	3.77	11	1
Average	1856.2	1088.9	767.2	1441.0	33.95	52	26

4.4. Drainage network parameters

As stated above, the basins are located on the eastern slope of the Precordillera system and piedmont. The piedmont is characterized by the presence of two levels of glacis, monoclinic crests and isolated hills (Duffar, 1978). The glacis are covered with quaternary, heterogeneous and poorly selected sediments. The lower level, with large extent, is deeply dissected and has a slope of 5%

west-east direction. The channels are generally narrow and have a V-shaped profile. They form a parallel to sub-parallel drainage network.

The basins under study have a high number of first-order channels; its average is 207 and its coefficient of variation is 40%. Approximately 70% of the 34 analyzed sub-basins have between 90 and 270 channels. This is an important indicator of the degree of dissection of basins, erosive activity and source of water and sediments; these are primary courses of short length (average length of 196 m).

Regarding the bifurcation ratio RB, indicating the degree of branching of the drainage network, its mean value for the studied basins is 3.6 and its coefficient of variation is 11%. According to Strahler (1964), in basins where the geological structure does not distort the drainage pattern, RB has a range of variation from 3.0 to 5.0, but remarkably table around 4.0, and rarely under natural conditions is its value 2.0 or less. Shreve (1966, cit Eagleson, 1974) point out RB values close to 2.0 for basins of order k=2 and RB=4.0 for basins of large k order, such as those studied.

The observed mean value of the length ratio RL is 2.0 and its coefficient of variation is 18%. Woodyer y Brookfield (1966, as cited in Eagleson, 1974) found a mean value of RL=2.0 for 14 basins with similar geometric characteristics in semi-arid regions of Central Australia. Rzhanitsyn (1960, as cited in Eagleson, 1974) found a mean value of RL=1.83 for 600 basins in the central region of European Russia. Morisawa (1959, as cited in Eagleson, 1974; 1962, as cited in Smart, 1981) determined a mean value of RL=2.6 in basins of the humid region of the USA. For both Horton's laws of composition of the drainage, the coefficients of correlation observed greater than 0.96 indicate a very good fit in all cases.

During or after a rainfall the surface runoff is gradually channeled into the different tributaries, concentrating finally in the main channel or collector. If the basin has a well-developed drainage network, the average distance to be traveled by the water is reduced and the water surplus rapidly reaches the closing point. This situation determines a strong correlation between Dd and the runoff coefficient (Gregory & Walling, 1973).

The mean drainage density for the study area is 11.0 km·km-2, with a low coefficient of variation. Eighty percent of the analyzed basins have medium to fine texture, indicating moderately well drained basins.

In the Piedmont region, the mean value of Ck is 0.117 km2 km-1. This means that, on the average, 11.7 Ha of surface is required to support one kilometer of channel. I.e. the surface runoff should drain, on average, 117 m to reach critical erosion velocity for formation of a furrow. The mean value of the average length of overland flow LES is low (LES=58 m). In both parameters the coefficient of variation is high, close to 84 %.

Stream frequency has an average value of 45 nº·km-2, being between 35 and 75 nº·km-2 in 70% of the analyzed sub basins. The F parameter indicates a large number of channels per unit area, resulting from an important erosive activity. Parameters analyzed, related to the drainage network for all sub-basins are presented in Table 4.

Table 4: Drainage network parameters

Basin	Stralher set NSk	Bifurcation ratio RB	Length ratio RL	Drainage density DD [km. km-2]	Constant of Channel Maintenance Ck [ha.km-1]	Average length of overland flow LES [m]	Stream frequency F [No.km-1]
SIS1	(274,79,16,3,1)	4.26	1.82	2.6	38.57	193	4
SIS2	(91,25,7,2,1)	3.17	1.40	7.8	12.9	64	35
SIS3	(306,79,22,7,1)	4.00	2.15	4.2	23.70	118	17
SIS4	(197,51,15,3,1)	3.82	2.03	9.3	10.73	54	44
SIS5	(126,37,11,3,1)	3.38	1.28	8.9	11.25	56	38
SIS6	(83,21,7,3,1)	2.94	1.72	13.8	7.25	36	56
SIS7	(150,28,9,2,1)	3.55	1.88	16.3	6.15	31	120
SIS8	(144,36,6,2,1)	3.61	2.34	1.9	53.29	266	9
PAP1	(440,97,26,5,1)	4.54	2.25	4.1	24.68	123	14
PAP2	(214,61,12,2,1)	4.12	2.08	15.4	6.49	32	101
PAP3	(252,65,11,3,1)	4.11	2.10	12.4	8.03	40	55
DL	(233,55,9,2,1)	4.14	2.63	12.6	7.91	40	60
FRI1	(201,44,9,3,1)	3.78	1.66	13.7	7.29	36	52
FRI2	(133,31,7,2,1)	3.50	2.10	13.4	7.46	37	46
FRI3	(288,69,12,3,1)	4.25	1.95	12.7	7.87	39	52
FRI4	(243,59,14,2,1)	4.21	2.21	14.1	7.09	35	50
MAU1	(266,61,20,4,1)	4.01	2.30	12.6	7.97	40	46
MAU2	(275,72,14,3,1)	4.23	2.18	9.6	10.4	52	44
MAU3	(218,58,17,6,1)	3.68	2.05	13.5	7.43	37	63
MAU4	(264,58,14,4,1)	3.99	2.07	9.2	10.88	54	25
MAU5	(369,90,19,5,1)	4.35	2.42	13.9	7.20	36	53
MAU6	(123,35,7,2,1)	3.49	1.86	12.9	7.77	39	53
MAU7	(81,21,6,2,1)	3.05	1.76	13.0	7.69	38	63
PET1	(120,34,10,2,1)	3.46	1.61	11.9	8.39	42	54
PET2	(228,53,13,2,1)	4.11	1.61	12.2	8.18	41	32
PET3	(231,50,12,3,1)	3.93	2.01	11.7	8.54	43	40
PET4	(76,20,5,2,1)	2.99	1.66	10.6	9.43	47	65
ELP1	(267,68,18,4,1)	4.06	2.25	11.0	9.12	46	33
ELP2	(127,33,6,2,1)	3.49	1.16	13.1	7.61	38	39
CBE1	(222,60,13,4,1)	3.86	1.56	8.2	12.22	61	18
CBE2	(214,51,10,4,1)	3.77	2.37	11.3	8.84	44	44
CBE3	(186,40,9,2,1)	3.84	2.02	13.0	7.66	38	46
CBE4	(87,23,6,2,1)	3.12	1.46	12.3	8.11	41	40
CA1	(318,81,21,5,1)	4.18	2.43	11.2	8.96	45	36
Max.		4.50	2.60	16.3	53.29	266	120
Min.		2.90	1.20	1.9	6.15	31	4
Average		3.80	2.00	11.0	11.68	58	45

All parameters, especially those related to the drainage network, are very sensitive to the scale and resolution of the base map. The results of the study confirm this situation, since some low outliers associated to sub-basins with lower resolution cartographic data (some sub-basins of the San Isidro and Papagayo systems) for the elaboration of the base map were found.

On the other hand, considering the drainage network as the final result of the interaction of a particular climate model on a particular geographical area, its most developed sectors are the sites with greater intensity of the erosive phenomenon. Consequently, the indexes that characterize the drainage network, such as Dd and F, allow identifying the sectors of basins where the erosion process is more intense. Dd quantifies the degree of development of the drainage network and is a measure of the rate at which water surpluses are discharged; F gives an idea of the intensity of the erosive phenomenon. Both indices are representative of the degree of disintegration and transportation of materials and their combination allows the identification of critical areas for their management. That is, they are a powerful tool for watershed management (Vich, 2004).

5. Conclusions

The rainfall-runoff relationship is a complex process, with many specific attributes that make it difficult to characterize with few parameters. Watersheds located to the west of the Mendoza metropolitan area, determine a high alluvial hazard region. Heavy rainfall episodes during the summer period can be dangerous because of the characteristics of these basins. The parameters studied indicate a very rugged relief with very steep slopes that, along with a sparse vegetation cover, generate a fast concentration of runoff and important alluvial floods.

However, other parameters indicate characteristics that mitigate the formation of dangerous floods. The elongated shape tends to flatten and retard the peak flow of the flood hydrograph.

Most of the analyzed basins have medium to fine texture soils and, according to drainage parameters, a large number of channels per unit area. This indicates moderately well-drained basins and important erosive activity. These parameters allow the identification of critical areas, constituting a deeply useful tool for watershed management.

The management of the watersheds located to the west of the Mendoza metropolitan area requires knowledge of their different characteristics. The morphometric analysis carried out in this study improves understanding, allows the identification and prioritization of management areas and provides useful information for decision-making, aimed at preventing dangerous contingencies.

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