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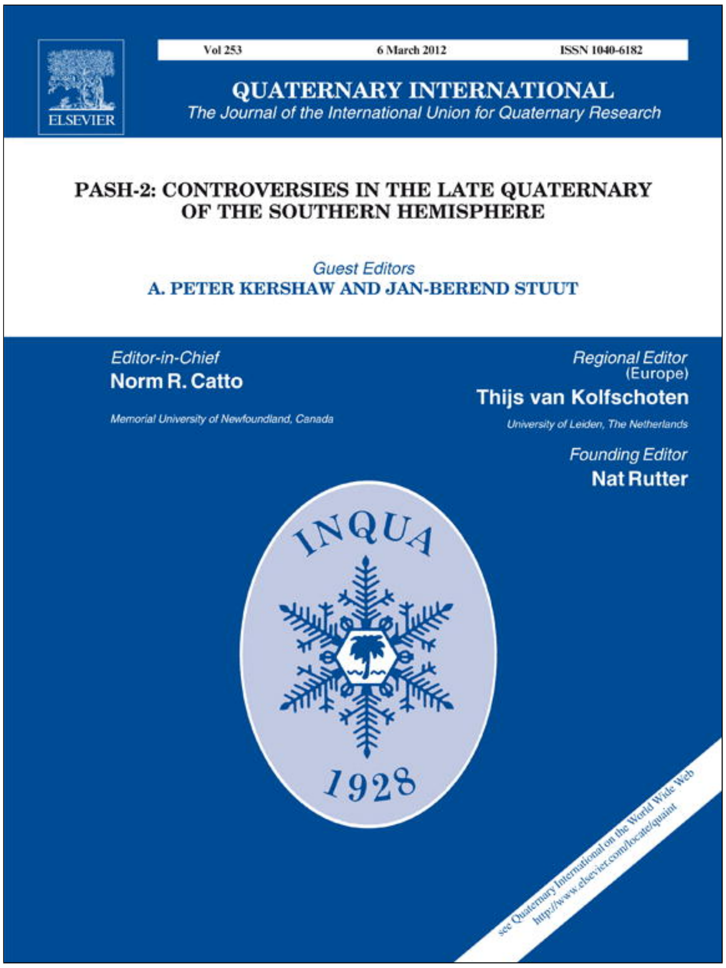

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PASH-2: CONTROVERSIES IN THE LATE QUATERNARY OF THE SOUTHERN HEMISPHERE

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Forum communication

Morphometric characterization of the Carrizal basin applied to the evaluation of flash floods hazard, San Juan, Argentina

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ABSTRACT

The Carrizal river basin is located to the northwest of San Juan Province in the Iglesia department. One of the main geological hazards that affect the Iglesia department is flash floods, produced by heavy seasonal rains, characterized by their high velocities and destructive power. The Carrizal river basin was selected as a test case to evaluate the potential magnitude of flash floods in relation to their associated hazard level. This paper evaluates some of the hydrological aspects of a torrential regime of Carrizal basin that can cause severe damage like the event that took place in the area during February 1944. Various morphometric characteristics of the Carrizal river basin were analysed in order to evaluate its flash flood hazard. For this purpose, the basin was divided into five sub-basins, according to lithological aspects, and some basic measurements (surface, perimeter, basin length, river beds, elevations and slope of the main river bed, and of a number of minor river beds) were calculated. These measurements allowed predicting approximately the behaviour of the basin in the presence of a series of theoretical rainstorms that may generate unusual runoff volumes. The predicted flash floods were compared against the Carrizal flash flood.

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1. Introduction

The morphometric characteristics of drainage basins provide a means of describing the hydrological behaviour of a basin. The estimation of the maximum theoretical discharges is of critical importance because they control the maximum flow velocities, their probable extent, their impact, and the possibility of building contention and/or mitigation works (Hungr, 2000).

The dry Andes and Preandes Mountains Ranges bordering the western boundary of South America are affected by various natural geologic processes. Flash floods are one of the most common types of geological hazards in the region, and they are localized process that occur in basins of a few hundred square kilometres or less (Borga et al., 2007), and on account of their unpredictable can cause problems to road networks in the highlands and mountain valleys.

According to NWS/NOAA (2010), a flash flood is a rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within 6 h of the causative event (e.g., intense rainfall, dam failure, ice jam). However, the actual time threshold may vary in different parts. Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters. Flash floods become even worse when the infiltration index is reduced by previous rainstorms.

Because mountainous areas are not highly low populated or in most cases, un-inhabited, historical catastrophic flash floods in Argentina have not been widely documented. In the province of San Juan, the most recent events occurred in 2005 and 2010 (Perucca and Esper Angillieri, 2009, 2011).

On 13th February 1944, few weeks after an earthquake had destroyed San Juan city, a sudden and violent flash flood (estimated peak discharge 600 m^3/s), devastated everything existing along its way. As a consequence, thirty-five people died, houses and most of the cattle and crops were devastated and buried under a mass of mud, rocks and branches (Esper Angillieri, 2007). There are no data about the volume of rainfall precipitated on that day or on previous days, and unfortunately there are neither newspaper records nor eyewitnesses.

In various articles, morphometric analyses were used for basin characterization Miller (1953), Boulton (1968), Gregory and Walling (1973), Gardiner (1975), Majumdar (1982), Costa (1987), Nag (1998), Topaloglu (2002), Moussa (2003), Sreedevi et al. (2004), Srinivasa Vittala et al. (2004), Mesa (2006), Esper Angillieri (2008) and Perucca and Esper Angillieri (2011), among others. The Carrizal basin and its drainage features were studied through

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topographical maps, air photographs and satellite imagery in order to predict the approximate behaviour of the basin during heavy rainfall and to calculate the potential hazard of flash floods.

2. Study area

The Carrizal basin covers an area of 372.53 km^2 in the northeast of San Juan province, Argentina. This basin includes some important orographic systems as the Volcán hills, with tallest peaks as high as 4500 m asl. (Fig. 1).

The San Juan province has a general arid and semiarid climate; the total annual rainfall average is very small with about 93.3 mm per year. Winter temperatures are generally mild, ranging between 1.0 and 18.0 °C, whereas summers are hot and very dry, with temperatures between 19.0 and 35.0 °C.

In the study area, the annual rainfall is below 44.9 mm. The temperature in summer reaches up to 35.4 °C (February) and in winter comes down to −12.1 °C in July (data recorded at the Rodeo Meteorological Station, Iglesia department, San Juan province).

During the December–March period, summer, heavy rainfalls of short duration commonly feed torrential freshets and floods characterized by large flow rates and high transport ratios of alluvial detritus. The steep gradients of the slopes help to drain quickly these precipitated volumes, funnelling them towards the Blanco river.

2.1. *Geology*

The Carrizal river basin shows a wide range of geologic units. The oldest rocks in the area are lower Ordovician sedimentary rocks, mainly composed of limestones, sandstones and lutites. This unit is unconformably overlain by a package of carboniferous sandstones and lutites, mainly of marine origin. The sequence continues with Miocene of argillites. The Quaternary covers the central area of the basin and is represented by two sedimentary units, composed of colluvial–alluvial deposits. Unconsolidated modern deposits, sands, silts and clay, are restricted to narrow river channels and to the valleys (Fig. 2). Data acquired from geologic sheets published by the Servicio Geológico Minero Argentino (Argentine Mining Geologic Service) on 1:250 000 scale.

3. Materials and methods

In the present study, base maps showing drainage details, basin delineation and morphometric characterization have been prepared from 1:100 000 toposheets, 1:15 000 aerial photographs, and digital satellite imagery (Landsat 7-TM). They were georeferenced to Geographical coordinate system (WGS84) using GIS software. The ordering of the digitalized streams of the basin was performed in GIS according to Strahler's system, 1964.

Altitudes were obtained from topographic sheets with a 50-m contour interval published by the Instituto Geográfico Nacional (Argentine National Geographic Institute), and from topographical information obtained from the Radar Shuttle Topographical Mission (USGS, 2000). Then a digital elevation model (DEM) with a 15 m grid spacing was interpolated.

The morphometric parameters were divided in basic parameters: area (A), perimeter (P), length (L), mean width (W), river network (Rn), maximum and minimum heights (H, h), total channel length (Tcl), stream order (Nn) and main channel length (Mcl); and derived parameters calculated in GIS by Table operations with the following equations:

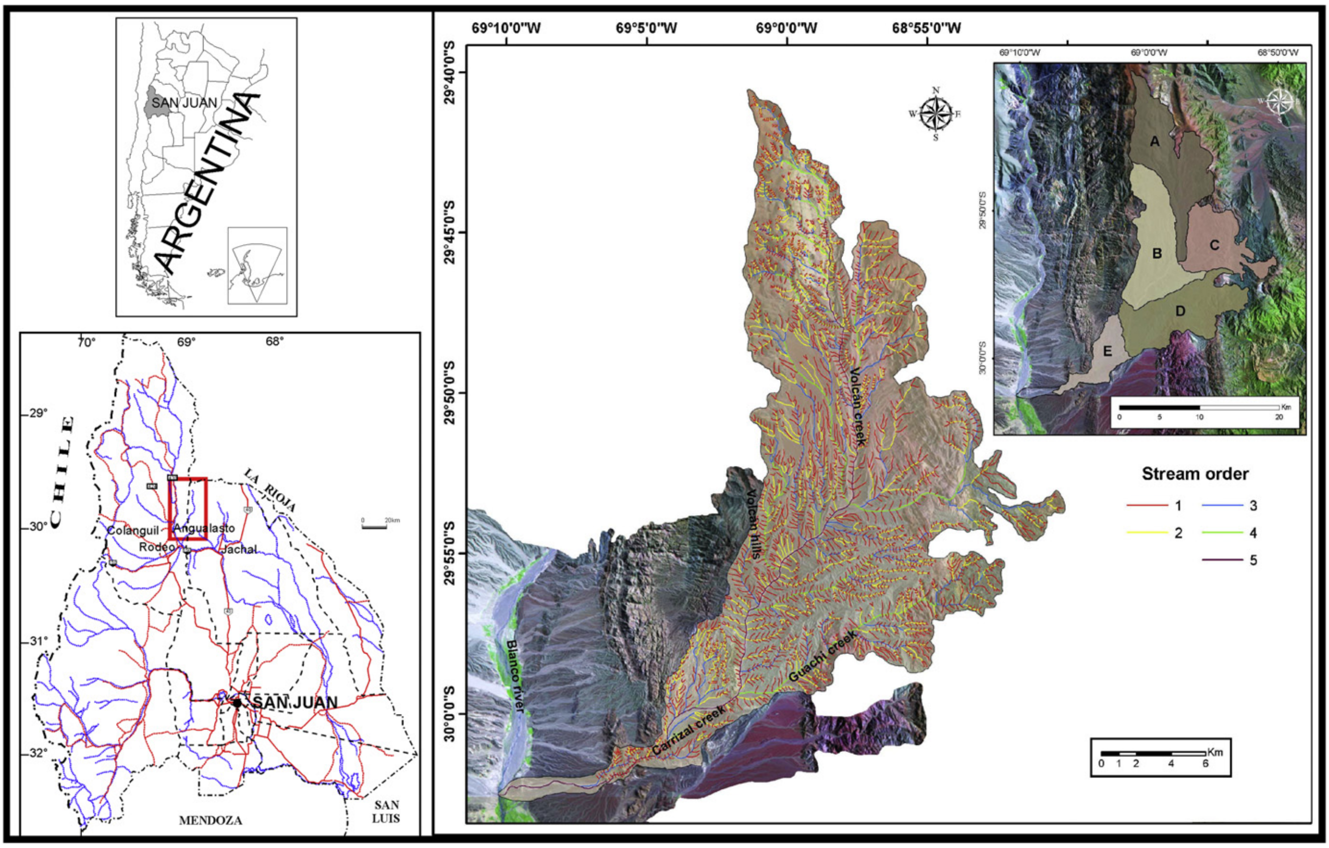

Fig. 1. Location of the study basin and sub-basins and their location in San Juan province, Argentina.

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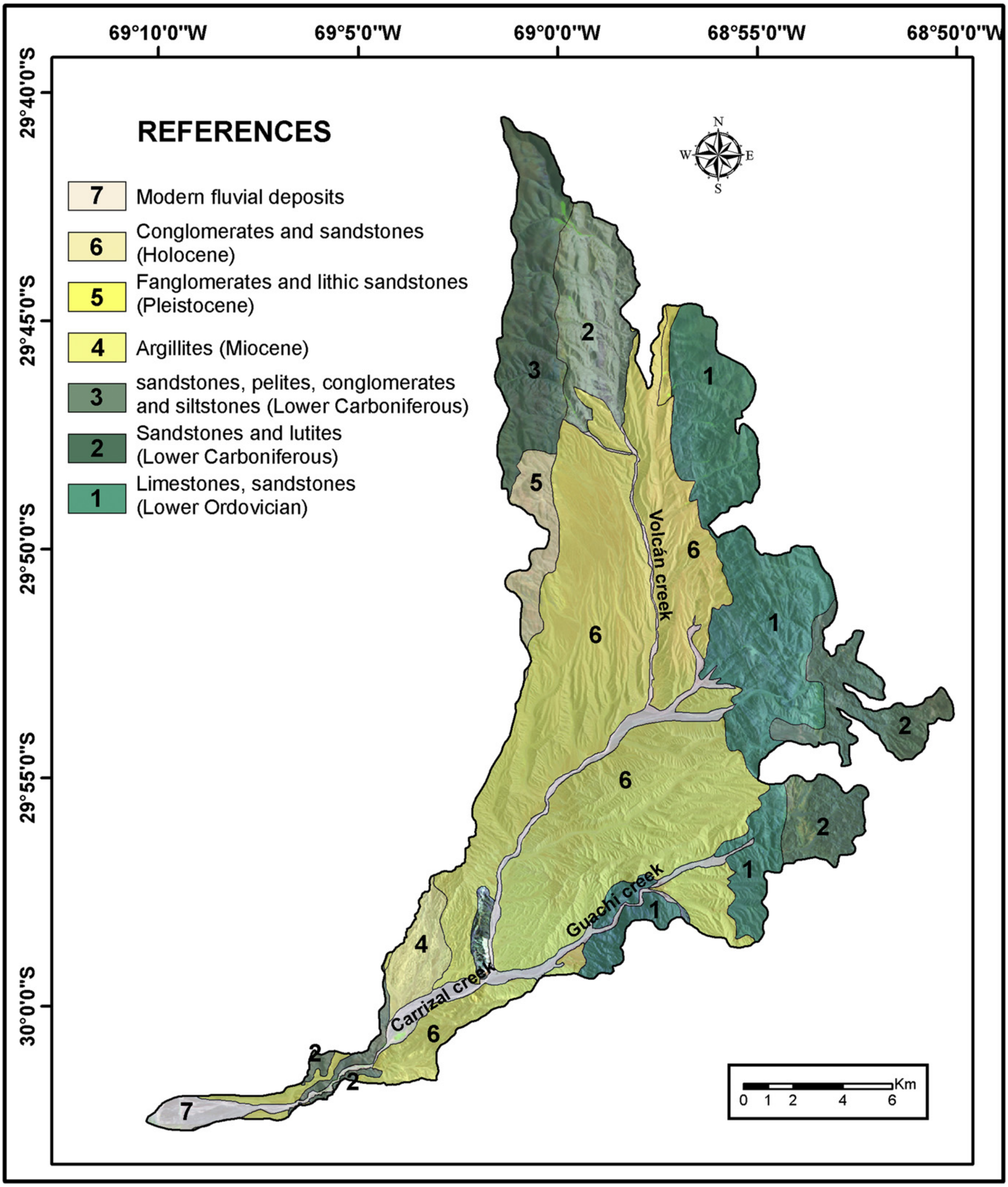

Fig. 2. Lithological map of the Carrizal river basin.

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Circularity index	$\mathrm{Rc} = 4\pi A/P^2$	(Miller, 1953)
Elongation ratio	$\mathrm{Re} = (\sqrt{4A/\pi})/L$	(Schumm, 1956)
Form factor	$\mathrm{Ff} = A/L^2$	(Horton, 1932)
Sinuosity index	$\mathrm{S} = Lcp/L$	(Schumm, 1977)
Basin relief	$\mathrm{Hr} = H - h$	(Hadley and Schumm, 1961)
Relief ratio	$\mathrm{Rr} = Hr/L$	(Schumm, 1956)
Melton ratio	$\mathrm{MR} = Hr/A^{0.5}$	(Melton, 1957)
Drainage density	$\mathrm{Dd} = Ltc/A$	(Horton, 1932)
Stream frequency	$\mathrm{Fn} = \sum N_n/A$	(Horton, 1932)
Drainage texture	$\mathrm{Td} = \sum N_n/P$	(Horton, 1945)
Bifurcation ratio	$\mathrm{Rb} = N_{n-1}/N_n$	(Horton, 1945)

The analysis of basin slope was performed in GIS environment. The slope functions calculate the maximum change in elevation over the distance between the cell and its eight neighbours. The output slope dataset was calculated as degree of slope.

Once the sub-basins were delineated, it was necessary to calculate the curve number (CN) for each sub-basin. CN is a parameter standardized by the Soil Conservation Service (SCS; now Natural Resources Conservation Service (NRCS)), (1986), and it is linked to the soil characteristics (humidity, infiltration, etc.). Its value ranges from 0 (high infiltration) to 100 (no infiltration) and it gives a picture of the water retention capacity of the basin.

The analysis of flash floods was made using weather records and, due to the lack of flow-rate gauging data, the mathematical simulation model of Rain-Discharge Transformation (Arhymo) was applied. The storms selected were the one of 26 December 1967, with 52 mm precipitated and 104 mm/h rain intensity, the one of 26 February 1981, with 40 mm precipitated and 48.9 mm/h rain intensity, and the one of 17 January 1985, with 29.5 mm precipitated and 40.2 mm/h rain intensity. As this model was designed for simulation of small basins, the Carrizal basin was split into five sub-basins (A to E), thus composing a more comprehensive morphometric and lithologic study (Fig. 1).

The following step entailed the simulation of the production of discharges down into the basin's collector (Blanco river) and the mouth of the Carrizal creek. Different scenarios were considered as regards the rainstorm area: a homogeneous precipitation for the entire basin; in three sub-basins; and in only one sub-basin without any previous humidity condition. Besides, previous rain was also considered (i.e. infiltration reduction).

Finally, on the basis of precipitation data and the resulting discharges, the return period (T) and the probability of flows occurrence were calculated by means of the Weibull (1939, 1951) proposal, using the following formula:

$$T = (N + 1)/n$$

Where

$T =$ return period
$N =$ number of years on record
$n =$ order number of maximum daily rainfall per annum in descending order (independently of the date of occurrence)

$$P = (1/T)^{*}100\%$$

Where

$P =$ probability that the event will be exceeded in any one year.

$$P_{(\mathrm{no})} = (1 - P)^N$$

Where

$P_{(\mathrm{no})} =$ the probability of the event not occurring in N years.

$$P_{(\mathrm{o})} = 1 - (1 - P)^N$$

Where

$P_{(\mathrm{o})} =$ probability of the occurrence for the hydrologic event in question in N years.

4. Results and discussion

The Carrizal basin is composed, from north to south, of three main creeks Volcán, Guachi and Carrizal (Fig. 1). The basic parameters and derived parameters are summarized in Table 1.

This 5th order drainage basin covers an area (A) of 372.53 km^2, has a perimeter (P) of 174.54 km, an axial length (L) of a bit over

Table 1
Morphometric parameters of Carrizal basin and sub-basins.

Carrizal basin										
Basic parameters										
		A [km^2]	P [km]	L [m]	H [m asl]	h [m asl]	Ltc [m]	Lcp [m]		
Wole basin		372.53	174.54	43 078.27	4489	1654	1407049.68	57 916.21		
Sub-basins	A	99.14	70.06	24 757.09	4489	2875		27 224.97		
	B	87.47	53.76	18 560.05	3927	2526		23 708.26		
	C	60.41	53.90	12 434.26	3692	2875		14 242.93		
	D	88.46	58.11	17 438.19	3393	2273		19 626.74		
	E	31.86	35.11	12 928.08	2719	1799		15 612.62		
Derived parameters										
		Rc	Re	Ff	S	Wm [m]	Hr [m]	Rr	MRN	Dd [km/km^2]
Wole basin		0.15	0.51	0.20	1.34	8647.64	2835	0.07	0.15	3.78
Sub-basins	A	0.25	0.45	0.16	1.10	4004.56	1614	0.07	0.16	
	B	0.38	0.57	0.25	1.28	4712.72	1401	0.08	0.15	
	C	0.26	0.71	0.39	1.15	4858.15	817	0.07	0.11	
	D	0.33	0.61	0.29	1.13	5072.77	1120	0.06	0.12	
	E	0.32	0.49	0.19	1.21	2464.78	920	0.07	0.16	
	O			Nn		Fn [n/km^2]		Td [n/km]		Rb
	1			3319		8.91		19.02		7.06
	2			470		1.26		2.69		5.88
	3			80		0.21		0.46		4.71
	4			17		0.05		0.10		17.00
	5			1		0.00		0.01		

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Table 2
Curve number (CN) for each sub-basin.

Sub-basin	A	B	C	D	E
CN	80	63	85	65	51
CN[a]	94	81	97	83	71

[a] previous humidity.

Table 3
Peak discharges obtained from the application of the mathematical model Arhymo.

Peak discharges (m^3/s)	Rain 52 mm		Rain 40 mm		Rain 29.5 mm	
	s	h	s	h	s	h
Up to the end of Carrizal creek						
Wole basin	322.8	913.7	168.3	603.1	67.8	357.6
Sub-basin A	131.7	320.5	72.0	223.5	30.8	142.1
Sub-basin B	23.4	131.3	5.3	73.3	i	32.6
Sub-basin C	140.1	289.3	84.4	212.0	42.9	144.5
Sub-basin D	31.8	156.3	9.1	90.8	0.3	43.4
Sub-basin E	0.2	28.8	i	12.0	i	2.7
Sub-basins A + C + D	149.4	716.7	136.4	482.0	54.0	292.5
Up to Blanco river						
Wole basin	d	d	162.5	d	d	d
Sub-basin A	52.0	167.4	21.9	105.0	9.1	58.4
Sub-basin B	8.3	66.9	1.9	30.3	i	11.5
Sub-basin C	46.4	126.6	22.6	82.9	10.8	48.8
Sub-basin D	12.8	96.9	3.7	49.2	0.1	17.9
Sub-basin E	0.1	23.3	i	8.3	i	1.5
Sub-basins A + C + D	101.2	596.9	89.8	382.9	29.5	217.4

s (No previous humidity conditions). h (previous rain). d (the river overflows). i (all the water seeps away).

43 km and a mean width (Wm) of 8647.64 m. The drainage patterns of the basin are subdendritic and parallel, and lower order streams mostly dominate the basin. The maximum elevation (*H*), is 4489 m asl. at its headwaters, and the minimum (*h*) is 1654 m asl, at the confluence with the Blanco River (Table 1).

The circularity index, the elongation ratio and the form factor have values much lower than the unit, which show an elongated basin, with steep relief (2835 m), fast discharge and a straight long main channel (57 916.21 m) of braided type. The Melton ratio (MR) is <0.3, what points to a great susceptibility of the basin to the occurrence of flows of low material content.

The low value of drainage density (Dd) indicates the predominance of unconsolidated modern deposits, however such basins respond rapidly to intense rainfall because of steep slopes and saturated soils due to rainstorms on previous days.

The high values of drained texture (Td) for lower order streams, specify the existence of impervious material at the headwaters of the basin. The mean bifurcation ratio (Rb) indicates the drainage pattern is influenced by geological structures.

In order to be able to assign a representative CN to each sub-basin, and keeping in mind that, as mentioned above, the Carrizal basin drains a wide range of lithological units and that the CN is closely related to the constituent material of the sub-basins (A to E, Fig. 1), the criterion for sub-basin selection was mainly lithological. The CN calculated to apply the mathematical model Arhymo is shown in Table 2.

In examining the resulting peak discharges (Table 3) we can observe that 40 mm storms can generate peak discharges of 600 m^3/s, like the 1944 flash flood, remembering that these values result from the application of the mathematical model Arhymo are only mathematical approximations. Their validity is controversial because it is difficult to predict the spatial extension of rainstorms without having more comprehensive hydrometeorological records. Besides, it should be kept mind that the majority of the analyses performed here are based on the resolution and precision of standard Landsat imageries and the elevation records.

Local people say that this is a yearly phenomenon, which takes place in the rainy season, and they also refer to serious floods in the 1910s, 1930s and 1980s, when there was severe damage to houses and crops.

Table 4
Return period and probabilities (Weibull, 1939, 1951).

Year	Precip [mm]	Intensi [mm/h]	n	T	P [%]	10 years		20 years		25 years		50 years		100 years	
						$P_{(no)}$	$P_{(o)}$	$P_{(no)}$	$P_{(o)}$	$P_{(no)}$	$P_{(o)}$	$P_{(no)}$	$P_{(o)}$	$P_{(no)}$	$P_{(o)}$
1967	52.0	104.0	1	29.00	3.45	0.70	0.30	0.50	0.50	0.42	0.58	0.17	0.83	0.03	0.83
1973	50.0	s/d	2	14.50	6.90	0.49	0.51	0.24	0.76	0.17	0.83	0.03	0.97	0.00	0.97
1982	50.0	22.7	3	9.67	10.34	0.34	0.66	0.11	0.89	0.07	0.93	0.00	1.00	0.00	1.00
1981	45.0	3.1	4	7.25	13.79	0.23	0.77	0.05	0.95	0.02	0.98	0.00	1.00	0.00	1.00
1970	36.0	17.2	5	5.80	17.24	0.15	0.85	0.02	0.98	0.01	0.99	0.00	1.00	0.00	1.00
1980	35.0	14.0	6	4.83	20.69	0.10	0.90	0.01	0.99	0.00	1.00	0.00	1.00	0.00	1.00
1975	30.0	s/d	7	4.14	24.14	0.06	0.94	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1976	30.0	15.0	8	3.63	27.59	0.04	0.96	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1969	27.0	2.2	9	3.22	31.03	0.02	0.98	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1987	26.0	13.0	10	2.90	34.48	0.01	0.99	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1989	25.7	8.6	11	2.64	37.93	0.01	0.99	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1978	25.5	25.5	12	2.42	41.38	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1979	25.5	14.2	13	2.23	44.83	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1968	25.0	5.3	14	2.07	48.28	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1972	25.0	8.3	15	1.93	51.72	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1991	23.0	2.6	16	1.81	55.17	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1986	22.5	5.6	17	1.71	58.62	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1994	20.5	10.3	18	1.61	62.07	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1983	18.0	24.0	19	1.53	65.52	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1977	15.5	s/d	20	1.45	68.97	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1990	14.0	6.2	21	1.38	72.41	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1974	11.5	7.7	22	1.32	75.86	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1993	11.5	2.9	23	1.26	79.31	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1971	11.0	22.0	24	1.21	82.76	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1992	10.0	1.2	25	1.16	86.21	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1988	9.5	1.1	26	1.12	89.66	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1984	4.0	1.0	27	1.07	93.10	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
1985	3.6	1.0	28	1.04	96.55	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00

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The rainfall data indicates a 7.25-year recurrence interval for rainstorms equal to or higher than 40 mm, a 13.79% probability of happening in any given year and a 77% probability for rainstorms to happen in 10 years (Table 4). Considering that the Carrizal river has a mean discharge not larger than 3 m^3/s, though just a 50% validity is considered, the results obtained show that there is a high probability for flash flood hazard, except in the special case that a storm concentrated exclusively in sub-basin E, whose results are low, but expected, considering that such sub-basin is composed of high permeability materials, mainly modern deposits, conglomerates and sands with low CN (greater infiltration).

5. Conclusions

The computed morphometric characteristics show that lower order streams mostly dominate the basin. The river network is of fifth order. The general pattern of the basin is subdendritic and parallel. It is an elongated basin with highly dissected areas, and the Dd of the basin indicates the predominance of unconsolidated modern deposits. The Melton ratio (MR) indicates a great susceptibility of the basin to the occurrence of stream flows.

The values obtained from the rain-discharge simulation point to a high probability for serious flash flood hazard, with peak discharges greater than 300 m^3/s. Furthermore, such values indicate that 40 mm storms can generate peak discharges of 600 m^3/s, like the 1944 flash flood. Such flash floods can certainly affect and cause serious damage to villages and towns located downstream the Carrizal-Blanco rivers confluence. When conditions of previous humidity (i.e. rainstorms of previous days) are considered, the peak discharges of basin outflows can multiply their average values. That is why, high intensity rainfall rates seem not to be sufficient to trigger a flash flood; a rainfall accumulation (i.e. a certain level of saturation) is also necessary.

It appears clearly the necessity to increase the existing knowledge of such events to provide adapted methods of analysis and technical solutions for flood prevention and control.

The methodology presented here is easy to reproduce and may be applied to other dry mountainous regions, as a useful tool to assess flash floods in relation to hazard.

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