Flash Flood Hazard Assessment in an Ungauged Piedmont Basin in the Sierras Pampeanas Western Region, Province of Córdoba, Argentina

Karina V. Echevarria, Susana B. Degiovanni, Mónica T. Blarasin and M. Jimena Andreazzini

Abstract In Argentina, in both mountain and piedmont basins, generally with insufficient hydrological data, flash floods are recurrent. The objective of this paper is to evaluate the flash flood hazard of a typical ungauged piedmont basin, the Arroyo (= creek) Chuchiras, province of Córdoba, Argentina, through the analysis of geomorphological, sedimentological, hydrological, and anthropogenic variables that control the behavior of these fluvial systems. The concept of hazard represents the susceptibility and natural fragility of a region exposed to a threat. The susceptibility was evaluated through the following indicators: slope, aspect, valley depth, landscape and landforms, and road networks. Five classes of flash flood susceptibility and hazard were defined. To assess the threat, analysis was made taking into account temporal distribution and intensity of precipitation, field hydrological evidence, and eyewitness reports. The Manning and the paleo-hydraulic methods were used to estimate mean velocity values during the extraordinary event flash flood which occurred on February 4, 2014. The flash flood hazard in the western piedmont of the Sierras Grandes de Córdoba is the result of the combination of variables: low permeability rocks in the upper basin; important topographical contrasts between the fault scarp and piedmont area; and streams with torrential regime and high energy (velocity, competence, and transport capacity) that make up distributary systems in the distal-middle piedmont and high intensity rainfalls. A 26% of the study area presents high/moderately high flash flood hazard, associated with the lower reaches and proximal-middle active alluvial fan of Arroyo Chuchiras; 64 and 10% of the investigated sector correspond to low/moderately low and moderate classes of flash flood hazard, respectively.

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1 Introduction

The occurrence of floods is the most frequent among all natural disasters, affecting both rural and urban settlements. Flooding is a global phenomenon which causes widespread devastation, economic damages, and loss of human lives. Particularly in the past twenty years, the number of reported flood events has been increasing significantly. Only in 2010, 178 million people were affected by floods and 8000 human beings were reported dead (Jha et al. 2012).

Specifically, flash floods represent one of the most dangerous and deadly geomorphological hazards. In general, they are characterized by intense rainfall in short time periods. These floods are enhanced by topography and affect rather small areas, but sometimes, they can affect larger areas (Gaume et al. 2009). In turn, the growing urbanization without land use planning in the piedmont areas has favored the impacts of these events. In this sense, there are several international projects that study the flash floods, in gauged and ungauged catchments. Among them, Gaume et al. (2009), Marchi et al. (2010), and Borga et al. (2014) may be cited, who made a review and characterization of these events in Europe. Gutiérrez et al. (1998), Hooke and Mant (2000), Phillips (2002), Fernández Lavado et al. (2007), and De Waele et al. (2010) studied geomorphological (and in some cases sedimentological) changes related to extreme flood events. On the other hand, Ogden et al. (2000), Gaume et al. (2004), Anquetin et al. (2010), Koutroulis and Tsanis (2010), Nikolopoulos et al. (2011), Catane et al. (2012), and Garambois et al. (2014, 2015) applied hydrological models, whereas Carpenter et al. (1999), Dawod et al. (2011), Bajabaa et al. (2014), and Elkhrachy (2015) used GIS tools, for hydrological analysis and flash floods mapping, respectively. In addition, there are several works related with the estimation of paleo-floods, such as Williams (1984), Maizels (1983), Martín Vide et al. (2002), and Lang et al. (2004), among others.

In many towns and cities of Argentina, in both mountain and piedmont areas, these types of flood events are recurrent. Thus, those occurred in the provinces of San Luis (Luján, Concarán and Quines, 2015), Salta (Tartagal, 2006, 2008), and Córdoba (San Carlos Minas—1992– and Jesús María, Río Ceballos, and Unquillo —2015–) may be highlighted. However, few of these works included their analysis, characterization, and prevention; Ambrosino et al. (2004), Esper Angillieri (2007), Gil (2011), and Busnelli and Horta (2014) should be cited among them.

In Argentina, and particularly in the province of Córdoba, an important urban expansion without planning management is recorded in piedmont areas of the Sierras Pampeanas. The urban expansion is linked to growing touristic development during last decades. Thus, there are numerous villages settled along rivers and streams, a situation that generates different flash flood risk events. Therefore, it is necessary to develop maps of flood hazard and risk, which may contribute to build up adequate territorial management and/or to mitigate the impacts caused by low and high recurrence floods.

Nowadays, the general tendency is to produce hazard flood maps using rainfall data and computer-based models. The data needed in these models include a comprehensive record of daily rainfall data, roughness coefficient of the channel, and detailed topographic maps or digital elevation models (DEMs). Nevertheless, when there is little data availability, the results of the models are not reliable (Fernández Lavado et al. 2007). Unfortunately, these methods may not be applied in many developing countries, like Argentina, because of insufficient data available.

In this sense, geological, geomorphological, and hydrological basic studies are relevant, as well as eyewitness reports that describe previous flood events and help to characterize the magnitude and spatial-temporal distribution of the flash flood.

In this framework, this paper presents a methodology based on the assessment of different indicators for estimating the flash flood hazard.

The analysis was made in a basin that presents the typical piedmont environmental problems in the province of Córdoba. On February 4, 2014, rainfall of 140 mm in only 3 h was recorded in the town of Villa de Las Rosas (Sierras Grandes). This unusually high precipitation triggered an important flash flood in the Arroyo Chuchiras basin.

The main objective of this work is to evaluate the flash flood hazard of the Arroyo Chuchiras basin through the analysis of the geomorphological, sedimentological, hydrological, and anthropogenic main variables that control the behavior of a piedmont fluvial basin.

2 Study Area Description

The Arroyo Chuchiras basin is located in the southern portion of the Traslasierra valley (San Javier Department, province of Córdoba, Argentina) (Fig. 1).

The Arroyo Chuchiras drains the western slope of the Sierras Grandes de Córdoba, discharging into the piedmont area, where a distal alluvial fan has developed. The climate is semiarid and mesothermal (Thornthwaite 1948), with an average annual rainfall of 628 mm, calculated from the data of a station located in the lowland plain area (the city of Villa Dolores, 1961–2014 series; data from the National Weather Service). There is a gentle precipitation gradient from the highest mountain elevations (800 mm isohyet) to the piedmont plains (700 mm isohyet; Capitanelli 1979). Almost 77% of the rainfall is concentrated both in spring and summer.

From the geological point of view and under the influence of the Sierras Pampeanas geological setting, the area shows the classical tectonic block arrangement defined by regional faults (Niña Paula, Los Molinos and Nono faults, among others). Toward the East, the Sierras Grandes are formed by metamorphic and granitic rocks (Precambrian–Paleozoic), which show the highest altitudes and rough slopes in the region. In the piedmont area, two levels of Cenozoic alluvial fans are recognized (Fig. 2) with a strongly undulated relief and evidence of neotectonic activity (Bonalumi et al. 1999).

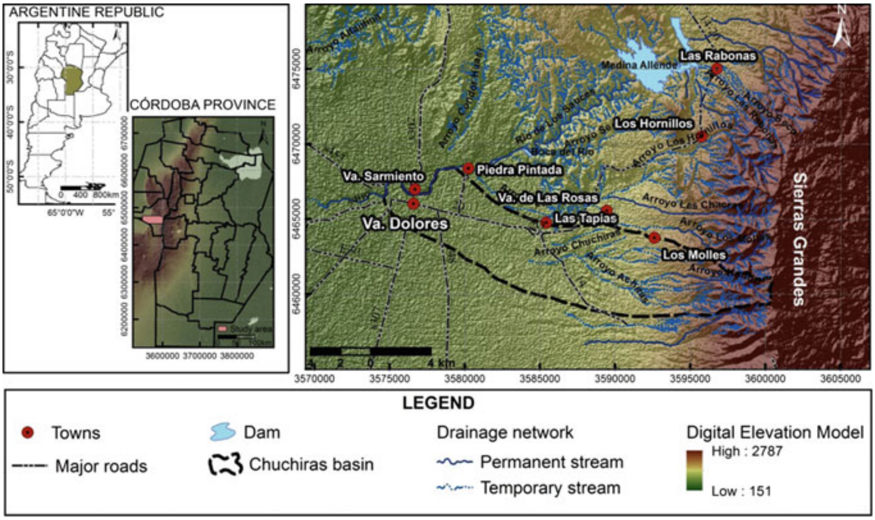

Fig. 1 Location of the study area. Digital elevation model from *SRTM* (Shuttle Radar Topography Mission) and hydrology features of the studied zone

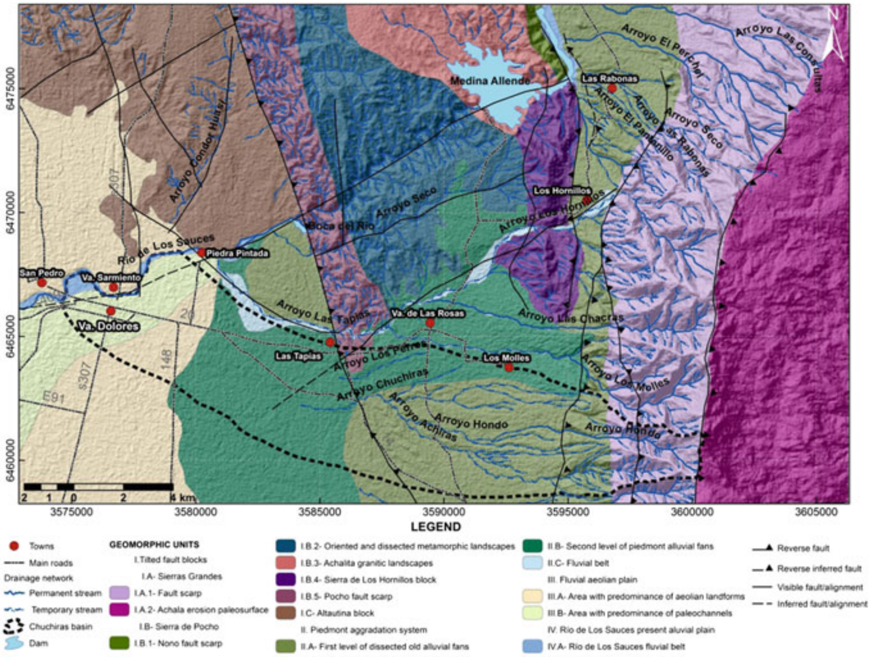

Fig. 2 Geological and geomorphological map of the study area

The Arroyo Chuchiras, like other streams in this region, has a torrential hydrological regimen associated with the almost impervious lithology and steep slopes of their upper-middle basin and with intense summer precipitation. The Arroyo Chuchiras drains an area of about 112 km^2. The upper mountain basin represents only 10% of the total area, and it is drained by the Hondo and Achiras streams, which have a permanent hydrological regime. In low flow conditions, instantaneous discharge values of 0.023 up to 1.40 m^3/s have been measured. In the piedmont area, the Arroyo Chuchiras shows an ephemeral regime. In this environment, it receives water discharge contribution from numerous ephemeral runoff systems, which represent approximately 50% of the catchment area. In summer, the measured discharge in the trunk stream was 0.30 m^3/s.

Concerning land use, the region is characterized especially by extensive cattle raising, agricultural intensive activities, soil mining for bricks, and small urbanized areas.

3 Materials and Methods

3.1 Available Data

Although studies related to water resource problems have been carried out in recent years in Argentina, the lack of instrumentation is still a limiting factor when statistically representative precipitation series are required for the flash flood analysis. Pluviometers that are already located are insufficient, and precipitation records are available for just a few years and rather discontinuous periods.

To characterize the studied storm event, data provided by residents from several piedmont towns, such as Villa de Las Rosas and Las Tapias, were used.

For the relief analysis, the following sources of information were used:

1. Digital Elevation Model—SRTM (Shuttle Radar Topography Mission) available at the Web site of the United States Geological Survey, with a spatial resolution of 30 × 30 m. Therefore, the DEM resolution is not enough to reconstruct the topography of the channel affected by the floods at a proper scale. Because of this, cross sections cannot be systematically extracted from the DEM in order to calculate discharges.
2. Topographic maps of the National Geographic Institute of Argentina have not very high detail (1:50,000 scale), and the vertical interval between contour lines is 25 m. Then, and taking into account that during floods water levels can range from centimeters to few meters, these maps are useless for flood hazard mapping. Google Earth satellite images allowed us to detect relief details which are unnoticeable in the DEM used here.
3. Finally, the obtained eyewitness reports from local residents were a very important information source. They included diverse data which gave an idea of the flash flood energy: water level during peak discharge, flood duration and

recurrence, transported sediment, preferential ways of water circulation, erosion and sedimentation sites, and damage caused by water flow, among other parameters.

3.2 Methodology

In this study, the concept of **hazard** (as stated by Cendrero 1987) represents the susceptibility and natural fragility of a region exposed to a certain **threat**. The **susceptibility** involves geological, geomorphological, lithological, hydrologic, and geotechnical aspects, among others, which together determine the behavior of an area exposed to a definite natural process (Panizza 1993). The **threat**, according to Hermelin (1991), is the probability of occurrence of a potentially destructive phenomenon, within a specific time period and for a given area.

In this work, susceptibility was evaluated through geomorphological (morphometric–morphodynamic), sedimentological, and anthropic indicators. The indicators were as follows: slope, aspect, valley depth, geomorphology (processes, features), and road networks. Each of these variables was reclassified with values between 1 and 5, the lowest values associated with a lower flash flood probability.

A set of maps related to topographic features was elaborated using DEM. A valley depth map was generated using the SAGA GIS software (Conrad 2006) and slope, and aspect maps were generated using ArcGIS 9x.

Valley depth was calculated as the vertical distance to a channel network base level. The algorithm consists of two major steps: (1) interpolation of a channel network base level elevation and (2) subtraction of this base level from the original elevation. The defined classes are not uniform because it was necessary to prepare intervals with different contour intervals to show clearly the topographic differences in both the piedmont and the plain areas.

Concerning the **slope map**, the slope tool was used, which calculates for each cell the maximum rate of change in relation to the neighbors, and it can be represented in percentage or grades. In the study area, the slopes vary between 0 and 265% (Instituto Geográfico Agustín Codazzi (IGAC) 1982). The ranges of reclassified values were assigned taking into account the water removal velocity. Then, the lowest values of flood susceptibility correspond to steeper areas, where water can flow faster, whereas the highest values were linked with lower slopes where the flooding probability is much higher.

The **aspect map** indicates the direction of each cell in relation to the north, taking each cell values between 0° (north) and 360°. This variable was analyzed according to the interference that the relief generates on the runoff direction. The west and northwest directions, which coincided with water flow pathways, represent lower values. Instead, the cells facing to the east acquire the highest values because they act as a barrier or obstacle to water flowing. The intermediate classes correspond to the remaining orientations.

For the geomorphological and anthropic variables, layers of vector format information were used, which were converted to raster format with a pixel size of 30 × 30 m.

The **geomorphological regional map** (scale 1:50,000) was reclassified according to the flooding probability. The higher values correspond to fluvial belts and to the active distal alluvial fans. Intermediate values were assigned to the piedmont alluvial fans, which are usually incised. The lower classes correspond to the fluvial–eolian plain without connectivity with the active fluvial systems and to the mountain sector, where the streams have deep valleys.

This analysis was complemented by another more detailed examination that provided a geomorphological scenario that restricted the active processes during the reference flash flood. Thus, the geomorphological analysis was made using Google Earth detailed images, fieldwork, and eyewitness reports. The analysis is focused on the alluvial fans and lowest channel reaches given that the highest reaches are abrupt and uninhabited. In the case of the alluvial fans, the analysis includes the observation of preferential stream channels, stagnant water, overflow in meanders, erosion, and deposition zones. Field evidence was collected looking for the following: critical points of overflow, big boulders displaced by flow energy, tree roots covered by finer sediments, vegetation influence, and sediment retention.

Moreover, the survey related to anthropic aspects focused mainly in the **road network analysis**, because it is considered the variable that generates the greater interference with the drainage network. The roads influence the runoff spatial distribution, favoring the connectivity or causing interference in the water flow. In this study, a minimal interference of the road network is considered the more favorable situation. Although the affected area can be increased, the water level and velocity would be lesser, and therefore, damage degree would be lower.

In contrast, deep roads concentrate the runoff, increasing the water level and velocity. Even though the flooded area is smaller in these cases, the impact is greater due to their magnitude. The roads that are perpendicular to water flow direction generate interference or obstruct the natural drainage.

Finally, the flash flood susceptibility **map** was obtained using map algebra tool operations contained within ArcGIS 9x. Each variable had equal weight. The susceptibility value of a cell was considered as the sum of all the values of the variables under analysis. Five susceptibility classes were defined.

To assess the **threat**, the analysis was made taking into account temporal distribution and intensities of precipitation, field hydrological evidence, and eyewitness reports. The mean velocity values and water-level heights were used to estimate the threat magnitude. In some selected sections, during low flow conditions, water discharge was measured using a flow meter. To calculate the peak discharges, the following equation was applied:

$$Q = A * v$$

where Q is the discharge, A is the area of the cross section, and v is water velocity.

Cross sections were measured, taking into account water-level marks considering vegetation, sediment distribution, erosion features, and witness reports. These methods were applied in the two major tributaries (the Achiras and Hondo streams) and in the trunk stream.

The Manning and the paleo-hydraulic (Costa 1983) methods were used to estimate mean velocity values during the flash flood occurred on February 4, 2014.

Subsequently, the Manning equation was used:

$$v = \frac{R^{\frac{2}{3}} * S^{\frac{1}{2}}}{n}$$

where R is the hydraulic radius (A/Wp), A is the cross-sectional area, Wp is the wet perimeter, S is the channel slope (calculated for a stream reach from contour lines from topographic maps), and n is the roughness coefficient. Based on channel and floodplain characteristics (dominant particle sizes, type and percentage of cover vegetation, etc.), a "weighted n" was established (Chow 1959).

The paleo-hydraulic method is based upon obtaining the mean flow velocity by means of measuring the intermediate axis of the largest boulders moved by the flow (Costa 1983).

$$v = 0.182 * d^{0.4873}$$

where v is the water velocity, and d is the mean value of five intermediate axes of the five largest boulders displaced by flood. This method was applied in several studies (Maizels 1986; Gallardo and Colombo 1996; Beckwith 2001; Fernández Lavado 2007; Halcsik 2013).

To analyze the spatial distribution of the threat, hydro-geomorphological features and witness reports were used.

Finally, a **flash flood hazard map** was obtained based on the susceptibility classes, the threat magnitude, and spatial distribution. With this information, five classes of flash flood hazard were defined.

4 Results and Discussion

4.1 Susceptibility Analysis

4.1.1 Morphometric Indicators

The classes obtained for morphometric indicators (valley depth, slope, and aspect) and their spatial distribution are shown in Figs. 3, 4, and 5 and Table 1.

When these indicators are analyzed together, they show that the Arroyo Chuchiras upper basin has morphometric characteristics that favor a fast evacuation of channel flow. In the piedmont area, the gradients are in general between 7 and

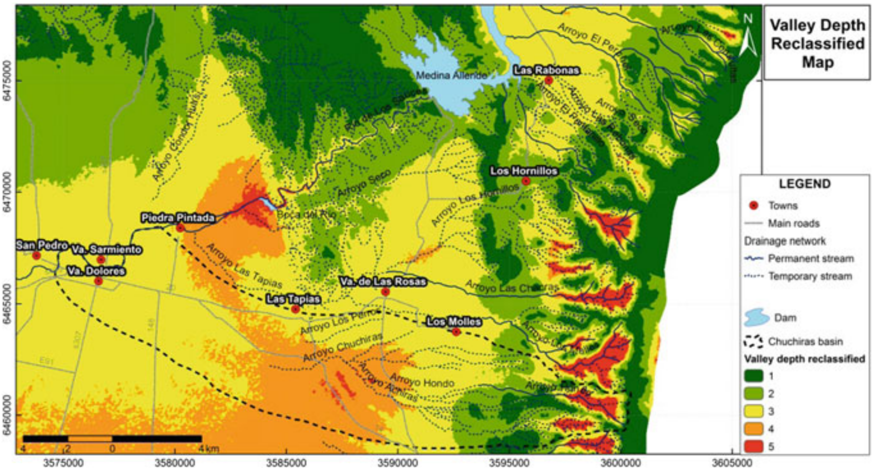

Fig. 3 Reclassified valley depth map, according to flash flood susceptibility.

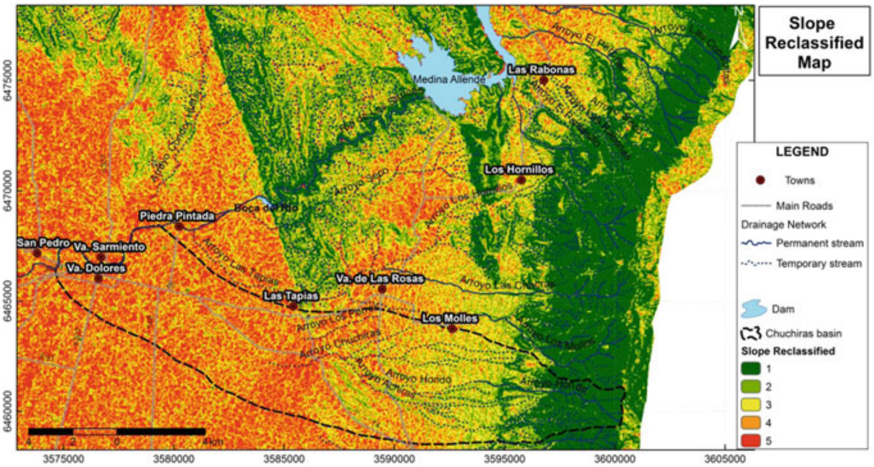

Fig. 4 Reclassified slope map, according to flash flood susceptibility.

12%, with the highest values in the uplift front of the first alluvial fan level. This environment is incised by the main stream, and it is the place where many secondary channels originate (low valley depth values). All the tributary streams converge in a sector related to the Pocho fault line. From this line to the west, the value of the slope decreases markedly and the aspect values are more variable, with a dominant northwest direction. In addition, the valley depth values increase in relation to the previous unit. From a morphometric point of view, this area shows high flash flood susceptibility.

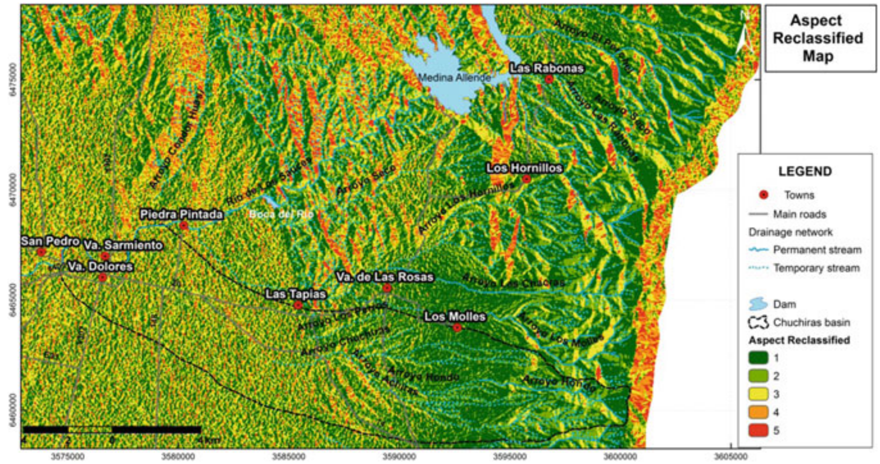

Fig. 5 Reclassified aspect map, according to flash flood susceptibility

Table 1 Susceptibility ranges for each variable

Range	Morphometry			Geomorphology	Road network
	Valley depth	Slope	Aspect		
1	0–80.56 m	>25%	225°–315°	Deep valleys, high local relief (mountain areas). Channel incision >6 m. Dominant processes: erosion, transport. Fluvial–eolian plain, without connectivity with the fluvial system	Without roads, there are not interferences
2	80.56–161.39 m	12–25%	315°–0° and 180°–225°	Defined valley, moderate/high local relief. Main channel incision between 4.5 and 6 m. Dominant processes: transport, erosion. Fluvial–eolian plain, with very low connectivity with the fluvial system	Primary and secondary roads: parallel or oblique, not deepened
3	161. 39–261 m	7–12%	0°–45° and 135°–180°	Defined valley, moderate local relief. Main channel incision between 3 and 4.5 m. Dominant processes: transport, much localized avulsion and overflows. Non-channeled flow in distal alluvial fan	Primary and secondary roads: perpendicular, low deepened

(continued)

Table 1 (continued)

Range	Morphometry			Geomorphology	Road network
	Valley depth	Slope	Aspect		
4	261–290.55 m	3–7%	90°–135°	Poorly defined valleys, minimum local relief. Distributary drainage network. Main channel incision between 1.5 and 3 m. Dominant processes: avulsion, overflows, moderate–fast sedimentation. Non-channeled flow in middle alluvial fan	Primary and secondary roads: parallel or oblique, deepened
5	290.55–530.48 m	0–3%	45°–90°	Poorly defined valleys, minimum local relief. Distributary drainage network. Main channel incision <1.5 m. Dominant processes: avulsion, overflows, erosion, fast sedimentation	Primary and secondary roads: perpendicular, deepened

4.2 Geomorphological, Sedimentological, and Morphodynamic Analysis

The piedmont area has a flash flood susceptibility degree between moderate analysis and high (Fig. 6). The moderate class is mainly related to two different geomorphological environments: (1) the faulted and raised old fans located in the first piedmont level and (2) the distal areas of the active alluvial fan of the Arroyo Chuchiras.

In the first environment, the drainage network is formed mainly by collector channels which show different incision degree and valley development. In general, these channels have the capacity to evacuate extreme flows without generating overflow. The channels are straight to slightly sinuous with moderate to high slope, dominated by transport processes, especially of very coarse bedload. In this area, some secondary distributary channels, corresponding to historical alluvial fans of the Los Molles and San Javier streams (outside the study area), are secondarily recognized. During extraordinary floods, these channels could be reactivated and they may transfer discharge toward the Arroyo Chuchiras basin.

The second environment, by contrast, is a plain with low local relief dominated by mantle-shaped runoff or slightly channeled flow systems in larger depressions, without erosion features. The sedimentation of finer materials dominated in these distal positions.

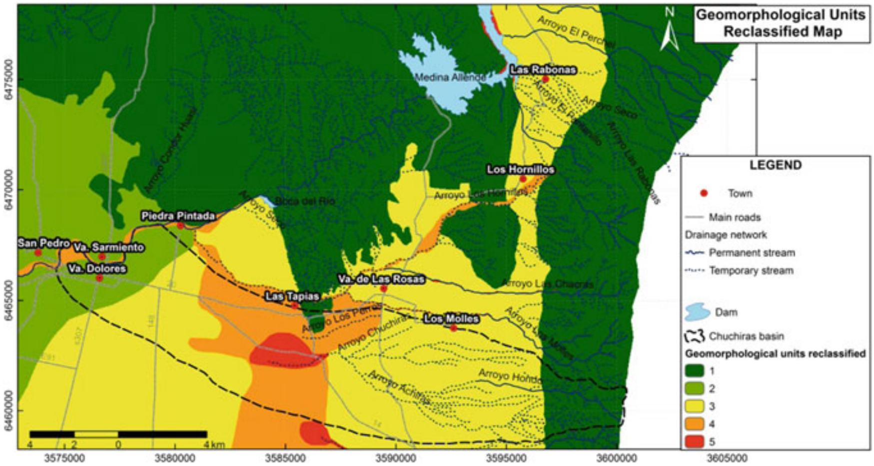

Fig. 6 Reclassified geomorphological unit map, according to flash flood susceptibility

The moderately high and high classes (approximately 15%) are associated with lower reaches and active alluvial fans of the Chuchiras and Los Perros streams, which interdigitate in the middle-distal piedmont sector. This sector shows a slightly undulating relief and local slopes that are less than 2%. The drainage network of both fans shows very few distributary courses, and it is formed by the main collector and preferential flow pathways which are generally not channeled, associated with wider and flatter topographic depressions. In the main channel, in general with lower incision, overflows during the flood events are common. It is enlarged with decreasing of the cross section by sedimentation or blockage caused by sediment and vegetation accumulation.

Lower susceptibility classes represent 60% of the area under study, and it includes the mountain basin of the Arroyo Chuchiras and also the transition zone between the distal piedmont and fluvial–eolian plains. In the first case, the courses that drain the scarp have narrow and deep valleys that transport large volumes of water without possibility of overflow. The straight and steep sloped channels have high competence and transport capacity. In the second case, it includes peripheral plains of the active alluvial fan of the Arroyo Chuchiras that has minimal probability of being affected by flash flood events.

4.3 Road Network Analysis

As shown in Fig. 7, roads and routes that are located in an oblique or transversal position to the regional slope dominate the basin. Thus, there are interference situations of moderate to high degree. In general, the roads are not very deep, but in the middle-distal piedmont plains, where local relief is lower and the drainage

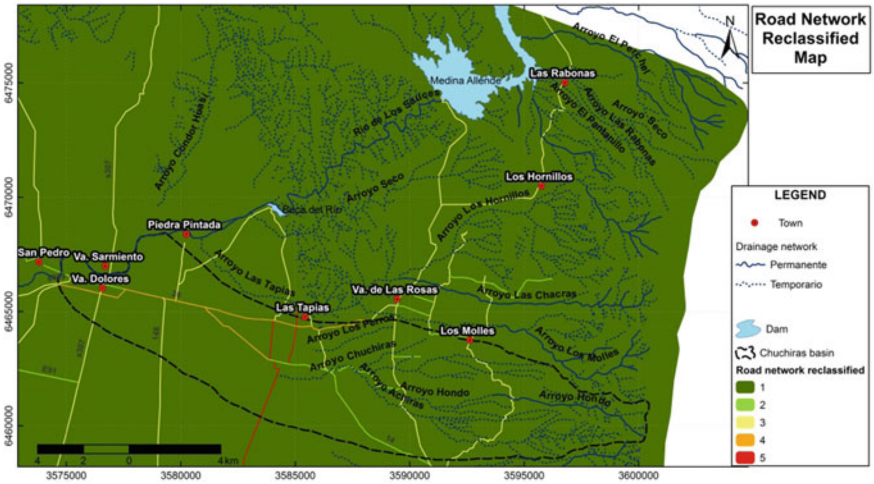

Fig. 7 Reclassified road network map, according to flash flood susceptibility

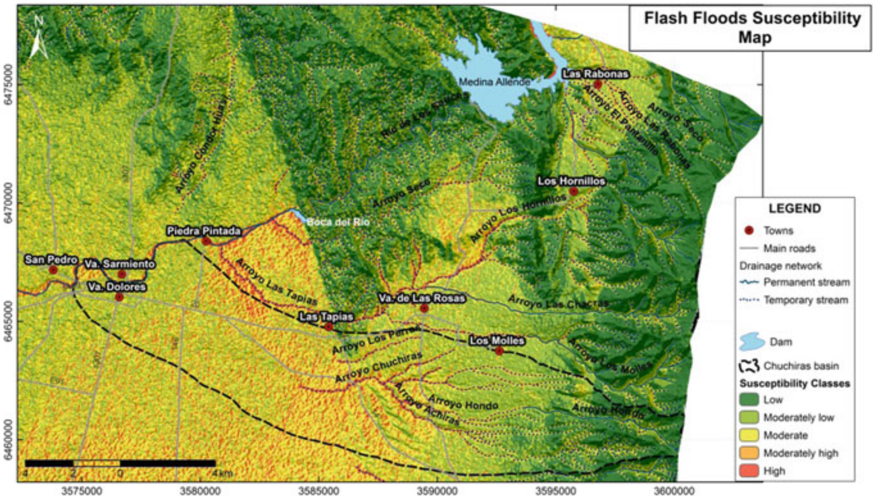

Fig. 8 Flash flood susceptibility map

network is poorly defined, there are high probabilities that the roads collect and modify water flow.

Finally, the **flash flood susceptibility map** is shown in Fig. 8. The spatial distribution of the classes is strongly conditioned by geomorphological features, slopes, and local relief. Thus, middle-distal piedmont basin (50% of the total area) presents moderate to high susceptibility, and both the proximal piedmont and the mountain sector belong to low and moderately low classes.

4.4 Threat Analysis

Concerning the magnitude of the threat, results of velocity and discharge estimates for the extraordinary event of the February 4, 2014, are shown in Table 2. High water values measured and witness reports are shown as well.

To characterize the threat, a flood discharge estimated in the order of 176–200 m^3/s (recurrence of 20–30 years, according to witness reports) is considered, associated with the Arroyo Chuchiras (P1), where the velocity, water surface elevation, and clasts size values were higher than the rest of the sections considered (Figs. 9, 10 and 11). At this point in the confluence of several streams, those that have headwaters and drain a significant area in the piedmont sector become relevant. In the considered event, the estimated flow values suggest that the rainfall was higher than those recorded in the mountainous area.

When the distribution and magnitude of the threat are analyzed together, it is possible to observe that, upstream of point 1, as you indicated, the channels are incised with low chances of overflow, so the threat is concentrated in the active channel. In this sector, the estimated velocity range between 1.7 and 2.4 m/s, the size of the transported clasts is equal to or greater than 100 mm and water height is less than 1 m (P6, P7, and P8).

Downstream of P1, in the middle to lower reaches of the Arroyo Chuchiras, the threat is spatially distributed, conditioned mainly by the geomorphological characteristics and processes in the alluvial fan. At this point, water can circulate westward to national route 148 or drive along the NW–SE topographic depression toward national route 20, as it was the case in the event of flood analyzed. In this area, the depth roads constitute a pathway of water circulation, where the velocities are equal to or less than 2 m/s, with clast sizes mobilized by the stream that vary between 76 and 140 mm (P2, P3, and P4).

Flood mark observations indicate that the height reached by the water was not higher than 1.5 m, decreasing significantly in the direction of national route 20.

Table 2 Water height values measured and reported. Velocity and discharge values estimated by Manning and Paleo-hydraulic methods

	Water height (m)	Manning method		Paleo-hydraulic method		
		Velocity (m/s)	Discharge (m^3/s)	Velocity (m/s)	Discharge (m^3/s)	Boulders diameter (d) (mm)
P1	1.70	3.3	200	2.9	176.7	300
P2	0.40	No data	No data	1.5	No data	76
P3	1.5	No data	No data	2.0	No data	140
P4	1	No data	No data	1.7	No data	100
P6	0.6	No data	No data	1.7	No data	100
P7	0.3	1.4	3.1	2.6	5.68	230
P8	0.65	2.4	13.2	2.4	13.3	200

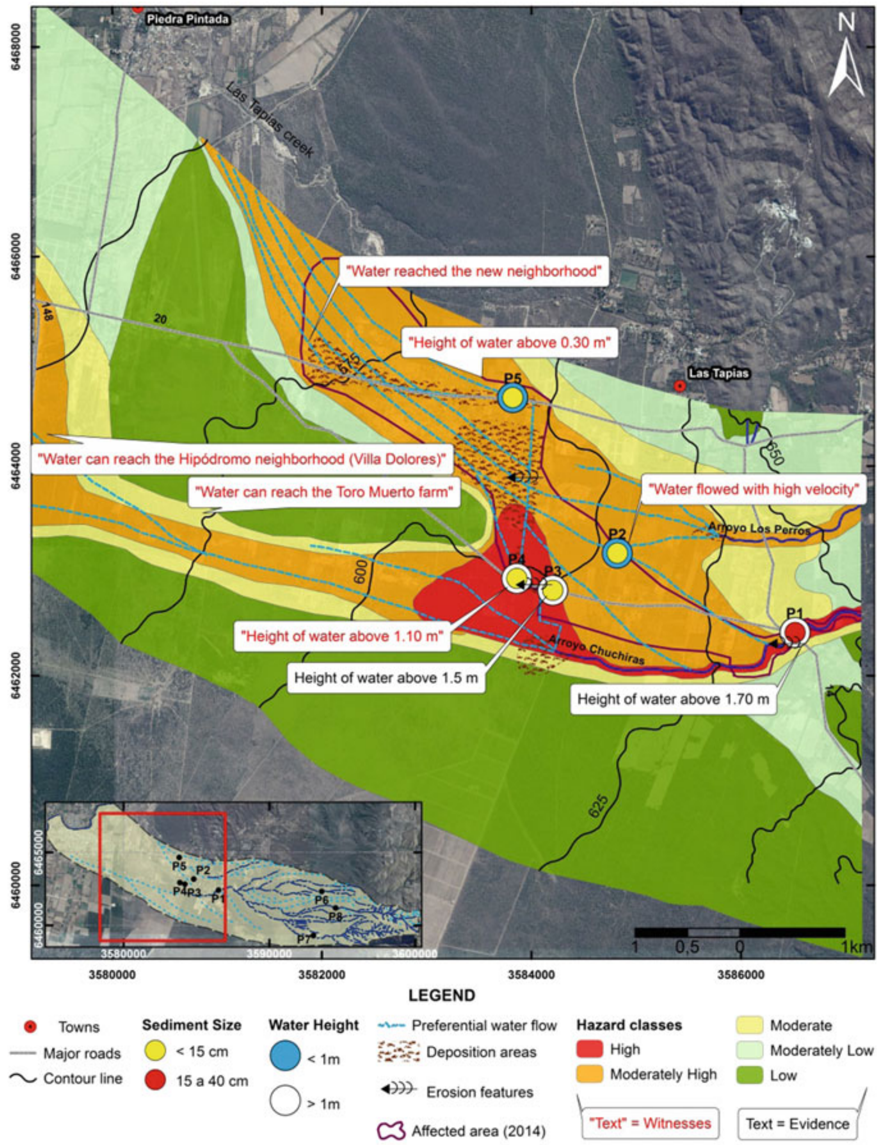

Fig. 9 Flash flood hazard map at the Arroyo Chuchiras lower basin, geomorphological and hydrological indicators and affected area during the 2014 flood

Fig. 10 Water height during the flash flood (**a**, **b**, **c**) and water-level marks considering the vegetation (**d**, **e**). Photograph locations in Fig. 9: **a** P4, **b** and **c** P5, **d** P1, **e** P3

Finally, with the available information of water height and velocity, three threat classes were defined (Table 3).

The threat behavior is as follows: (1) In P1, the threat is maximum and decreases downstream of this sections because water spreads over the alluvial fan, and consequently, the water level falls and velocity decreases and (2) during the peak discharge, water spreads over the fan, and velocity is higher in the preferential circulation channels (height threat) than in the intermediate zones (moderate–low threat).

Fig. 11 Clasts transported by the flow during flash flood event. Photograph locations in Fig. 9: **a** P4, **b** P3, **c** and **d** P1, **e** P2

Table 3 Threat classes defined for velocity and water height

Classes	Threat
High	Water height: >1 m and velocity: >2.5 m/s
Moderate	Water height: 1–0.10 m and velocity: 2.5—y 1 m/s
Low	Water height: <0.10 m and velocity: <1 m/s

Table 4 Flood flash hazard classes according to susceptibility and threat

Susceptibility	Threat		
	High	Moderate	Low
High	High	Moderately high	Moderate
Moderately high	High	Moderately high	Moderate
Moderate	Moderately high	Moderate	Moderately low
Moderately low	Moderate	Moderate	Moderately low
Low	Moderate	Moderately low	Low

4.5 Flash Flood Hazard Map Analysis

The classes defined by flood flash hazard and their spatial distribution are shown in Table 4 and Fig. 9, respectively.

As shown in Fig. 9, approximately 64% of the lower basin of the Arroyo Chuchiras presents low to moderately low flash flood hazard, mainly related to sectors at relatively high elevation, with a local relief generally less than 10 m. The two highest susceptibility classes (high and moderately high) account together for 26% of the total area. The high class is associated with the lower reaches and proximal-middle active alluvial fans of the Chuchiras and Los Perros streams. The moderately high class is associated with NW–SE topographic depressions, which correspond to the distal alluvial fan areas. The remaining 10% has moderate hazard and corresponds to peripheral areas of active alluvial plains (belts and fans fluvial plains).

Moreover, in Fig. 9, the flooded area during the event of February 4, 2014, is shown. In this flood, the Arroyo Chuchiras overflowed downstream when intercepting route 14 because of its reduced cross section and accumulation of vegetation, which obstructed water flow. The overflows followed natural runoff paths and partially deepened roads toward the NW–SE topographic depression, flooding route 20 and surrounding highly urbanized areas, which would be associated with moderately high and high hazard classes. In this event, flooding did not take place toward the west (the distal fan area of the Arroyo Chuchiras) due to the influence of the road network in the water flow.

As shown in Fig. 9, there is a high correspondence between the predictive map and the February 4, 2014, flood real scenario, showing also the impact of anthropogenic interventions in the natural susceptibility and the threat behavior.

5 Conclusions

The flash flood hazard in the western piedmont of the Sierras Grandes de Córdoba is the result of the combination of the following variables: (1) lower permeability rocks in the upper basin; (2) important topographical contrasts (local relief and slopes) between the fault scarp and the piedmont area; (3) rivers and streams with torrential regime and high energy (velocity, competence, and transport capacity) that make up distributary systems in the distal-middle piedmont; and (4) high intensity rainfalls concentrated in the summer season.

The threat magnitude is the result of the confluence of concentrated and not concentrated flows, being the latter quite relevant in the piedmont area.

The poor definition of the piedmont basin boundaries and the predominance of avulsion processes repeatedly promote the connection between neighboring basins. Thus, water transfer in between basins may occur, making difficult the threat estimation.

The road network has a moderate and more localized incidence, especially in the threat magnitude and distribution.

In basins lacking systematic information, the implementation of geomorphological methodologies shows results compatible with real scenarios. This suggests that predictive mapping could be a useful tool for land use planning and management.

Given that flooding in the area causes problems both in urban and rural areas, its mitigation requires interventions of different types. On one side, some flexible and sustainable engineering work is necessary in order to regulate the threat or to decrease the susceptibility, especially in populated areas and road infrastructure. On the other side, land use planning and management that take into account fluvial systems behavior are necessary. This will not only promote the hazard decrease but also will diminish the vulnerability, reducing this way the risk of catastrophic episodes.

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References

Ambrosino S, Barbeito O, Bertoni JC, Daniele A, Maza JA, Ubaldo Paoli C, Serra JJ (2004) Inundaciones urbanas en Argentina. INA, Córdoba, Argentina

Anquetin S, Braud I, Vannier O, Viallet P, Boudevillain B, Creutin JD, Manus C (2010) Sensitivity of the hydrological response to the variability of rainfall fields and soils for the Gard 2002 flash-flood event. J Hydrol 394:134–147. doi:10.1016/j.jhydrol.2010.07.002

Bajabaa S, Masoud M, Al-Amri N (2014) Flash flood hazard mapping based on quantitative hydrology, geomorphology and GIS techniques (case study of Wadi Al Lith, Saudi Arabia). Arab J Geosci 7:2469–2481

Beckwith DD (2001) Sedimentologic processes and glaciogenic landforms at the Herbert Glacier Ice Front, southeast Alaska: Colorado Springs, Colorado, Colorado College, Unpublished B.S. thesis, 93 p

Bonalumi A, Martino R, Baldo E, Zarco J, Sfragulla J, Carignano C, Kraemer P, Escayola M, Tauber A (1999). Hoja Geológica 3166-IV, Villa Dolores. Programa Nacional de Cartas Geológicas de la República Argentina, 1:250.000, 122 p., Córdoba

Borga M, Stoffel M, Marchi L, Marra F, Jakob M (2014) Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. J Hydrol 518:194–205. doi:10.1016/j.jhydrol.2014.05.022

Busnelli J, Horta LR (2014) Morfometría de cuencas montanas y metamorfosis fluvial, Tucumán. Revista de la Asociación Geológica Argentina 71(1):11–20 (Buenos Aires)

Capitanelli RG (1979) Clima. In: Geografía física de la Provincia de Córdoba. Editorial Boldt, Córdoba, Argentina

Carpenter TM, Sperfslage JA, Georgakakos KP, Sweeneyc T, Fread DL (1999) National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems. J Hydrol 224:21–44

Catane SG, Abon CC, Saturay RM Jr, Mendoza EPP, Futalan KM (2012) Landslide-amplified flash floods—the June 2008 Panay Island flooding, Philippines. Geomorphology 169–170:55–63. doi:10.1016/j.geomorph.2012.04.008

Cendrero A (1987). Riesgos geológicos, ordenación del territorio y protección del medio ambiente. 1° Curso de riesgos geológicos. Instituto Geológico Minero de España, Madrid, pp 327–333

Chow VT (1959) Open-channel hydraulics. McGraw-Hill, New York

Conrad O (2006) SAGA—program structure and current state of implementation. In: Böhner J, McCloy KR, Strobl J (eds) SAGA—analysis and modelling applications, vol 115. Göttinger Geographische Abhandlungen, pp 39–52

Costa JE (1983) Paleohydraulic reconstruction of flash-flood peaks from boulders deposits in the Colorado Front Range. Geol Soc Am Bull 94:986–1004

Dawod GM, Mirza MN, Al-Ghamdi KA (2011) GIS-based spatial mapping of flash flood hazard in Makkah City, Saudi Arabia. J Geogr Inf Syst 3:225–231. doi:10.4236/jgis.2011.33019

De Waele J, Martina MLV, Sanna L, Cabras S, Cossu QA (2010) Flash flood hydrology in karstic terrain: Flumineddu Canyon, central-east Sardinia. Geomorphology 120:162–173. doi:10.1016/j.geomorph.2010.03.021

Elkhrachy I (2015) Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA). Egypt J Remote Sens Space Sci 18:261–278. doi:10.1016/j.ejrs.2015.06.007

Esper Angillieri MY (2007) El aluvión del 13 de febrero de 1944 en la Quebrada del Carrizal, Departamento Iglesia, provincia de San Juan. Revista de la Asociación Geológica Argentina 62 (2):283–288 (Buenos Aires)

Fernández Lavado C, Furdada G, Marqués MA (2007) Geomorphological method in the elaboration of hazard maps for flash-floods in the municipality of Jucuarán (El Salvador). Nat Hazards Earth Syst Sci 7:455–465

Gallardo G, Colombo F (1996) Caracterización paleohidráulica de algunos litosomas conglomeráticos paleógenos de la cuenca del Ebro. Ejemplos en la Conca de Barberá (Tarragona). Geogaceta 19:109–112

Garambois PA, Larnier K, Roux H, Labat D, Dartus D (2014) Analysis of flash flood-triggering rainfall for a process-oriented hydrological model. Atmos Res 137:14–24. doi:10.1016/j.atmosres.2013.09.016

Garambois PA, Roux H, Larnier K, Labat D, Dartus D (2015) Parameter regionalization for a process-oriented distributed model dedicated to flash floods. J Hydrol 525:383–399. doi:10.1016/j.jhydrol.2015.03.052

Gaume E, Livet M, Desbordes M, Villeneuve JP (2004) Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999. J Hydrol 286:135–154. doi:10.1016/j.jhydrol.2003.09.015

Gaume E, Bain V, Bernardara P, Newinger O, Barbuc M, Bateman A, Blaškovicová L, Blöschl G, Borga M, Dumitrescu A, Daliakopoulos I, Garcia J, Irimescu A, Kohnova S, Koutroulis A, Marchi L, Matreata S, Medina V, Preciso E, Sempere-Torres D, Stancalie G, Szolgay J, Tsanis I, Velascom D, Viglione A (2009) A compilation of data on European flash floods. J Hydrol 367:70–78. doi:10.1016/j.jhydrol.2008.12.028

Gil V (2011) Geomorfología fluvial de la cuenca del arroyo El Negro, Buenos Aires, Argentina. Revista Universitaria de Geografía 20:151–169

Gutiérrez F, Gutiérrez M, Sancho C (1998) Geomorphological and sedimentological analysis of a catastrophic flash flood in the Arfis drainage basin (Central Pyrenees, Spain). Geomorphology 22:265–283

Halcsik CR (2013) Investigating late Pleistocene and Anthropocene flood deposits along North Boulder and Caribou Creek, Colorado Front Range. Unpublished graduation thesis. Beloit College, Wisconsin

Hermelin M (1991) Introducción a la Geología Ambiental. Geología Ambiental y Geomorfología aplicada en Colombia. Asociación de Geocientíficos para el Desarrollo Internacional (AGID) Reporte 16:3–20

Hooke JM, Mant JM (2000) Geomorphological impacts of a flood event on ephemeral channels in SE Spain. Geomorphology 34:163–180

Instituto Geográfico Agustín Codazzi (IGAC) (1982) Estudio general de suelos y zonificación de tierras. Estudio general de suelos de la región nororiental del departamento del Cauca. Bogotá, Colombia

Jha AK, Bloch R, Lamond J (2012) Cities and flooding. a guide to integrated urban flood risk management for the 21st century. International Bank for Reconstruction and Development and International Development Association, Washington, DC

Koutroulis AG, Tsanis IK (2010) A method for estimating flash flood peak discharge in a poorly gauged basin: case study for the 13–14 January 1994 flood, Giofiros basin, Crete, Greece. J Hydrol 385:150–164

Lang M, Fernández Bono JF, Recking A, Naulet R, Grau Gimeno P (2004) Methodological guide for palaeoflood and historical peak discharge estimation. In: Benito G, Thorndycraft VR (eds) Systematic, Palaeoflood and historical data for the improvement of flood risk estimation. Methodological guidelines. CSIC—Centro de Ciencias Medioambientales, Madrid

Maizels JK (1983) Paleovelocity and palaeodischarge determination for coarse gravel deposits. In: Gregory KJ (ed) Background to palaeohydrology: a perspective. Wiley, pp 101–139

Maizels JK (1986) Modeling of Paleohydrologic change during deglaciation Géographie physique et. Quaternaire 40(3):263–277. doi:10.7202/032648ar

Marchi L, Borga M, Preciso E, Gaume E (2010) Characterization of selected extreme flash floods in Europe and implications for flood risk management. J Hydrol 394:118–133. doi:10.1016/j.jhydrol.2010.07.017

Martín Vide JP, Martín Moreta PJ, López Querol S, Machado MJ, Benito G (2002) Tagus river: historical floods at Talavera de la Reina. In: Thorndycraft VR, Benito G, Barriendos M, Llasat MC (eds) Palaeofloods, historical data & climatic variability. Applications in flood risk assessment, CSIC—Centro de Ciencias Medioambientales, Madrid

Nikolopoulos EI, Anagnostou EN, Borga M, Vivoni ER, Papadopoulos A (2011) Sensitivity of a mountain basin flash flood to initial wetness condition and rainfall variability. J Hydrol 402:165–178

Ogden FL, Sharif HO, Senarath SUS, Smith JA, Baeck ML, Richardson JR (2000) Hydrologic analysis of the Fort Collins, Colorado, flash flood of 1997. J Hydrol 228:82–100

Panizza M (1993) Riesgo geomorfológico y vulnerabilidad ambiental. Quaderni Instituto Italo Latino Americano (IILA), Serie Scienza 6. México

Phillips JD (2002) Geomorphic impacts of flash flooding in a forested headwater basin. J Hydrol 269:236–250

Thornthwaite C (1948) An approach towards a rational classification of climate. Geogr Rev 38 (1):221–229

Williams GP (1984) Paleohydrologic equations for rivers in developments and applications of geomorphology, pp 343–367