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The impact of rainstorms on floods in ephemeral channels in southeast Spain

L.J. Bull [a,*], M.J. Kirkby [a], J. Shannon [b,1], J.M. Hooke [c,2]

[a] *School of Geography, University of Leeds, Leeds, LS2 9JT, UK*
[b] *Department of Geography, King's College London, University of London, Strand, London, WC2R 2LS, UK*
[c] *Department of Geography, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth, PO1 3HE, UK*

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Abstract

This paper presents and discusses data on rainfall, stage and estimated discharge for a large flood occurring in two catchments in southeast Spain in September 1997. Rainfall and stage were recorded using automatic logging equipment and discharge was estimated using measurements of channel cross-sections and water depth estimated from trash lines. Total precipitation in the Rambla de Torrealvilla was 50 mm in 2 days with maximum rainfall intensities of 80 mm h^{-1}. Total rainfall in the Rambla de Nogalte was 195 mm in 3 days, with maximum intensities of 200 mm h^{-1}. In the Torrealvilla, this rainfall produced three flood peaks with maximum stage approaching 2.5 m. In the Nogalte, there was only one flood peak, which was 0.5 m deep. Estimated discharge varied widely throughout both catchments with maxima of 120 m^3 s^{-1} in the Torrealvilla and 60 m^3 s^{-1} in the Nogalte. Maximum discharges occurred at times of high rainfall intensity, but intensity alone did not explain why some tributaries had very small discharges. Variations in discharge in the ephemeral channels were due to combinations of lithology, morphology and land use. The predominantly marl catchment of the Torrealvilla had a lower threshold rainfall intensity than the schists of the Nogalte. Within each catchment sub-basins characterised by steep, gorge like terrain and sub-basins where agriculture had been abandoned both resulted in higher flood discharge. The contributing areas for the September storms were up to two thirds of tributary catchment areas. Comparison of rainfall data records shows that the September flood was the fifth largest on record and had a recurrence interval of 7 years. The largest (1973) flood, which is known to have caused substantial damage and a number of deaths, was only a 30-year event. The floods on the Torrealvilla destroyed at least two check dams and

* Corresponding author. Tel.: +44-113-233-3300; fax: +44-113-233-3308; E-mail: jbull@geog.leeds.ac.uk
[1] Tel.: +44-171-873-2738.
[2] Tel.: +44-1705-842-589.

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evidence suggests that these had little effect on reducing the impact of the floods.

Keywords: Ephemeral streams; Discharge; Rainfall intensity; Lithology; Land use; Morphology

1. Introduction

The conditions, position and connectivity of runoff and sediment source areas in semi-arid catchments have a profound effect on flood characteristics of ephemeral streams. The relationship between rainfall, the source areas of runoff and the flood hydrograph is complex and, because of the discrete nature of each convective cell, an individual storm is unlikely to affect the entire drainage basin and successive storms will affect different parts of a catchment (Schick and Lekack, 1987). Total annual precipitation for the region is less then 500 mm, and this is concentrated in a few winter months. Rainfall in the Mediterranean is usually very intense (Obled and Tourasse, 1994; IGN, 1995), exhibits an erratic temporal and spatial distribution, and can be very localized (Thornes, 1976; Alonso-Sarria and López-Bermúdez, 1994). The likelihood of very large floods is therefore small because the precise conditions needed to produce outflow from sub basins across the whole of a catchment rarely occur.

This paper presents partial records of rainfall and runoff for floods in two catchments in southeast Spain in September 1997. The recorded rainfall data are linked to estimates of peak flood discharge that were made throughout the catchments following the storms. These data are used to investigate variations in discharge throughout the ephemeral channel systems and to estimate rainfall intensities and return periods for previous large floods. These estimates of changing flood discharge are some of the first of their kind and allow us insight into conditions promoting floods.

2. Methodology

2.1. Study area

The work was carried out in two catchments; the Rambla de Nogalte located on the border of the Provinces of Murcia and Almería, and the Rambla de Torrealvilla located in the Province of Murcia, southeast Spain (Fig. 1). Characteristics of the two study basins are summarised in Table 1. The Rambla de Nogalte is the larger basin and drains mainly metamorphic rocks and conglomerates, dominated by red mica schist, but with localised outcrops of blue mica schist. The soils derived from the brownish-red mica schist are thick, but soils associated with the bright blue, flaky mica schist, are thin with sparse or no matorral vegetation cover. Mountains leading down to the main channel surround the basin, which is a dynamic catchment with a broad wandering gravel bed river. Much of the catchment is characterised by convex hillslopes gently sloping towards the channel. The Nogalte is predominantly used for almond cropping which leaves a mainly bare surface between planted trees, although in some areas matorral is

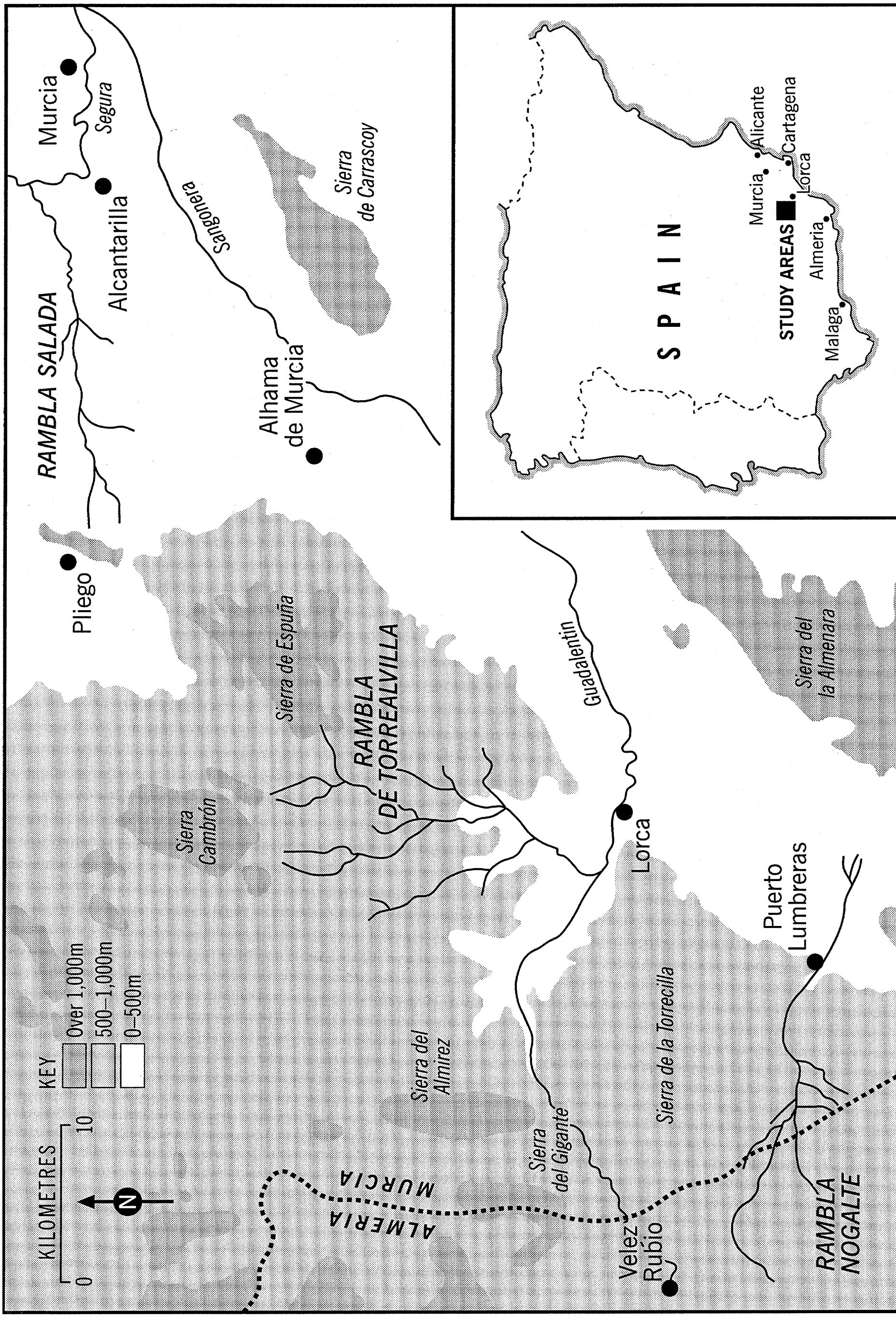

Fig. 1. Location map of study sites.

Table 1
Characteristics of the study basins

Characteristic	Rambla de Nogalte	Rambla de Torrealvilla
Area (km^2)	171	113
Lithology	metamorphic and conglomerates	marls and sedimentary rocks
Nature of slopes	convex	dissected pediments
Dominant processes	creep / wash and rilling	splash, wash and mass failures at gully heads
Land use	almond / olives	scrub / dry crops with outliers of forest

prevalent. Matorral is natural scrub, composed mainly of anthyllis, grasses, rosemary, and thyme. Matorral is found on steeper slopes and provides a more continuous cover of vegetation compared with tree crops. The headwaters of the Rambla de Nogalte are well connected with the highland areas and sediment yield is largely transport limited due to significant amounts of gravel throughout the system.

The Rambla de Torrealvilla drains varied lithology, including large areas of marls and other sedimentary rocks. The catchment is characterised by a steep sided channel cut into a relatively flat piedmont surface, with surrounding high relief. The lower part of the catchment is characterised by large areas of undissected pediments, within which there are well-developed box-shaped channels (arroyos) with steep sides which undergo active lateral and headward retreat. Channel reaches vary between bedrock sections, sandy beds and reaches of coarse cobbles and boulders. Gully expansion and re-filling have occurred episodically on more than one occasion, and it is surmised that the entire pediment surface reflects periods of mainly depositional activity. Small upland areas of resistant rocks persist, but are generally not well connected to the arroyo systems. The Torrealvilla is used for growing wheat, water melons and lettuces. Those areas not used for arable farming tend to be left as matorral and scrub which results in small outliers of forest on rounded hill tops. There are also some small areas of natural vegetation and abandoned agriculture.

2.2. Instrumentation and calculations

Rainfall was measured at seven locations in the Nogalte catchment and at one location in the Torrealvilla catchment using Casella 0.2 mm tipping bucket rain gauges with integral loggers. Rainfall was recorded every minute. Rainfall intensities were calculated from the number of 0.2 mm tips per minute during periods of high intensity rainfall and from the interval been tips when intensities are low. Flow stage was recorded at two locations in the Nogalte and at one location in the Torrealvilla using the Metrolog logging system with Druk pressure transducers (PTX 530-1521). All data loggers were standardised and set to GMT.

The magnitude of the last major flood was estimated using three different methods. Firstly, using trash lines and measurements of the channel cross-section and channel slope. Straight, uniform sections of channel were chosen for discharge estimates where trash lines were well preserved. Trash lines were located for both sides of the channel and were checked to be at the same level using a clinometer. The width, depth and hydraulic radius (R) were measured and the Manning's n roughness coefficient (n) estimated. Manning's n was estimated from cross-section characteristics, grain size and vegetation (Barnes, 1967; Acrement and Schneider, 1990). The channel slope (S) of the reach in question was used rather than the estimated water surface slope to increase the accuracy and reproduction of data. These variables were used to calculate the flow velocity (v) using Manning's equation:

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

and the discharge (Q in $m^3\ s^{-1}$) using:

$$Q = vA \tag{2}$$

where A represents the cross-sectional area (m^2).

Secondly, some cross-sections were surveyed using a geodimeter to measure cross-sectional area in detail and to survey slope of the channel and flood surface accurately. These measurements were then used in the Manning equation as above. Flood levels were confirmed by readings on crest stage recorders at certain locations (cross-sections surveyed by both methods gave comparable results, providing a check on the tape and clinometer method).

Thirdly, discharges (Q) were estimated at check dams using the equation to estimate flow over broad crested weirs (Ackers et al., 1978):

$$Q = C_d C_v \frac{2}{3} \left(\frac{2g}{s} \right)^{0.5} bh^{1.5} \tag{3}$$

where C_d = coefficient of discharge; C_v = coefficient of velocity; b = width of check dam (m); h = flow depth above weir (m).

The coefficient of velocity accounts for any velocity at the upstream trash mark and the coefficient of discharge accounts for any energy loss between the upstream trash mark and the crest of the check dam. Values of 1.0 were used for these coefficients, which assumes the ideal case, that there is no energy loss and a stationary body of water upstream. However, measurements were unlikely to be accurate enough to warrant using alternative values (Ackers et al., 1978).

Runoff has been estimated by assuming that soil water storage is controlled by the Green and Ampt (1911) equation:

$$f = A + \frac{B}{S} \tag{4}$$

where f is the infiltration rate (mm/s), A is the steady infiltration rate due to gravity, S is the total infiltrated so far into the suction store, B is a constant, so that the B/S term is the suction component.

The gravity component of infiltration (A), in which water flows through soil pores under the hydraulic gradient provided by gravity, is determined by the hydraulic conductivity. The second component of infiltration (B/S) is due to suction. Peak runoff q_{pk} can then be calculated using the following equation:

$$q_{pk} = R - f \tag{5}$$

where q_{pk} is the peak runoff generated in mm h^{-1}, R is the rainfall, and f is the maximum infiltration rate.

The contributing area (A_c) in km^2 can then be calculated as:

$$A_c = 3.6 \frac{Q_{pk}}{q_{pk}} \tag{6}$$

where Q_{pk} is the estimated peak discharge in m^3 s^{-1} from field evidence, q_{pk} is the peak runoff generated in mm h^{-1}, and 3.6 is a constant of conversion.

3. Results

3.1. Storm characteristics

3.1.1. Nogalte

Fig. 2 shows rainfall intensities from 11 March 1997 to 5 January 1998. The floods in the Nogalte were caused by the storms on the 29 September 1997. For this day, all the rain gauges registered three intense rain events. At most rain gauges, the first two storms had similar maximum intensities, approaching 200 mm h^{-1} and the third storm was much less intense at approximately 50 mm h^{-1}. The maximum rainfall intensities were much higher than expected.

These data can be plotted at a much greater temporal resolution to determine the detail of the individual storms that produced flow in the main channel (Fig. 3). Sites sub 9 and sub 12 both show a double peaked rainfall event followed by lower intensity bursts of rainfall. The initial intense storm produced maximum rainfall intensities approaching 200 mm h^{-1} with storm duration of about 15 min, and the second had maximum intensities of 150 mm h^{-1} over approximately 10 min. At site sub 9, the two bursts of rain were separated by about 5 min of very slight rain, while at site sub 12, the peaks were also 5 min apart but the rainfall was still relatively intense. These sites experienced a much larger total rainfall than the other sites.

At sites sub 7 and S2, there were three and two intense bursts of rain, respectively, but the maximum rainfall intensity was below 100 mm h^{-1}. At both sites, these peaks of rain occurred over approximately 20 min. At sites S1 and S3, there was a single very intense burst of rain with maximum intensity greater than 200 mm h^{-1}. These individual storms lasted for about 20 min. At site S3, there was a short lived preceding peak with maximum intensity of 75 mm h^{-1}. At site N1, there was one double peaked intense storm, the initial spike had maximum intensity of 150 mm h^{-1} and the second spike approximately 75 mm h^{-1}. This double peaked event lasted 14 min.

The timing of maximum intensity rainfall was slightly different between the gauge sites. At sites S1, S2 and N1, the maximum intensity was registered at 9:52. At sites sub 9 and sub 12, the first peak intensity was a few minutes after this at 9:58 and the second

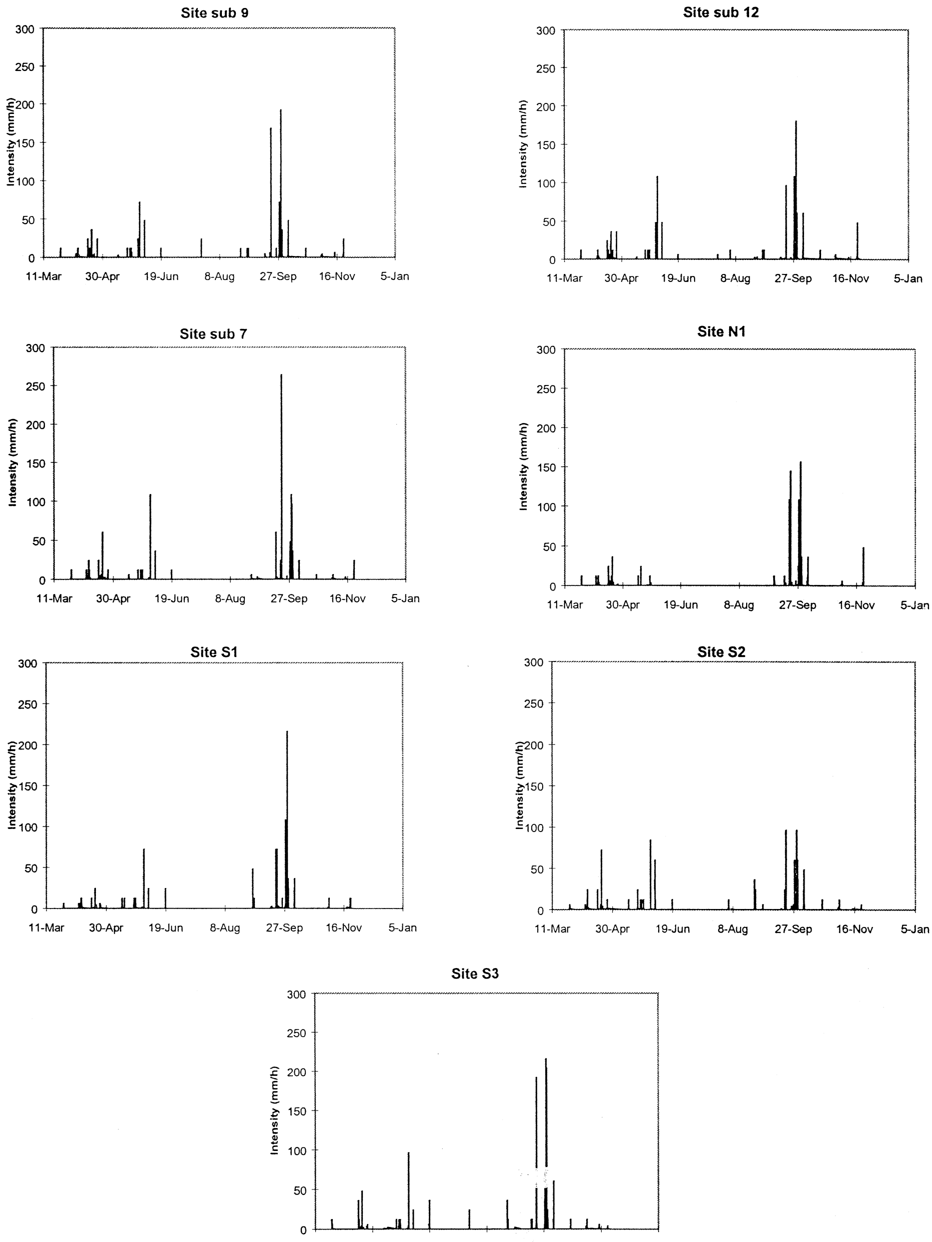

Fig. 2. Variation in rainfall intensity for the Rambla de Nogalte catchment.

maximum intensity was at 10:14. At sites sub 7 and S2, the maximum intensities were recorded at 9:50 and 9:57 while the final burst at site sub 7 was recorded at 10:04. The storm therefore possibly moved in a north-easterly direction through the catchment.

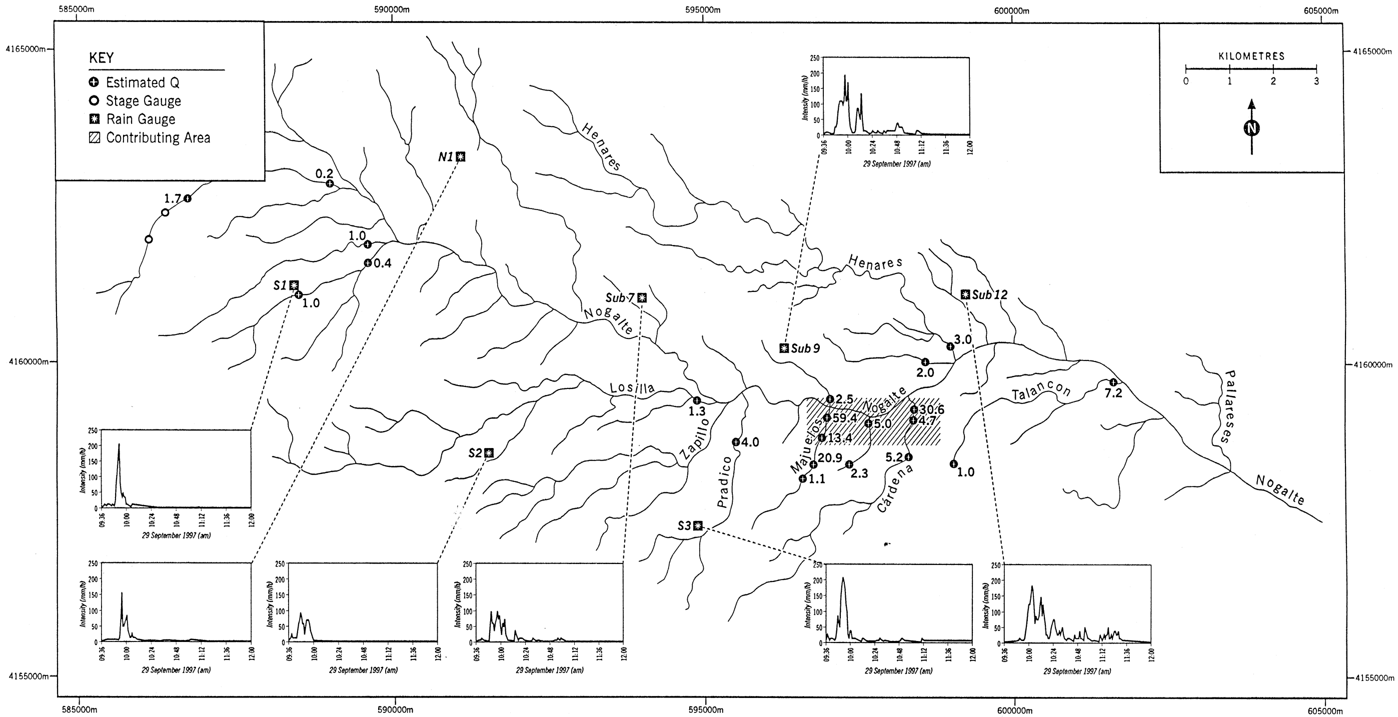

Fig. 3. Variation in rainfall intensity for the 29 September 1997 and estimated discharges for the Rambla de Nogalte.

3.1.2. Torrealvilla

There is only one record of rainfall within the Rambla de Torrealvilla catchment. This shows that there were four rainfall events during this period in September (Fig. 4), the first was on the 27 September 1997 and the others on 29 September 1997. The first storm registered 15 mm in 60 min, the second 10 mm in 27 min, the third 8 mm in 60 min, and the final storm recorded 14.5 mm over an 8-h period, although there were intense bursts within this. The maximum rainfall intensities are plotted on Fig. 4 and are much lower than for the Rambla de Nogalte (maximum of 80 mm h^{-1} compared with 200 mm h^{-1}). The second storm is the most intense with maximum intensity approaching 80 mm h^{-1}, while the first and third storms have similar maximum intensities at approximately 50 mm h^{-1}.

3.2. Stage records

3.2.1. Nogalte

The stage record for the Rambla Nogalte is shown in Fig. 5. The two stage recorders were 700 m apart. The flood at each stage gauge consisted of a single sharp peak with a steep rising and falling limb, with slight attenuation of the flood hydrograph at the downstream gauge. The steep recession limb reflects the importance of Hortonian overland flow in these environments, limiting infiltration and routing of water that would sustain stream discharge (Pilgrim et al., 1988). In this catchment, there was only one flood wave, which peaked at 9:36 at the upstream gauge and 10:32 at the downstream gauge (Fig. 5). The velocity of the flood wave was 0.75 km h^{-1}. The nearest rain gauge is at site S1 where it began raining at 9:50 and stopped at 10:04. Therefore, although this gauge is only 2.5 km away from the stage recorders, the rainfall record is not accurate enough to relate it to increases in stage. This highlights the localised extent of intense storm cells and variations over very small distances.

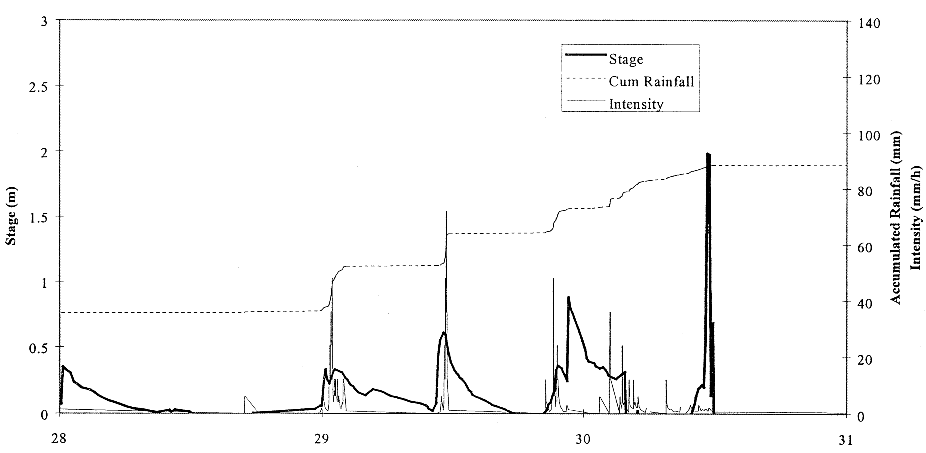

Fig. 4. Plot of accumulated rainfall, rainfall intensity and stage in the Rambla de Torrealvilla.

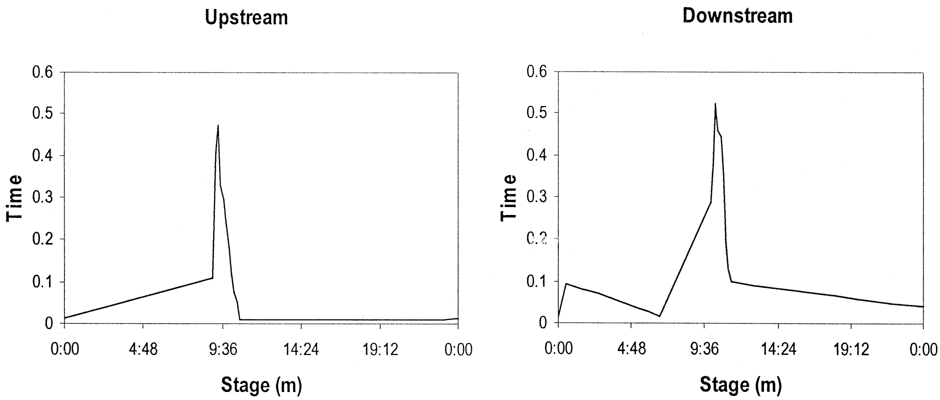

Fig. 5. Plot of stage in the Rambla de Nogalte.

3.2.2. Torrealvilla

Each rainfall event produced a peak in stage in the main channel characteristic of ephemeral channels (Fig. 4). Each increase in stage had a steep rising limb with a bore, previously reported by Hubbell and Gardner (1944), Leopold and Miller (1956), Renard and Keppel (1966) and Frostick and Reid (1979). The floods were short lived; three out of four floods were over in 2 h and the fourth flood only lasted approximately 3 h. The floods in the Rambla de Torrealvilla were double peaked events. On two occasions, the double peaks were of similar magnitude and on the final flood the first peak was much less than the second peak (stage of 0.65 and 1.2 m). Maximum stage was recorded at 2.5 m during the final rainstorm but the flow damaged the pressure sensor so the flow peak is not accurately recorded in Fig. 4. The second increase to peak stage tended to occur approximately 30 min after the initial increase in discharge and may be related to contributions from tributaries. However, high discharges were only found in the main channel so differences in flow routing are unlikely to produce this second increase in stage.

The four floods occurred in quick succession, so the discharge never returned to zero between floods. The magnitude of the discharge increased from the first to the final flood, and the final flood resulted in large scale scour and sediment transport within the channel. This final flood also ripped out the pressure transducer. Average velocity is likely to have increased throughout the train of floods as the channel bed remains wet and less water will be lost to infiltration. Hassan (1990) who showed that the average flow velocity was greater for wet channels than dry channels supports this.

3.3. Variation in estimated discharge throughout the catchments

3.3.1. Nogalte

Rain gauges in the Nogalte showed that rainfall covered the whole extent of the catchment, yet flow in the main channel was slight in the upstream sections, and intermittent and not continuous in the downstream reaches. Estimates of discharge showed that the area of the catchment most affected was the Rambla de los Majuelos (59.4 m^3 s^{-1}), the Rambla de Cárdena (30.6 m^3 s^{-1}) and the Rambla de los Merchones (5.03 m^3 s^{-1}) (Fig. 3).

The position of the storm cell is vital in terms of generating flow and the magnitude of the resulting discharge. The largest discharges in the Rambla de Nogalte were produced by the storms that had the highest intensity but these storms were also characterised by a single sharp burst of rain (Fig. 3). Even though rain fell throughout the catchment, intensities were not high enough at the other sites to produce high discharges. However, rainfall intensity alone explains the two high flows, but does not explain the lack of flow in some of the other tributaries, such as the tributaries draining the north side of the catchment, opposite the area of high discharge (Fig. 3). This led us to examine lithology, morphology and land use as factors combining with high rainfall intensities to produce high discharges.

3.3.2. Torrealvilla

The effects of the floods on the Torrealvilla catchment are much more complex compared to the Nogalte, and the floods were much larger (Figs. 3 and 6). In the headwaters, only two out of the five tributaries showed evidence of major flows, the Barranco del Madrono (42 m^3 s^{-1}) and the Barranco del Muerto (42.5 m^3 s^{-1}). These two tributaries extend much further north and have much larger catchment areas than the other three headwaters. The three headwaters with minimal flow only extend to the small hills, so the flow is therefore likely to be due to extended rainfall in the region to the north rather than intense rainfall locally.

In the main Rambla de Torrealvilla, discharge was estimated at 107.6 m^3 s^{-1} below the junction of headwater tributaries, then dropped to 28 m^3 s^{-1} further downstream and continued to decrease to the junction with the Barranco del Prado to 23.5 m^3 s^{-1}. The check dam at this point had partially failed, with one of the top sections of gabions being rolled downstream for approximately 30 m. The decrease in discharge is likely to be caused by transmission losses and lack of contributions from runoff, and indicates that the center of the storm cell was unlikely to be located close to the main Torrealvilla. The area immediately surrounding this main section of the channel has been bulldozed flat and is used for agriculture. This has reduced the connectivity between the slopes and the main channel and limits runoff contributions to the main flow in this section of the catchment. Below the junction with the Barranco del Prado discharge increased to 86.5 m^3 s^{-1}, and carried on increasing downstream to 105 m^3 s^{-1}. Thus, the inflows along this section are greater than the transmission losses, possibly indicating that the storm cell was located over the channel. Contributions from the Rambla del Estrecho were negligible at 14.1 m^3 s^{-1}. Rainfall was therefore unlikely to have been concentrated in the Estrecho catchment.

The catchment of the Barranco del Prado was more complex and field evidence suggested that discharge varied quite dramatically within this area of the Torrealvilla catchment. Most flow was along the main Barranco del Prado, with only a minor contribution from the Barranco de Casa Mora (2 m^3 s^{-1}). The discharge steadily increased downstream from 13.9 m^3 s^{-1} at the channel head to 73.3 m^3 s^{-1} just

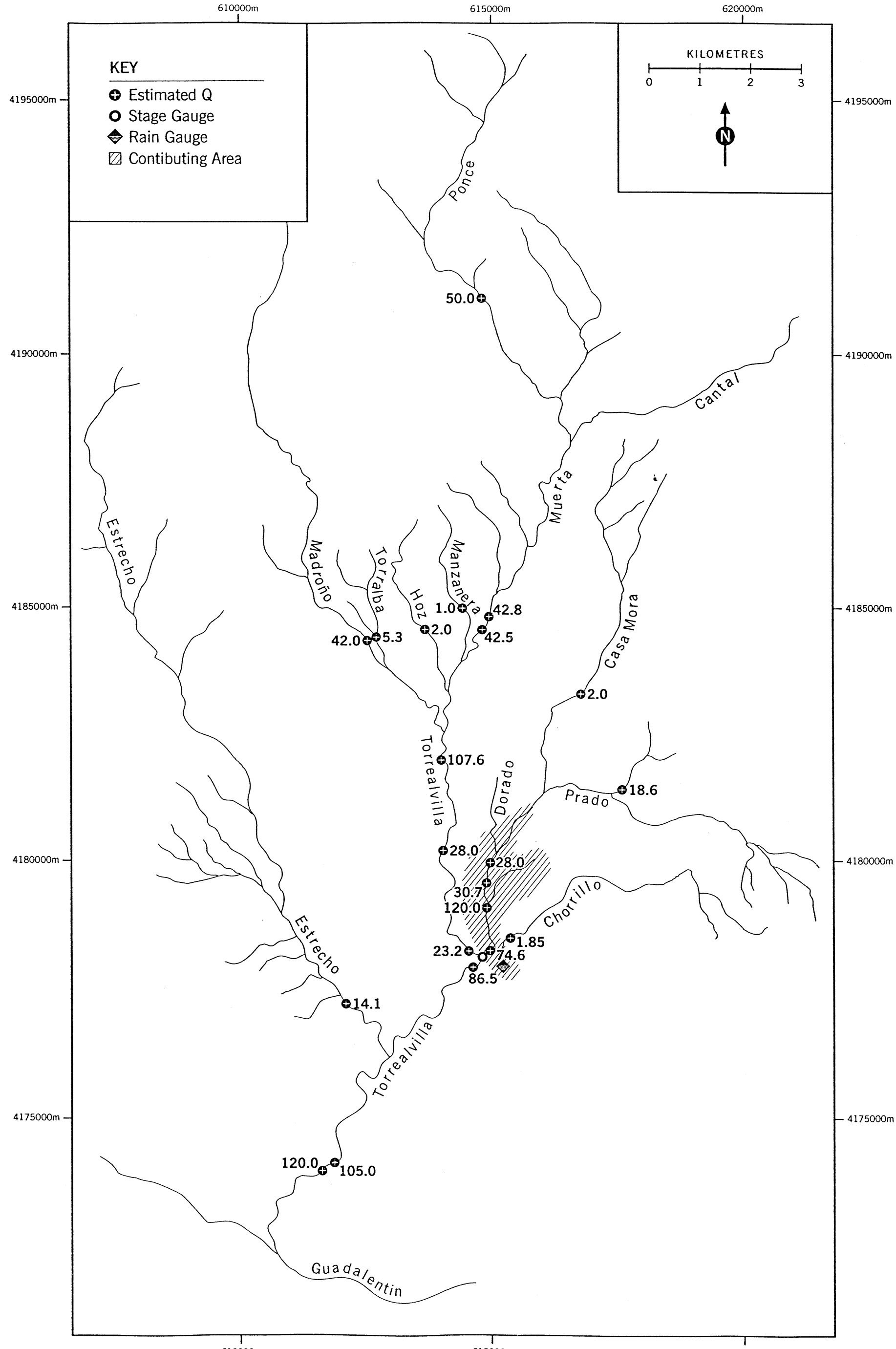

Fig. 6. Map of the variation in discharge in the Rambla de Torrealvilla.

upstream of the monitoring section. Approximately 150 m upstream of this point there was a check dam that had been completely ripped out by the flood. An estimate of discharge here was 120 m^3 s^{-1}. Contribution from the Rambla del Chorrillo was small, estimated at 1.85 m^3 s^{-1}, although a tributary to the Chorrillo is likely to have produced most of this. This tributary is narrow with near vertical walls and showed evidence of major flow that had resulted in undercutting large sections of the walls. These had then failed, some during flood water recession, and they now block the tributary. Flow from this tributary resulted in a debris fan being deposited which blocked the Rambla del Chorrillo and ponded any flowing water.

Field evidence thus suggests that the storms responsible for the floods were probably located over the Barranco del Prado, but not within the Chorillo catchment. An especially intense storm cell may have been located immediately upstream of where the failed check dam is located.

Table 2
Estimates of contributing area (A_c, Eq. (6)), for the Cárdena and the Prado catchments

Values of B	Values of A					
	5	10	20	50	100	
Estimates for the Rambla Cárdena (Nogalte catchment)						
5	205.8	200.8	190.5	159.4	106.2	Peak runoff rates for the Nogalte (S3) raingauge
10	203.7	198.3	188.0	156.7	101.9	
20	199.9	194.8	184.2	151.8	95.9	
50	192.5	187.0	176.1	142.3	75.0	
100	183.4	178.0	166.5	128.9	61.0	
5	0.52	0.54	0.57	0.68	1.02	Contributing areas (km) for the Rambla Cárdena (peak $Q = 30$ m/s)
10	0.53	0.54	0.57	0.69	1.06	
20	0.54	0.55	0.59	0.71	1.13	
50	0.56	0.58	0.61	0.76	1.44	
100	0.59	0.61	0.65	0.84	1.77	
Values of B	Values of A					
	1	2	5	10	20	
Estimates for Rambla del Prado (Torrealvilla catchment)						
2	69.1	67.9	64.8	59.6	49	Peak runoff rates for the Torrealvilla (aqueduct) raingauge
5	67.8	66.6	63.4	58.0	47.0	
10	66.3	65.0	61.8	56.1	44.6	
20	64.0	62.6	59.1	53.1	40.9	
50	60.0	56.8	53.0	46.8	31.1	
100	56.8	49.8	45.5	37.0	18.0	
2	4.17	4.24	4.44	4.83	5.88	Contributing areas (km) for the Barranco del Prado (peak $Q = 80$ m/s)
5	4.25	4.32	4.54	4.97	6.13	
10	4.34	4.43	4.66	5.13	6.46	
20	4.50	4.60	4.87	5.42	7.04	
50	4.80	5.07	5.43	6.15	9.26	
100	5.07	5.78	6.33	7.78	16.00	

3.4. Calculations of runoff thresholds and contributing areas

Table 2 shows calculations for two rain gauges, located in the Cárdena sub-catchment of the Nogalte and the Prado sub-catchment of the Torrealvilla using Eqs. (4)–(6). A range of plausible values for A and B in Eq. (4) have been used to estimate the contributing area for the estimated peak discharges of 30 $m^3 s^{-1}$ for the Rambla Cárdena and 80 $m^3 s^{-1}$ for the Barranco del Prado.

It can be seen that, with the lower rainfall intensities and higher discharges in the Torrealvilla, it is probable that runoff thresholds are lower and contributing areas larger. Using the range of values shown in Table 2, it is suggested that the most realistic thresholds for the Torrealvilla are for $A = 2–10$ mm, with B less clearly determined, associated with a contributing area of approximately 4 km^2. In the Nogalte, a higher threshold of $A = 20–50$ mm seems to be appropriate, corresponding to a contributing area of 0.8 km^2. These areas appear to correspond reasonably well with areas that appeared to have generated large volumes of runoff in the field, with evidence of gullying or rilling, sediment transport and clear flow routes from hillslopes into the main channels. For the Nogalte, the area of high runoff generation on the Cárdena and neighboring tributaries is very similar to the area of incision into the blue flaky mica-schists.

4. Discussion

4.1. Variations in discharge due to lithology

The argument that flood discharge is influenced by lithology is supported by the difference in lithology and discharges between the two study catchments, but also by variations locally within the basins. Differences in lithology between the two catchments results in a lower threshold rainfall for the Torrealvilla than that for the Nogalte. Initial estimates of the thresholds (as calculated above) are 50 and 150 mm h^{-1}, respectively. Flood discharge is also influenced by transmission losses, which are likely to be higher on the Nogalte (schists) than on the Torrealvilla (marls). The Torrealvilla shows evidence of a slight delay between rainfall and peak discharge, from which it can be inferred that there may be multiple flow paths to the main channel and some of these delay runoff and thus peak stage. Runoff in the Nogalte is quick, and is effectively straight down to the channel, whereas in the Torrealvilla there may be more infiltration on the flat surfaces.

In the Rambla de Nogalte, the two tributaries where maximum discharges were estimated both have sections composed of blue mica schist while the remainder of the catchment is composed of red mica schist. The blue mica schist is likely to produce much higher rates of runoff than the red schist and so contributes to the high discharges. This is also supported by the development of predominantly blue schist alluvial fans at the junction of the two tributaries with the main channel. From this, it can be inferred that runoff and therefore erosion is greater on the blue schists than the red, otherwise, red mica schist material from upstream would also be found in the alluvial fans.

4.2. Variations in discharge due to morphology

The influence of morphology on flood discharge is supported by local variations within the Rambla de Nogalte catchment. The areas that show effects of flooding are narrow bedrock channels, ranging from 3 to 7 m wide, with evidence of groundwater flow in the Rambla Cárdena and Rambla de los Majuelos. These channels are fairly steep, over 2° in places, stepped with potholes cut into the bedrock. Upstream, where evidence suggested very small discharges, the channels are wider, less steep, gently sloping, with an infiltrating gravel bed. The gorge-like morphology is likely to have produced very quick runoff and efficient routing of water to the main channel, and is likely to be a factor producing high discharges at this specific location. Both tributaries also have large debris fans at the junction with the main channel and have sections of bedrock. This demonstrates that these channels have a history of more frequent flow compared with the other tributaries and this may be due to two reasons. First, predominant rainfall conditions may mean that intense rain has a tendency to fall over the same area always producing flow in these two channels. Second, the channel morphology and the bedrock in sections of these channels limits infiltration, increases the speed of runoff and results in high magnitude events.

4.3. Variations in discharge due to land use

The importance of land use in influencing flood discharges is highlighted by the difference between the two catchments and within the basins. Differences in lithology and morphology between catchments has led to different land use that in turn influences rainfall thresholds, and the location of high discharges. The land use in the Torrealvilla encourages infiltration and multiple flow paths, while that in the Nogalte encourages runoff. Areas that are subject to frequent ploughing, such as around almond and olive trees and land used for wheat or melon crops, have higher infiltration rates since the crust is continually broken up. The surface is also rough which encourages ponding of any runoff. Areas of natural vegetation develop a hard surface crust that increases runoff and decreases infiltration. Areas of abandoned agriculture are likely to have even higher rates of runoff because of hard surface crusts and limited vegetation. These areas often tend to be quite smooth which results in quick runoff from the generating area because of fewer opportunities for ponding. Consequently, local variations in land use may influence resulting discharges, for example, the area of high discharge in the Torrealvilla is an area of natural matorral cover that encourages high runoff rates due to surface crusting.

The area immediately surrounding the failed check dam in the Torrealvilla appears to produce much higher rates of runoff than other areas. This section of the channel is deeply incised with gullies extending headwards into a limited area of higher ground. This is an area of natural vegetation and limited agriculture and is therefore likely to have developed surface crusting. The gullies demonstrate the higher rates of surface runoff, but direct runoff more quickly into the main stream. The gullied area is unlikely to be large enough to equate to the contributing area responsible for the high discharge, but gives an idea of the area of immediate response.

4.4. Recurrence interval of the floods

Despite the relatively large magnitude of these floods the erosion of the main channel was not extensive. Significant channel incision did take place in some parts of the upper Torrealvilla and in the lower sections of the main Torrealvilla extensive reaches of cobbles were cleaned out. Erosion in the Prado catchment was only evident at breaks in slopes at man made terraces which produced a series of headcuts along the main channel, but only one very active headcut. This was associated with some very large scale piping (50 m diameter). One section of the headcut had retreated by 1.5 m and

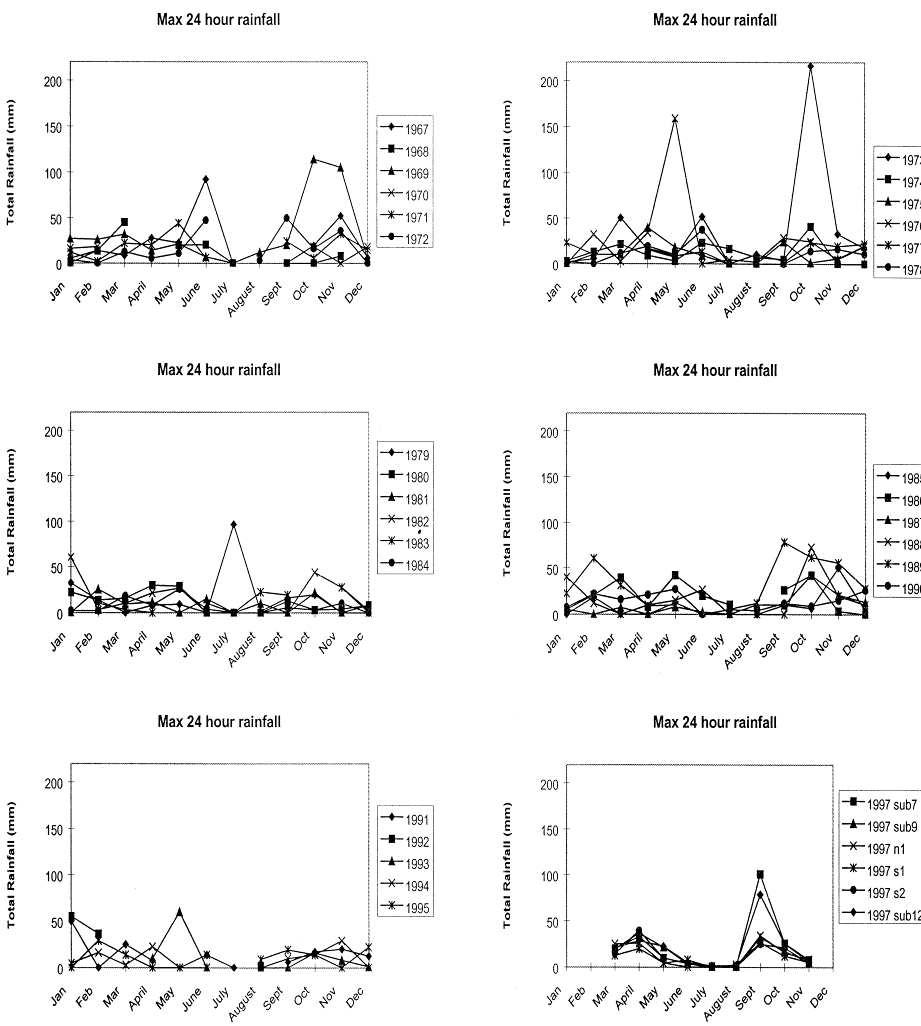

Fig. 7. Plot of the 30-year record of rainfall in the Nogalte.

there was evidence of smaller erosion around the rest of the channel headcut indicated by freshly exposed roots and mass failures. For the magnitude event studied, erosion may be limited to breaks in slope rather than occurring throughout the length of the channels.

Comparison of our data can be made with a 30-year record from Vélez Rubio that contains information on the monthly precipitation and the 24-h maxima rainfall from 1967 to 1995. To compare the two data sets we have calculated 24-h maximums for our data record and compared this with the 30-year record. Results are presented in Fig. 7. These plots show that the flood we have studied is the fifth largest flood in the record. The notable large floods occurred in 1967, 1969, 1973, 1976, 1979 and 1997. The largest flood was the 1973 flood that had a devastating effect on the Nogalte and was responsible for a number of deaths. This flood wiped out the evidence of larger floods before it, although the present channel is likely to be a product of the 1976 flood (the second largest on record). These data can be used to estimate the recurrence interval of the flood (Fig. 8). This shows that the floods recorded in 1997 had a recurrence interval of 7 years. This agrees with previous estimates of flood recurrence intervals for floods carrying out similar amounts of channel reworking (Conesa-Garcia, 1995). The estimated recurrence interval has been calculated using 24-h maximums to allow comparison with longer-term rainfall records. However, within the catchments the recurrence interval is likely to have been spatially variable since intensive short bursts of rainfall, rather than the 24-h rainfall totals, appeared to be the key factor in producing the high flows.

The floods in both catchments are therefore likely to be channel forming floods and not very rare. This is useful in terms of understanding the catchment dynamics and inter-relationships because it allows an insight into threshold events. It also allows discrimination between areas of the catchment and raises questions concerning factors influencing discharges that have remained previously unmentioned. If a much higher magnitude, rare event, had been recorded, the evidence would have been destroyed and

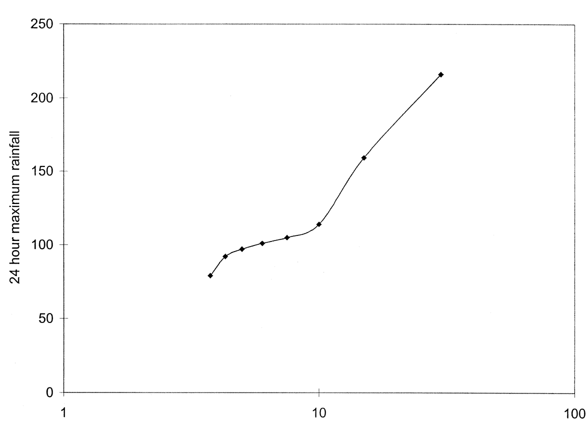

Fig. 8. Flood frequency curve for the Rambla de Nogalte.

all that could have been reported is that there was a large flood that reworked most of the channel.

5. Conclusions

The data record from the rain gauges in the Rambla de Nogalte catchment showed that the network is too sparse to accurately relate rainfall to discharge. The difference in timing between flow and rainfall at the stage gauging site and rain gauge S1 showed how rainfall varies over distances as small as 2.5 km. Thus, the intense storm cells that result in flows in semi-arid channels may be much smaller than estimated by Renard and Keppel (1966) and Diskin and Lane (1972). If rain gauges were going to be used to estimate discharge they would need to be located at the source of each tributary and possibly part way down the sub-basin as well. This would need a total of approximately 30 rain gauges rather than 7.

The rainfall record does show that rainfall intensities are much higher than expected, with maximas greater than 200 mm h^{-1}. These high intensity bursts of rain are short lived, not usually lasting longer than 15 min. However, from comparisons of estimates of discharge and rainfall, the nature of high intensity bursts of rainfall is more important in terms of generating flow in the channels in semi-arid areas, than daily totals.

Factors that combined to produce high flood discharges were lithology, morphology and land use. Thus, specific areas of catchments may be prone to higher discharges more frequently than the rest of a catchment. Comparison of data records showed that the flood in the Nogalte had a return interval of 6–7 years. It is assumed that the floods in the Torrealvilla were of a similar frequency since the rainfall intensities and amounts were less than in the Nogalte, but the Torrealvilla has a lower threshold for flooding.

In terms of erosion and management, the floods were of a marginal nature and were likely to be on the threshold of causing major channel reworking. Floods in both catchments were responsible for shifting and re-depositing a lot of material within the channel, but there was not much change in channel heads or drainage density. In the Nogalte, alluvial fans at the junction of Los Majuelos and Cárdena with the main channel received much more material and in the Torrealvilla some bedrock sections were cleaned out of cobbles. However, there was not much damage to surrounding farmland. The erosion caused is slightly more than resulted from a flood in 1989 which was slightly smaller than this 1997 flood and reported by Conesa-Garcia (1995). For the largest flood on record to re-occur, rainfall intensities greater than 200 mm h^{-1} are likely to be needed over most of the Nogalte catchment. These would produce flow from tributaries simultaneously which would result in a floodwave along the whole length of the main channel. This flood has a recurrence interval of only 30 years and could occur any time in the near future.

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