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AN OBJECTIVE CLASSIFICATION OF RAINFALL EVENTS ON THE BASIS OF THEIR CONVECTIVE FEATURES. APPLICATION TO RAINFALL INTENSITY IN THE NORTH-EAST OF SPAIN

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ABSTRACT

In the present paper a system of rainfall events classification on the basis of their hydrometeorological characteristics has been proposed. The final objective is characterisation of the different event classes and their application in modelling of IDF curves and design hyetographs. Recourse was had for this purpose to definition of a parameter related with the greater or lesser convective character of the precipitation and designated as β^*, while its distribution throughout the entire series of the sample was studied. Besides this, the main features of the different classes obtained and their relationship with floods and rainfall damage events have been analysed. The intensity series of the Jardí pluviograph (Barcelona, Spain) between 1927 and 1981 was used as a sample series.

KEY WORDS: rainfall intensity, convective rainfall, rainfall classification, Spain.

1. INTRODUCTION

It is very well known that pluviometric episodes can be of highly diverse characteristics, which is clear from both their spatial and temporal distribution. These characteristics depend on the physical mechanisms responsible for the rainfall or other hydrometeors which occur, which mechanisms in turn depend upon the particular meteorological situation on a larger or smaller scale. We are thus faced with a problem which presents many factors and is therefore difficult to deal with. The solution of taking the episodes to be of one type or another in function of their geographical provenance or their associated synoptic meteorological situation would, though simple, be too trivial. To make a generalization, for example, that all rains coming from the East are of one type, while rains from the West are of another type would be a source of numerous mistakes. This type of solution would, furthermore, call for ad hoc, single studies for each working zone.

A more correct solution is to study the nature of the process which gave rise to the precipitation. In this case a distinction could be made, essentially, between precipitation of convective origin and precipitation of stratiform origin, which classification should not be identified with classification of the rainfall associated with a storm or rainfall associated with a front, as has unfortunately sometimes occurred. In a simplified form, it would be a matter of associating the first type with clouds of convective type, such as cumulonimbus, and the second, with clouds of stratiform type, such as nimbostratus. Convective systems could, in their turn, be subdivided in function of their structure and life-cycle, into unicellular, multicellular, supercellular or Mesoscale Convective Systems or Complexes (Byers and Braham, 1949; Browing and Ludlam, 1962; Fujita, 1985; Doswell *et al*, 1996). In this case, however, the main problem would lie in the need to have information from meteorological satellites and radars, which would hinder the feasibility of the process. Also, within a system of eminently convective origin, it is possible to find rain of stratiform character. Indeed, in certain situations, the contribution of stratiform precipitation to the total precipitation within a Mesoscale Convective System can be as great as 50% (Doswell, 1993). Similar observations are currently giving rise to ongoing discussion about the physical concept implicit in the term "convective precipitation", though this clearly lies outside the scope of this paper.

A third possibility would consist in studying the intensity (I) threshold(s) exceeded. In Spain, the National Meteorological Institute defined the rainfall risk situations during the PREVIMET campaign on the basis of the following thresholds of average hourly intensity:

light rainfall	$I \leq 2$ mm/h
moderate rainfall	$2 < I \leq 15$ mm/h
heavy rainfall	$15 < I \leq 30$ mm/h
very heavy rainfall	$30 < I \leq 60$ mm/h
torrential rainfall	$I > 60$ mm/h

However, these thresholds vary considerably from one country to another, which means that it would be difficult to obtain a universal classification on the basis of the different thresholds.

Finally, it should be stated that the mitigation produced by rain in the short-wave radio links brought the problem into the field of telecommunications. Here, it has been observed that rainfall rates above 0.8 mm/min can generate problems in radio links (Vilar and Burgueño, 1991). Analogies were then drawn up, such as convective rain equals rain from storms (Rice and Holmberg, 1973), or development work done on more complex expressions including climatic values (Dutton *et al*, 1974; Dougherty and Dutton, 1978; Dutton and Dougherty, 1979). Establishing an analogy between rain of convective origin and storm-origin rain would involve underestimating the former, since the WMO requires the definition of thunderstorm to include the presence of lightning, which does not always occur with rainfall of convective origin. Another more widespread analogy involved considering convective rain to be all convective rain within a threshold of 48 to 50 mm/h (Dutton and Dougherty, 1979; Watson *et al*, 1982). The problem with this classification would be that not all rain of convective origin exceeds that threshold, while not all rain which does exceed said threshold is convective in character. On the other hand, it does have the great advantage of being a simple, objective and (up to a point) universal classification.

The objective of this paper lies precisely in an attempt to overlap the various considerations set out above in order to find an objective method of classification which at the same time has a plausible physical interpretation. This objective also considers the introduction of a parameter permitting classification of the types of pluviometric events and, consequently, one which is useful for subsequent hydrological modelling. To this end recourse was had to the 1927-1981 series of rainfall intensities provided by the Jardí pluviograph situated near the city of Barcelona.

2. BACKGROUND

The Jardí pluviograph is situated in the Fabra observatory, on the slopes of Tibidabo mountain, at an altitude of 414 m a.s.l. and at a distance of 7.5 km from the sea, inland from the city of Barcelona. Given that the operation of this pluviograph has been extensively described in previous publications (Jardí, 1921; Puigcerver *et al*, 1986; Burgueño *et al*, 1993; Llasat and Puigcerver, 1985, 1997), suffice it to say that for this work the instantaneous intensity of rainfall was converted into 1-minute and 5-minute mean intensities (these being the most typically used intervals of measurement in current automatic pluviographs).

The first study carried out on the basis of individual analysis of each precipitation episode recorded on the Jardí pluviograph between 1960 and 1979 showed that some 55% of the annual precipitation was of convective character (in the case of mixed episodes the convective character was considered to be dominant), while 70% at some stage exceeded an intensity episode of 0.8 mm/min (Llasat and Puigcerver, 1997). Approximately 40% of the annual precipitation was thus of convective character with intensity exceeding 0.8 mm/min at some stage of the episode. This value was at variance with the 32% obtained for precipitation due to storms, a difference which increased when monthly values were considered. For the same period it was found that the rain from episodes of non-convective character in which the intensity at some point exceeded that threshold accounted for less than 0.001% of total annual rainfall time, and in no case exceeded an intensity of 3 mm/min (Llasat, 1997).

The discussion of the previous paragraph could be based on terms of a β parameter which related rains of different origins with total rainfall. This parameter was introduced by Rice and Holmberg (1973) for modelling attenuation in radio links due to rain, being defined as:

$$\beta = \frac{\text{annual stormy precipitation}}{\text{total annual precipitation}}$$

where they seemed to take stormy precipitation as that in which the threshold of 0.8 mm/min is exceeded. Given the inherent difficulty of evaluation of this numerator, the authors themselves, along with Dutton and Dougherty (Dutton *et al*, 1974; Dougherty and Dutton, 1978; Dutton and Dougherty, 1979; Watson *et al*, 1982) proposed calculating it empirically on the basis of the mean annual precipitation, the mean annual number of stormy days and the maximum monthly precipitation observed over thirty consecutive years. In the case of the precipitation recorded by the Jardí pluviograph, the application of such formulae gave a value of 0.16 (Llasat and Puigcerver, 1985), a value in accordance with that proposed by Rice and Holmberg (1973) for Barcelona, but differing from that proposed by Dutton *et al* (1974).

Later, and following this same line, the next parameter was defined (Llasat and Puigcerver, 1985, 1997) in which, where reference is to be made to annual values, the word “monthly” may be replaced by the word “annual”:

$$\beta_o = \frac{\text{monthly precipitation from episodes of convective type}}{\text{total monthly precipitation}}$$

Thus, and in the light of the above observations, β_o would in the case of the Jardí pluviograph series have the value 0.55. In order to be able to compare this with the proposal made by Rice and Holmberg (1973), all that would then be required would be to select those episodes which, in addition to being convective, exceed the threshold of 0.8 mm/min, thereby providing a new parameter β_1 defined as:

$$\beta_1 = \frac{\text{monthly precipitation from episodes of convective type which } I_1 > 50 \text{ mm/h}}{\text{total monthly precipitation}}$$

which would mean that β_1 would have a value of 0.38 in the case of the above-mentioned series. If this is compared with the value of 0.37 obtained by Burgueño (1986) for the 1927-1981 series on the same pluviograph and attention is paid exclusively to the factor of there existing at a particular moment of the episode a 1-minute intensity (I_1) 50 mm/h (independently of whether or not this was convective), then the two values can be seen to be similar. If the monthly distribution is also analysed, then it can be concluded that the error made in equating episodes in which the 1-minute intensity of 0.8 mm/min with convective episodes is insignificant. While it is true that the homogeneity of the two time intervals may be debatable, a study carried out on the precipitation series for Barcelona (Rodriguez *et al*, 1999) does confirm this homogeneity. Thus, the hypothesis of taking an episode to be convective when a threshold of 50 mm/h is exceeded at some point is not unreasonable, and less unreasonable still if it is born in mind that the problems (hydrological, radio links, rescue services, etc.) are not usually caused by low intensities. Finally, meteorologically speaking, convective systems of a certain size (from unicellular storms to mesoscale convective storms) usually give intensities exceeding that threshold, that is, exceeding 0.8 mm/min.

3. MAKING THE CRITERIA PROPOSED FOR THE 1-MINUTE SERIES SUITABLE FOR THE 5-MINUTE SERIES

As stated at the beginning, the new measuring networks usually record the rain at intervals of 5 minutes or more, for which reason it is useful to take ΔT = 5 minutes. A similar change also affects the threshold intensity, which can no longer be 50 mm/h, but must after the increase of time interval be reduced due to the consequences of the attenuation provoked in the high-intensity peaks. By way of example, it suffices to compare the β value calculated on the basis of 1-minute intensities exceeding 50 mm/min and the value obtained by working with the 5-minute series: 0.182 compared with 0.128, respectively .This is equivalent to saying that

$$\beta_1 = 1.421\ \beta_5$$

where β_5 refers to the 5-minute series and a rainfall rate threshold equal to 50 mm/h.

Figure 1 shows the monthly variation of β_1 and β_5. In both cases the maximum is recorded in July and the minimum is recorded in February. The two-parameter quotient shows that the greatest discrepancies arise during the winter months, while it is in summer that the coefficient is closest to one unit. The explanation is to be found in the fact that during the winter the threshold of 50 mm/h is rarely exceeded and, when this does occur, the time over which this intensity is maintained is very short. In summer, on the other hand, the minute-intensity remains above 50 mm/h over relatively long periods of time, that is, very high intensities are reached, so that when the averaged interval is extended to 5 minutes the threshold imposed continues to be exceeded.

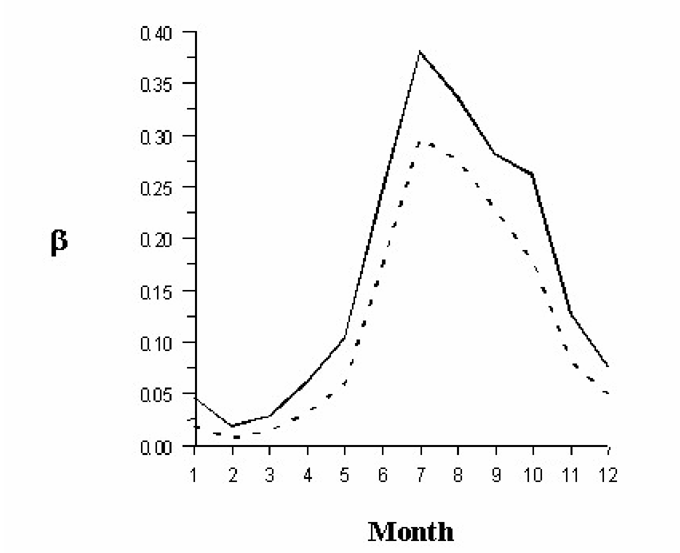

Figure 1. Monthly evolution of β_5 (continuous line) and β_1 (discontinuous line) in basis to the 5-minute series and 1-minute rainfall series of Barcelona (Spain), respectively .

Figure 2 shows the values $\beta_{L,5}$ takes when working with a 5-minute series in function of the intensity threshold, L. It can be observed that the proportion of precipitation which exceeds the threshold of 50 mm/h when working with a 1-minute series (0.182) is equivalent to that which exceeds the threshold of 36 mm/h when working with a 5-minute series, which can be formulated as:

$$L_1 = 1.428\, L_5 \qquad \text{for } \beta = 0.182$$

which expression relates the intensity thresholds for accumulation times of 1, L_1, and 5 minutes, L_5.

Based on the above equivalence, a value of 35 mm/h will be taken as the 5-minute mean intensity threshold (a multiple of 5 is chosen to facilitate subsequent calculations). From analysis of the 5-minute series it can be obtained that for 1.454 % of the mean annual time for which it rains, the precipitation presents a mean 5-minute intensity exceeding 35 mm/h, responsible for 18.2% of the total annual precipitation.

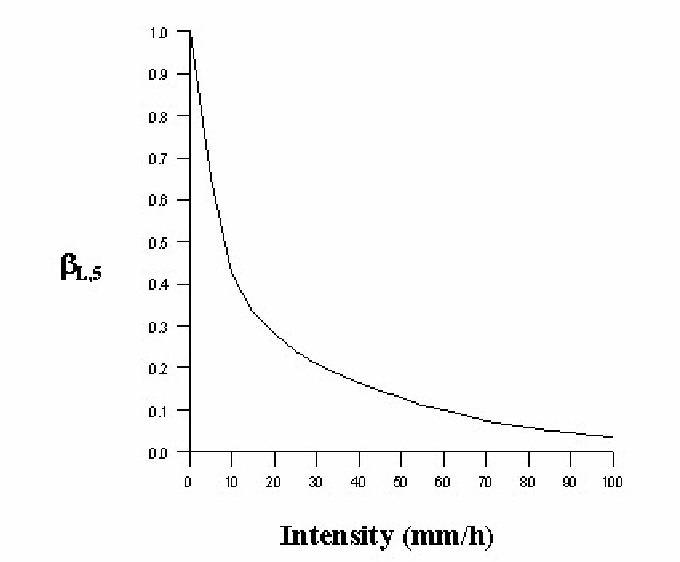

Figure 2. Evolution of the average value of $\beta_{L,5}$ in function of L (intensity threshold in mm/h) in basis to the 5-minutes rainfall series of Barcelona (Spain).

4. UTILIZATION OF THE PARAMETER β* FOR CHARACTERIZATION OF EPISODES

The foregoing values relate to the monthly and annual distribution of convective precipitation. In order to model episodes, however, it is useful to have a parameter for each one of them. The methodology proposed herein for resolving that objective consists in taking as a point of departure a mean intensity threshold within a given time interval, and introducing a parameter which takes account of the ratio between the rainfall which exceeds that threshold and total rainfall in an episode. This parameter is designated as $\beta^*_{L,\Delta T}$ and, unlike the previous ones, is of meteorological rather than climatic character. To calculate it, it suffices to use the expression

$$\beta^*_{L,\Delta T} = \frac{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)\theta(I - L)}{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)}$$

in which

ΔT is the time-interval of accumulation of the precipitation, expressed in minutes

N is the total number of ΔT integration steps into which the episode is subdivided

$I(t_i, t_i+\Delta t)$ is the precipitation measured between t_i and $t_i+\Delta t$ divided by Δt, that is, the mean intensity in the said interval expressed in mm/min or mm/h

θ (I-L) is the Heaviside function defined as:

$$\theta\ (I\text{-}L) = 1 \text{ if } I>L$$

$$\theta\ (I\text{-}L) = 0 \text{ if } I<L$$

$$\theta\ (I\text{-}L) = 1 \text{ if } I=L$$

in which the last condition is imposed by the author herself. The definition of episode is quite subjective. In this case it was felt that it is possible to distinguish between two different episodes when the time which elapses between them without rainfall exceeds 1 hour, which permits an assurance that the two episodes come from different “clouds”. If in the above definition the term “episode” is replaced by “month” or “year” and ΔT = 1 minute and L = 50 mm/h are taken, we arrive at the definition of β_1 presented in the previous sections. It can be noted, too, that the monthly β_1 value (as defined in the previous section) and the mean monthly value of $\beta^*_{50,1}$ do not have to coincide: indeed, the latter will be slightly lower than the former.

The previous section explained the presupposition of an intensity threshold of 35 mm/h for the 5-minute series as against the threshold of 50 mm/h for the 1-minute series. Based on this, we will hereinafter take ΔT=5 min and L=35 mm/h, simplifying the notation of $\beta^*_{35,5}$ which will be represented as β^*. The monthly distribution of the percentage of rainfall events with β^* other than zero shows that the maximum pertains to the month of August, with 18.3%, followed by September with 15%. In February and March, on the other hand, the percentage falls to 1.9% and 1.8%, respectively (Table 1).

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
N	339	317	560	650	673	494	293	453	574	641	496	424
$N\ \beta^* > 0$	10	6	10	25	34	51	35	83	86	89	40	13
$\%N\beta^* > 0$	2.9	1.9	1.8	3.8	5.0	10.3	11.9	18.3	15.0	13.9	8.1	3.1
$P\ \beta^* > 0$	157	257	289	390	582	999	871	1854	2173	2162	1008	402
$\%P\beta^* > 0$	20.2	16.9	13.3	14.1	19.8	43.3	59.8	64.1	55.4	51.4	34.4	20.6

Table 1. Monthly distribution of the rainfall events (N) and the total rainfall (P) in Barcelona (1927-1981), discerning the convective cases from the total events.

In order to obtain fuller information, the mean intensity of each episode has been represented in function of its duration for those cases in which β^* >0 (Figure 3). It can be observed that, while 88% of the non-convective events (β^* =0) present average hourly intensities of less than 40 mm/h and durations of less than 2 hours, in the case of events with β^* >0, this percentage decreases to 65%. If the same type of curve is constructed for the different seasons of the year it can be observed that, with the exception of autumn, the durations are in general less than 240 minutes and that, where this value is exceeded, the mean intensities are lower than 10 mm/h.

Stated another way, those episodes in which at a given moment the 5-minute intensity of 35 mm/h is exceeded are of a duration of generally less than 4 hours. In the case of autumn, this generalization loses a certain amount of validity as a result of the by no means negligible number of episodes with β*>0 and durations ranging between 4 and 8 hours. It should also be noted that neither in winter nor in spring is the mean intensity of 40 mm/h exceeded. Figure 4 shows the seasonally adjusted curves corresponding to the average intensity-event duration function in the cases in which β*>0 (correlation coefficients comprise between r = 0.6 for the summer and r =0.8 for the spring).

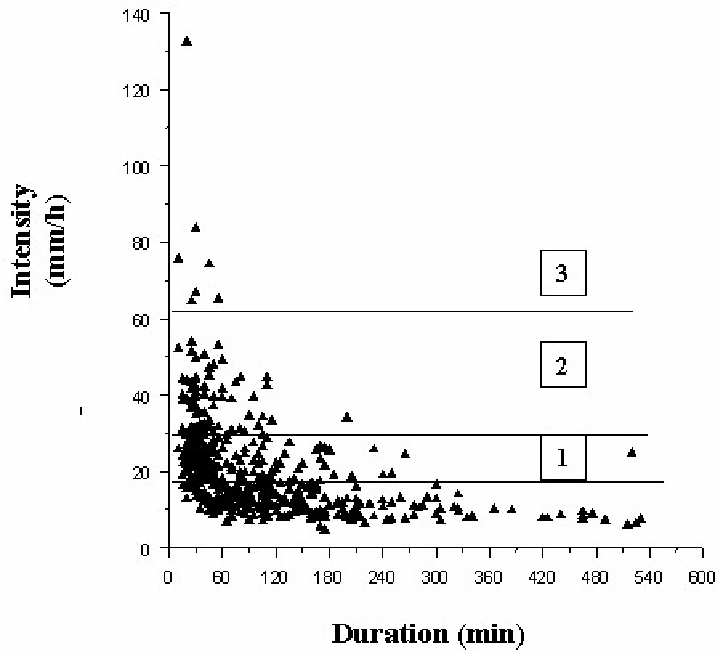

Figure 3. Distribution of the average intensity (mm/h) of the rainfall events with β*>0 in function of their duration. Events are classified in function of their average intensity: 1) heavy rainfall; 2) very heavy rainfall; 3) torrential rainfall.

Figure 5 has been constructed in order to show more clearly the differences between the characteristics of those episodes with β*>0 and those others with β*=0, and showing the adjustment curves corresponding to the various seasons of the year for episodes with β*=0. Noteworthy is the fact that the slope of the curves is in this case positive, that is, the episodes of greatest mean intensity are also those of longest duration. Although it might seem unexpected, this result can be explained by the low values of the mean intensities achieved, together with how little the real values match the adjustment curves, with values between r=0.2 for the summer and r=0.3 for the winter. It is interesting to note, too, that the annual curve lies between those for autumn and spring, while the summer continues to be shown as the season for which the highest mean intensities are recorded.

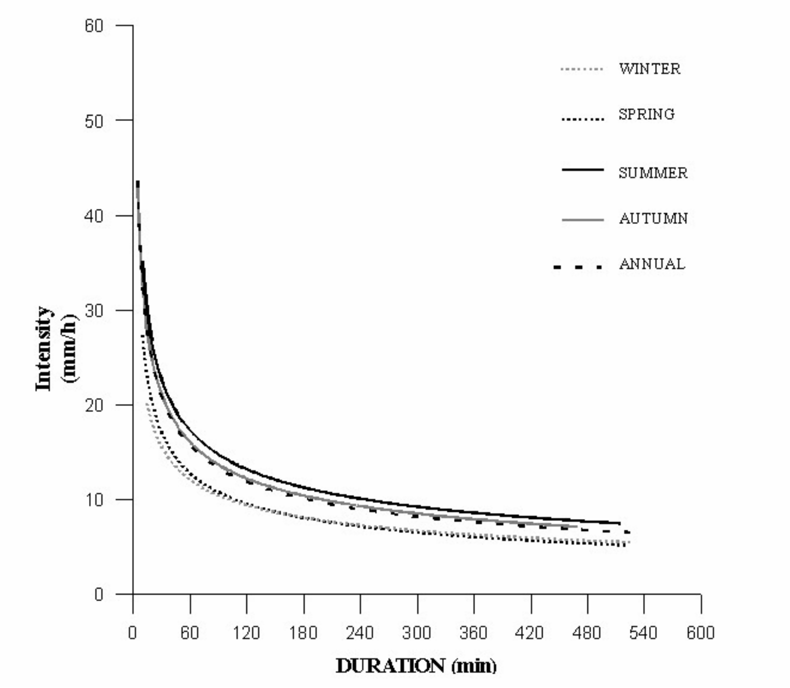

Figure 4. Adjusted curves corresponding to the average intensity duration function in the cases with β*>0.

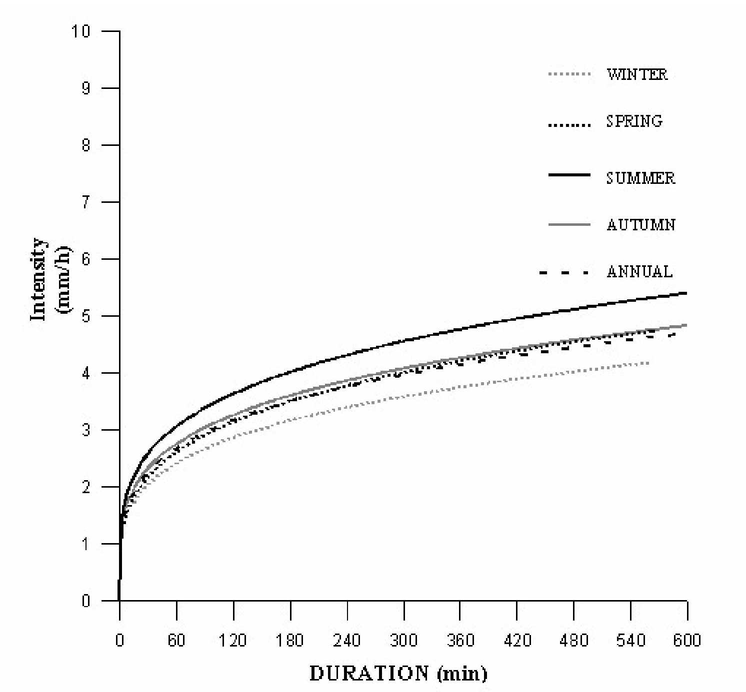

Figure 5. Adjusted curves corresponding to the average intensity duration function in the cases with β*=0.

Analysis of the maximum 5-min intensities achieved in those events with β* other than zero shows that, except on one occasion, 75 mm/h has never been exceeded in winter, while in spring this threshold rises to 100 mm/h, in summer to 200 mm/h and in autumn to 225 mm/h. Similarly, all these extreme intensities are recorded in episodes with a duration of less than 1 hour (in autumn there are some occasional episodes which lasts two hours) and with values of β* close to one unit. Finally, to conclude this discussion, it is worth stressing than the episodes in which the precipitation exceeds the 5-minute threshold of 35 mm/h by 50% or more generally have durations in winter of less than 1 hour, of less than 2 hours in spring, 3 hours in summer and 4 hours in autumn.

Finally, and for the purposes of information, it would be useful to find the correlation which exists between the mean intensity (I_{av}) of an episode and the maximum 5-minute intensity (I_{max}). To that end it is possible to use a potential adjustment of the type:

$$I_{max} = a\, I_{av}^{\,b}$$

Table 2 shows the values of the various parameters for the different seasons of the year. A similar correlation could be established between the maximum 5-minute intensity recorded on any particular day, I_{max} and the total accumulated precipitation on that same day, R. Although the correlation is smaller than in the previous case, the usefulness of the formula lies in the order of magnitude it provides.

$$I_{màx} = 4.1546\, R^{0.6014}, \qquad r = 0.8174$$

It may be noted that this adjustment is better for accumulated daily precipitations lower than 20 mm, but gets worse for abundant precipitations.

Year	a= 1.6994	b=1.1871	r=0.8839
Winter	a=1.6704	b=1.2251	r=0.9285
Spring	a=1.6930	b=1.1746	r=0.9234
Summer	a=1.6794	b=1.1705	r=0.9490
Autumn	a=1.6934	b=1.2158	r=0.9357

Table 2. Values of the various parameters for the correlation which exists between the mean intensity of an episode and the maximum 5-minute intensity for differet seasons of the year, in Barcelona.

5. PROPOSAL FOR A CLASSIFICATION OF EPISODES IN FUNCTION OF THE PARAMETER β*

If in analysis of the previous figures account is also taken of the distribution of the various values of β* it can be observed that there is a certain tendency for the values close to one-unit value to pertain to episodes of very short duration and high intensity, while β* values lower than 0.5 usually pertain to episodes of more than one-hour duration and maximum 5-minute intensities never exceeding 150 mm/h. All this suggests the possibility of using β* as a pluviometric episode characterization parameter.

Firstly, then, the previous section contains a proposal for use of the term “convective” for all episodes in which β* is greater than zero. Secondly, a proposal is made for the following classification of pluviometric episodes according to their greater or lesser convective character:

$\beta^* = 0$ non-convective

$0 < \beta^* \leq 0.3$ slightly convective

$0.3 < \beta^* \leq 0.8$ moderately convective

$0.8 < \beta^* \leq 1.0$ very convective

From all the above it can be obtained that 92% of rainfall episodes in Barcelona are non-convective, providing 63.5% of the total precipitation, and that 8% are convective and provide 36.5% of the total precipitation. To go into further detail, 3.8% pertain to slightly convective episodes, 2.9% to moderately convective episodes and 1.3% to very convective episodes. In winter, the distribution between moderately convective and slightly convective episodes is quite close (approximately 50% of each type), with the difference that the moderately convective episodes generally last less than 2 hours, a threshold which the slightly convective episodes usually exceed. In spring there is a considerable increase in very convective episodes (usually lasting less than 1 hour), although the most dominant episodes are the moderately convective ones (with durations between half an hour and 3 hours). In summer the number of slightly convective episodes decreases markedly, while the very convective episodes then exceed 40% and can last up to 2 hours, while the moderately convective episodes can last some 3 hours. In autumn, finally, the percentage of the very convective episodes decreases to become similar to that of the slightly convective episodes, while over 50% of episodes are moderately convective. It is worth stressing that some of the latter can have a duration of 5 hours. And it is precisely the extraordinary rainfalls and catastrophic floods which are usually linked with moderately convective episodes (though with β*>0.5) of long duration.

Regarding the maximum 5-minute intensities, it is worth noting that 55% of the very convective episodes exceed the threshold of 125 mm/h, 63% of the moderately convective are between 75 mm/h and 125 mm/h and 59% of the slightly convective between 35 mm/h and 75 mm/h.

6. UTILIZATION OF PARAMETER β* FOR CHARACTERIZATION OF THE DESIGN HYETOGRAMS

Firstly, the IDF curves were calculated on the basis of the 5-minute series of the Jardí pluviograph for each season of the year and for the return periods of 2, 5, 10, 25, 50, 100 and 500 years. There exist other studies of the IDF curves for the above-mentioned pluviograph (Burgueño, 1986) but they refer to the 1-minute series and no distinction at all is made in them between the different seasons of the year. As in those studies, a Gumbel-type distribution was taken to be valid for use as an adjustment function (Ven Te Chow, 1988).

Figure 6 represents the seasonal IDF curves. Linking this back to the previous paragraph, it is observed that the episodes with 5-min intensity above 150 mm/h show a return period of 500 years in winter and spring and 10 years in summer and autumn. In this season, the maximum 5-minute intensity, corresponding to a return period of 100 years, rises to 230 mm/min. Also worthy of note is the fact that in winter it is necessary to go beyond a return period above 2 years to find episodes whose 5-minute intensity exceeds 35 mm/h, that is, β* other than zero.

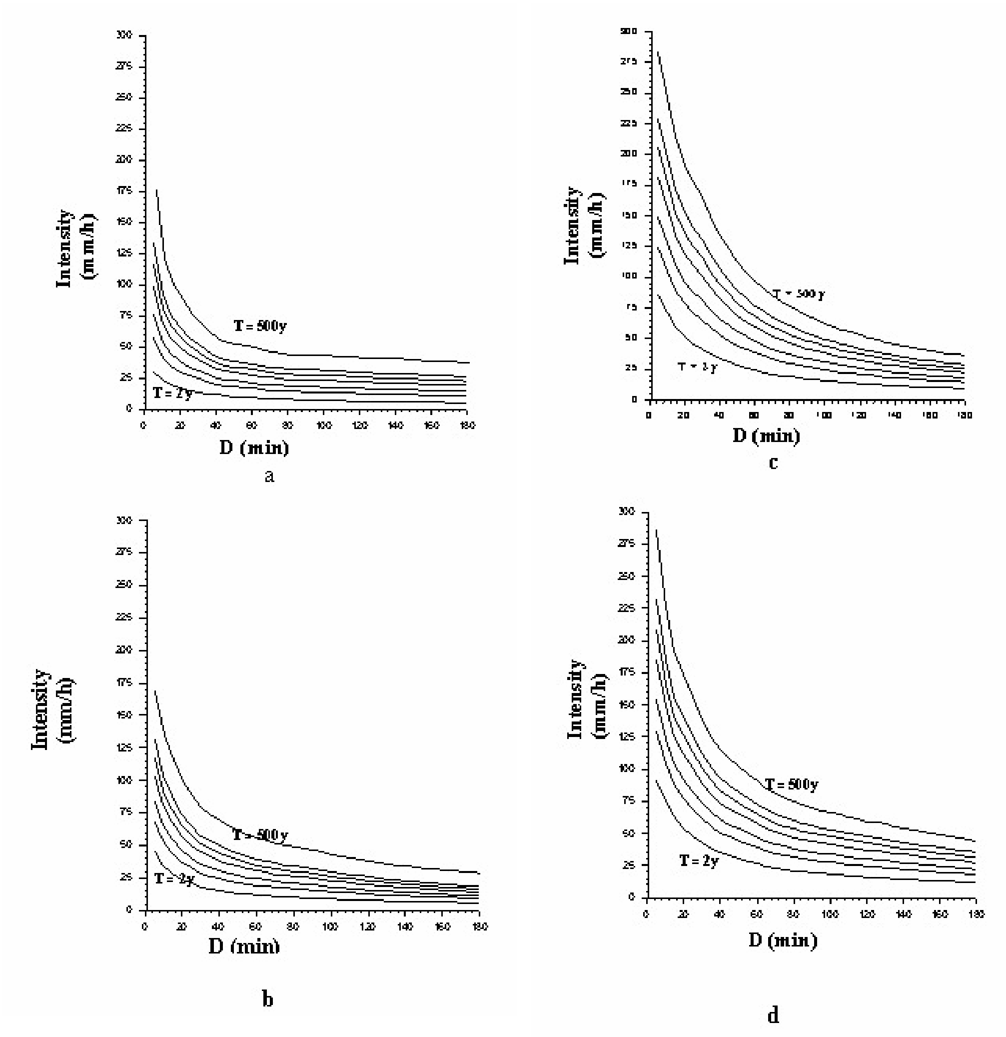

Figure 6. a) Curves IDF for Barcelona in winter. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years. b) Curves IDF for Barcelona in spring. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years. c) Curves IDF for Barcelona in summer. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years. d) Curves IDF for Barcelona in autumn. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years.

Figure 7 shows the annual IDF curves. It can be seen the similarity between this last figure and this another one corresponding to autumn season.

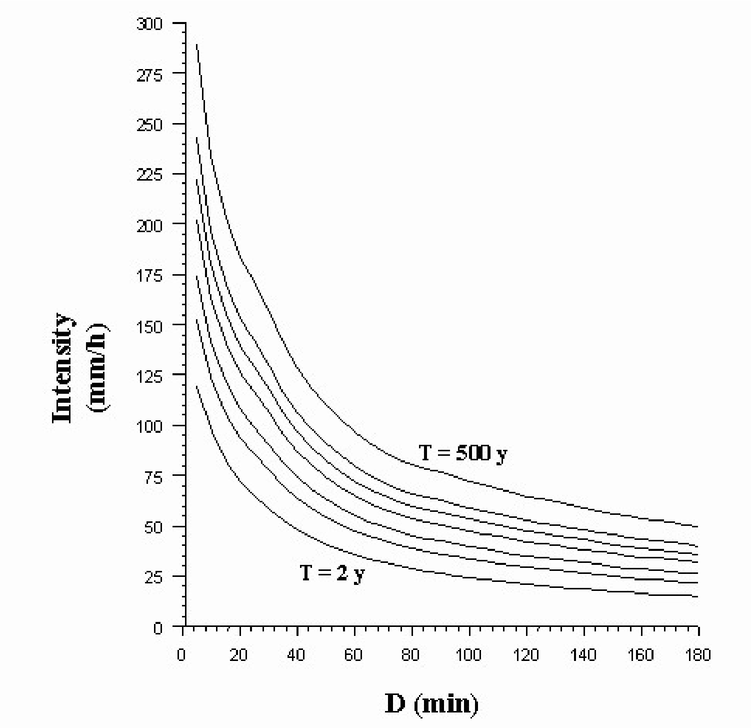

Figure 7. Curves IDF for Barcelona for all the year. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years.

Secondly, the design hyetograms were constructed on the basis of the IDF curves by using the alternating blocks method. A change was nevertheless made in the application of this method, by supposing that the maximum intensities in the episodes of heavy intensity are recorded approximately within the first one-third of same (in the first half for very brief episodes), which derives from a study carried out using the minute series of the Jardí pluviograph (Lorente and Redaño, 1991). The same paper shows that for episodes of 1 hour approximately 80% of the precipitation falls in the first 30 minutes. Indeed, for a duration of 20 minutes the maximum intensity is achieved in the second 5-minute interval, that is, between the first 5 and 10 minutes, while for a duration of 90 minutes this is attained between minutes 25 and 30. This curve was therefore used for locating the maximum intensity and the blocks alternated, starting from the left in order to accord greater weight to the first part of the episode.

Figure 8 shows the design hyetogram obtained from the annual IDF curve for a return period of 10 years and supposing an episode duration of 75 minutes. The preceding methodology was used in constructing it. Figures 9 a and 9 b show the hyetograms corresponding to the seasonal IDF’s for the aforesaid duration and return period. It is easy to see the overvaluation which would be involved in taking the annual hyetogram as representative of the winter.

Thirdly, each hyetogram was characterized by means of the value of β*, and β* has been represented for each season of the year in function of the return period and of the duration of the corresponding pluviometric episode. One of the results is shown in Figure 10. In line with the observations carried out for the IDF, the return period of 2 years does not appear in the winter graph. The utilisation of these curves provides information on the greater or lesser convective character of the episodes. The advantage of this is that it allows to obtain a design hietograph for any duration. Thus, for a return period of 2 years and a duration of 20 minutes, the episodes are very convective, with a β* value of 0.8 (80% of the precipitation exceeds the 5-min intensity of 35 mm/h) and a mean maximum intensity of 75 mm/h according to the annual IDF. Thus defined, for a return period equal or less than 2 years, convection remains predominant where the duration of the episode is less than 70 minutes. Those events for which 50 mm of cumulated rainfall are recorded in 30 minutes (that is typical in some Mediterranean regions to characterize heavy rainfall events) have a return period above 10 years (Figure 7) and are very convective (Figure 9). These results are in accordance with the maximum life cycles of the usual unicellular or multicelular "storms". But catastrophic rainfalls in this region are usually related with rainfall events that last a minimum of two hours; for this duration the return period for a very convective event (β*>0.8) is above 100 years (Figure 10) and the mean 5-minutes maximum intensity overcomes 60 mm/h, which represents a cumulated rainfall comprised between 60 mm and 120 mm approximately.

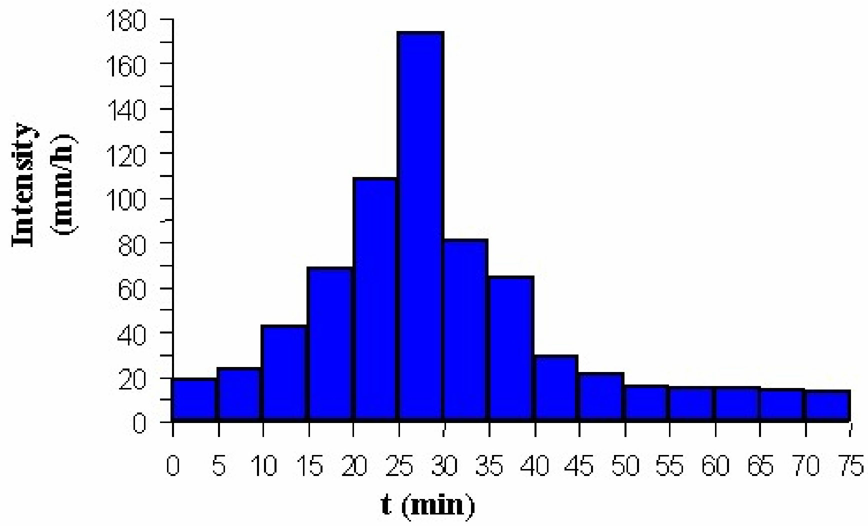

Figure 8. Hietograph obtained from the annual IDF curve corresponding to a return period of 10 years and duration of 75 minutes.

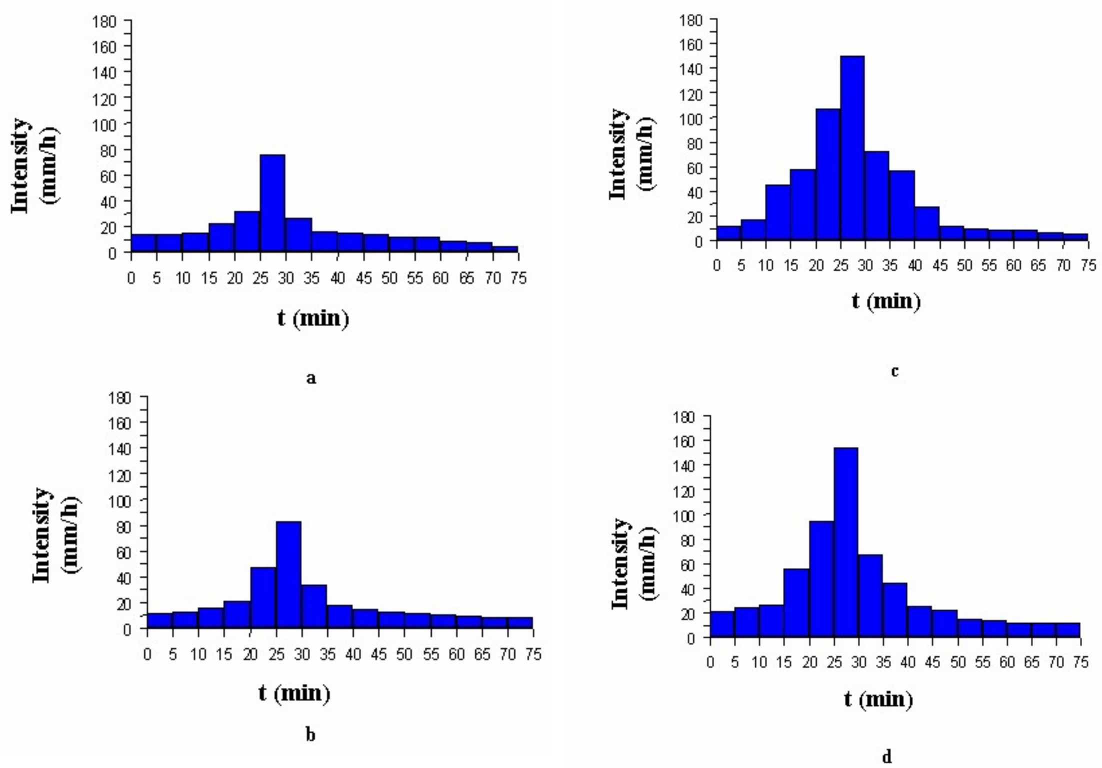

Figure 9. a) Hietograph obtained from the winter IDF curve corresponding to a return period of 10 years and duration of 75 minutes. b) Hietograph obtained from the spring IDF curve corresponding to a return period of 10 years and duration of 75 minutes. c) Hietograph obtained from the summer IDF curve corresponding to a return period of 10 years and duration of 75 minutes. d) Hietograph obtained from the autumn IDF curve corresponding to a return period of 10 years and duration of 75 minutes.

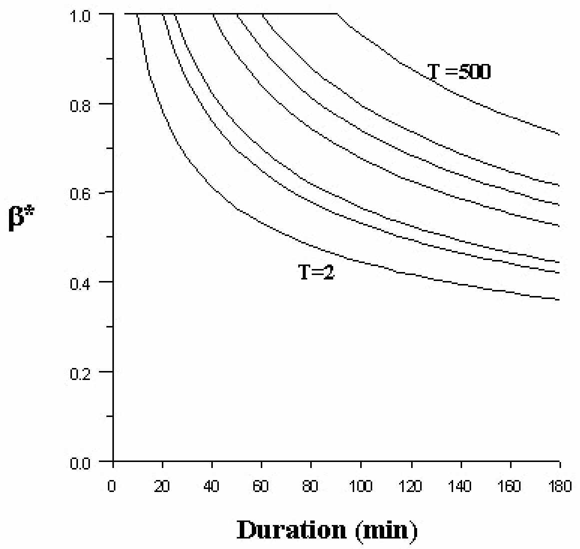

Figure 10. Curves of β* (all year) corresponding to the hyetographs obtained from the IdF curves. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years.

The same kind of figure can be represented for each season (Figure 11). For instance, for a 2 years return period and an event duration of 40 minutes, the β* value is 0.63 (63% of 5-minute rainfall rate is above 35 mm/min) and the maximum intensity deduced from figure 7 is 50 mm/h. If the event was recorded in winter, the maximum intensity would be 13 mm/h and the 5-minutes rainfall rate would always be less than 35 mm/h, but if the event was produced in autumn the maximum would be 38 mm/h and β* would be 0.48.

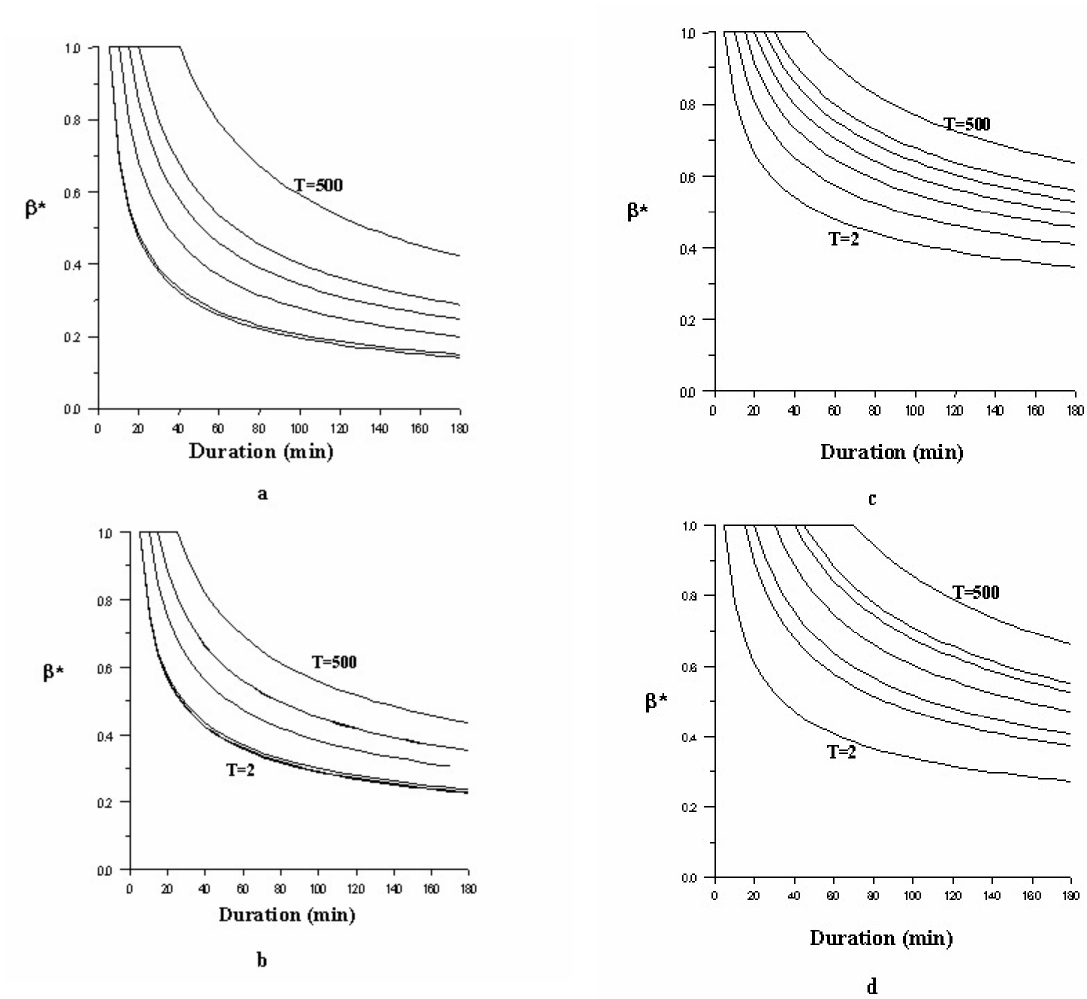

Figure 11 a) Curves of β* (all year) corresponding to the hyetographs obtained from the winter IdF curves. The curves have been designed for return periods T=2 (its value is 0), T=5, T=10, T=25, T=50, T=100, T=500 years. b) Curves of β* (all year) corresponding to the hyetographs obtained from the IdF spring curves. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years. c) Curves of β* (all year) corresponding to the hyetographs obtained from the IdF summer curves. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years. d) Curves of β* (all year) corresponding to the hyetographs obtained from the IdF curves. The curves have been designed for return periods T=2, T=5, T=10, T=25, T=50, T=100, T=500 years.

After obtaining the design hietographs in function of the season of the year, duration and return period, the β* coefficient has been calculated for each one of them. With this information it is possible to represent a graph showing the relationship between the β* values and the event duration for each return period.

7. APPLICATION OF THE β* CLASSIFICATION TO HEAVY RAINFALL EVENTS THAT HAVE PRODUCED DAMAGES

In order to analyse the potential use of this kind of classification to identify rainfall events that have produced damages, the period 1987-1996 has been analysed. The sample consists of those rainfall events that have produced damages in any part of Spain during this period and for which the average rainfall intensity and the duration is known. With these conditions 25 heavy rainfall events have been selected, 76% of which have occured in Catalonia. Although the greatest part has cumulated rainfall above 100 mm in 24 hours, some events have had a very short duration (less than one hour) but strong intensities. The greatest hourly rainfall amount gathered has been 152.9 mm during the Biescas (Aragón) event (Riosalido *et al*, 1997). Figure 12 is the same that Figure 3 but those new events have been included. It is interesting to see that all those events are over or above the curve defined by the function:

$$I = 734.2\, D^{-0.6912} \qquad r^2 = 0.987$$

All of them are convective , but their peculiarity is that their average intensity is above the usual average intensity for the due duration.

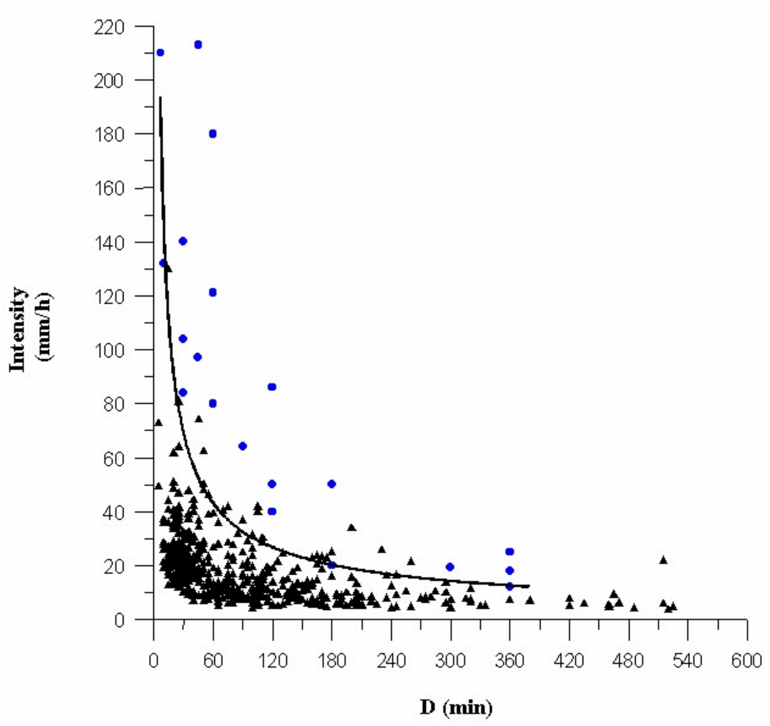

Figure 12. Distribution of the average intensity (mm/h) of the rainfall events with β*>0 in function of their duration (circles) and the rainfall events that have produced damages (triangles).

8. CONCLUSIONS

This paper has centred on seeking a method of objective classification and at the same time a plausible physical interpretation of pluviometric episodes, so that they can be introduced into hydrometeorological modelling. To this end, recourse was had to the 5-minute series of intensities, 1927-1981, provided by the Jardí pluviograph sited close to the city of Barcelona (Spain).

For this purpose, and after considering the antecedents in this field, the parameter $\beta^*_{L,\,\Delta T}$ has been defined. In the particular case in which ΔT=5 min and L=35 mm/h, the notation de $\beta^*_{35,\,5}$ has been simplified and represented as β* . The use of the term "convective" is then proposed for all those episodes in which β* is greater than zero. Likewise, and in order to facilitate subsequent work, the hypothesis that all the rain from a "convective" episode can be treated as such in its entirety was taken to be valid, without any need to enter into consideration of its internal structure (as long as there is no intention of working in the field of the microphysics of the associated processes).

From analysis of the 5-minute series it can be deduced that for 1.454 % of the mean annual time for which it rains, the precipitation presents a mean 5-minute intensity exceeding 35 mm/h, and is responsible for 18.2% of the total annual precipitation. Between 1927 and 1981 some 8% of the episodes recorded on the Jardí pluviograph exceed at some time the threshold of 35 mm/h, that is, they present values of $\beta^* > 0$, providing 36,5% of total annual precipitation. The largest number of events occurs in autumn, with mean value of 12 episodes; the largest percentage of the total nevertheless occurs in August, with just over 18%, providing 64% of the total precipitation. With the exception of autumn, these are episodes with a duration of less than 4 hours, and are shorter the greater the intensity reached.

It is thus possible to draw up a classification of the rainfall events in the light of their greater or lesser convective character. It can be noted that the very convective episodes ($0.75 < \beta^* \leq 1.0$) last less than 1 hour, while the slightly convective ones ($0 < \beta^* \leq 0.25$) last for longer than that time threshold. The duration of the moderately convective episodes ($0.25 < \beta^* \leq 0.75$) increases throughout the year from winter to autumn, in which last season they can last some 5 hours. This threshold, however, is only exceeded by the slightly convective episodes. The catastrophic rainfall episodes and floods are usually linked with moderately convective episodes of long duration.

The intensity and duration ranges established by the above classification coincide broadly with the properties of the various convective systems. The episodes termed very convective, of short duration and high average intensity, would have their origin in unicellular or multicellular (we might remember here that the life-cycle of a storm cell ranges between 20 and 30 minutes) storms, arising mainly in summer. The moderately convective episodes which are of high mean intensity and duration exceeding one hour would correspond to highly organized convective systems composed either of multicellular or supercellular storms or, in extreme cases, of Mesoscale Convective Systems (Doswell, 1993; Llasat, 1997), in which it is possible for 50% of the precipitation to be stratiform. This type of situation is inherent to the autumn and includes all those related with catastrophic rainfall and flooding.

With a view to future modelling of the IdF curves, it is important to note that although the very convective episodes generally last less than 1 hour, a high percentage of the non-convective episodes also lie within this time interval. It is therefore advisable first to classify the events making up the pluviometric series and then construct the IdF curves for each class, since the properties of these different kinds of episodes are not the same. Similarly, any rainfall episode lasting more than 5 hours is non-convective or slightly convective in nature, and this threshold can be reduced where related strictly to certain parts of the year.

Regarding the dominant meteorological situations for each type of episode, it is difficult to lay down features common to all of them, except for the situations inherent to extraordinary rainfall episodes (Llasat and Puigcerver, 1994). However, some previous results of the spatial distribution of β^* in basis to the 5-minute rainfall rate for a 125 raingauges distributed in the Internal Basins of Catalonia (approximately 17.000 km^2) shows the possibility of drawing up synoptic meteorological configurations for each interval of β^* (Llasat *et al*, 2000). Similarly, work has begun on application of the methodology proposed herein to other series in the Mediterranean area, mainly those showing good correlation with the Barcelona series (Llasat and Rodriguez, 1997). In order to improve Figure 12 a research about the damages produced by historical heavy rainfall events has been started within the framework of the SPHERE European project.

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