A two parameter design storm for Mediterranean convective rainfall

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MS No.: hess-2016-644

Status: Open Discussion on HESSD

Final Response

On behalf of myself and my co-author, I am grateful to the Editor, Prof. Matjaž Mikoš, and all the Referees for their reviews and their very helpful and detailed comments. Each comment was answered point by point during the open discussion period and afterwards we revised all highlighted issues and improved the manuscript accordingly. All the items highlighted by the referees have been considered.

Regarding the major concern of referee #1 about possible overlapping with Andrés-Doménech et al, 2016, we made clear that the contents of the present research are new and original, and the necessary link with previous data-work (Andres-Domenech et al, 2016) is referred section 3.

The present work responds to the programmed continuation originally scheduled in the framework of the research project that supports this publication and its objectives. To meet the concern of reviewer #1, text in the introduction section (section 1 of the manuscript) has been improved in order to clarify the scope of the research and the link with previous studies. More details on this issue are given in the point-to-point response to reviewer #1.

The most important changes and corrections in the paper refer to the following:

a) A more concise statement of the assumptions, scope and limitations of the paper, thus improving the introduction section and better stating the paper's objectives.

b) Added considerations at the conclusions-section about the inherent limitations of the method and its range of applicability in hydrology engineering.

c) An improved discussion concerning the meaning of the three identified storm families (section 3.2.).

d) A better discussion of the comparison with the alternating block method (section 5 and table 5).
e) Nine new references have been included in the new version of the manuscript.

Furthermore, all the editorial remarks and other minor corrections have been addressed in the revised manuscript, submitted now to HESS.

Below we provide a detailed summary of the changes made in the manuscript. The numbered items refer to each topic answered to each referee during the open discussion. The original queries and detailed replies to the referees are given right after.

Finally, a marked-up version of the manuscript is provided in order to identify all changes made in this new version.

Response to Referee Comment 2016-644-RC1 – Anonymous Referee #1

The authors are truly grateful for the interest and invaluable work reviewer #1 has devoted to the manuscript and to the research embodied in it. His/her criticisms and comments have been very enriching and have helped greatly to improve it.

We would like to underline specifically the improvements related to the framework of the research, as well as the broadening of the references to other research on this topic. Also, the list of minor remarks helped to make manuscript text clearer and significantly improved.

In answer to the referee, we have discussed and argued the basic questions raised, with corresponding modifications of the manuscript text.

Regarding the 26 specific (line-to-line) observations, all of them will be included appropriately in the revised version of the manuscript, except for the one on section 2.3. There we have preferred to leave the formulae unaltered; that is, with generic Δt instead of replacing it with the value $\Delta t = 10$ minutes. We have justified this decision subsequently in the answer to the reviewer.

1. On the overlapping with Andrés-Doménech et al. (2016)

The results here exposed have been developed in the framework of a research project funded by the regional government of the Comunidad Valenciana (Spain), scheduled for two years.

Preliminary advances were presented in a communication to the 4th IAHR Europe Congress, held in Liege, Belgium (Andres-Domenech et al, 2016). That presentation described the detailed treatment of the data registered by the hydrological information automatic system corresponding to the Valencia (Spain) series with a double goal: On the one hand, the identification of statistically independent convective events from rainfall records, which our paper refers to in section 3.1. On the other hand, the study of the suitability of a theoretical gamma-type temporal pattern to represent the above mentioned events.

The present research documents most of the ulterior theoretical work undertook, with further advances within the cited research project to its completion, including:

a) A new, compact and improved formulation of i(t), function representing the temporal pattern of rain intensity, and the presentation of a series of useful and necessary analytical properties derived from the former, for its appropriate application to practical cases of hydrological design.
b) The development of an original return period assignment methodology, which takes into account both the volume and the intensity of the event.
c) The development of a practical procedure to build the design storm for a pre-established temporal aggregation level Δt and a given return period T.
d) The application to a practical case study of the new methodology and the comparison of results with a traditional method.
e) A discussion of results and general considerations about the suggested methodology in the framework of applied urban hydrology engineering.

Therefore, the contents of this research are new, original, and the necessary link with previous data-work (Andres-Domenech et al, 2016) is referred in section 3. The present work responds to the programmed continuation originally scheduled in the framework of the research project funded by the regional government (*Generalitat Valenciana*) and to its objectives. After the concern of reviewer #1, text in the introduction section (section 1 of the manuscript) has been improved, to clarify the scope of the research, and the link with previous works.

2. On the design storm

The interesting review done by reviewer#1 brings to light several arguable aspects of design storms, not only of the one proposed herein, but also of the well-known alternating blocks method and others which are usually employed in engineering practice. Indeed, all of them show several limitations, and more specifically when used in hydrological applications that require a more complete and realistic representation of the rainfall phenomenon as main input of hydrological systems.

As reviewer #1 points out rightly, the introduction of a new combined variable (X_1) allows, methodologically speaking, the convenient return period assignment to a storm described by several relevant variables. Once a return period T is established, a single value of X_1 is deducted (section 3.4). Obviously, the bigger the magnitude or importance of the storm, the bigger the value of X_1.

This first step is not enough to define the design storm, since according to equation 26, there exist infinite ratios $\alpha=P/I_{10}$ congruent with that value of X_1. In practice, only three values α_1, α_2 y α_3, are chosen, according to the empirical evidence (figure 2), which finally result in three storms associated to the previously defined T.

As reviewer #1 indicates in its comment, those storms display different durations. But it is also worth noting that, in addition, their peaks of rain intensity, total depths, and also their temporal patterns, differ from one another. This last aspect should be extended only to the known shape differences derived from different values of φ parameter.

In other words, the resulting design storms are not the result of a mere and arbitrary choice of three different durations, but are based on the characteristics of real episodes, observed and statistically synthesized in figure 2.

The most traditional use of design storms in hydraulic engineering applications contemplates the sole existence of one unique storm for each T. While maintaining a similar working framework and objectives, the present research represents a step forward, as it contemplates three storms based on observed rainfall registers, for a given T.

As mentioned before, such storms show differences among them, with regard to peak intensity, total cumulative rainfall depth, shape and also duration. The latter, as stated by reviewer #1, is a desirable quality. As a matter of fact, we totally agree with reviewer #1 regarding the interest of using a range of rainfall inputs with different durations and characteristics in hydrological engineering applications. There are several approaches to proceed this way, including direct use of historical records, rainfall stochastic models (temporal and space-time), Montecarlo simulation, and others.

Notably, the authors have had the opportunity of working intensively on some of the above mentioned methods, and more particularly on the use of space-time stochastic rainfall models as input data of water resources systems. As reviewer#1 highlights, we believe these methods (at least when working in a certain range of hydrological engineering problems), are not replaceable by simplified approaches such as the “design storm” ones. Some examples of the work of the authors on this matter can be looked at in the references here below

Garcia-Bartual, R. (2003): Synthetic Flood Scenarios for Risk Assessment in Large Dams, in “Hydrological Risk: Recent advances in peak river flow modelling, prediction and real-time forecasting”. Assessment of the impacts of land-use and climate changes”. EUROPEAN SCIENCE FOUNDATION. CNR-GNDCI Publ. No. 2858. Ed. BIOS. ISBN 88-7740-378-0. 369-389.

Salsón, S. and García-Bartual, R. (2003): A space-time rainfall generator for highly convective Mediterranean rainstorms. Natural Hazards and Earth System Sciences, vol. 3. 103-114. Ed. European Geophysical Union.

Frances, F., R. García-Bartual and G. Bussi (2012): High return period annual maximum reservoir water level quantiles estimation using synthetic generated flood events, in “Risk Analysis, Dam Safety, Dam Security and Critical Infrastructure Management”. Taylor and Francis, ISBN 978-0-415-62078-9. 185-190.

However, the research undertaken herein is essentially framed in the context of design storm formulation. Consequently, it emerges from premises which are different from the above mentioned methods and has, therefore, its inherent limitations.

With regard to the shape of the function, another issue mentioned by reviewer #1, there is no doubt that rainfall intensity empirical records show a extremely wide range of patterns. They are difficult to reproduce by means of a single analytic function such as the one proposed herein, or a method such as the one used in the alternating blocks method. It should be pointed out, though, than in the latter, the peak is always located at the centre of the storm while duration is basically arbitrary. In the case of the gamma function, the relative position of the peak is variable (it depends on the value of φ), although it comes always before the central point as reviewer #1 states. This hypothesis clearly implies a simplification of reality, but is also statistically consistent since, according to what is described in the manuscript, it is derived from real sequences of rainfall intensities and its corresponding patterns found in selected rainfall events, unlike the temporal pattern of alternating blocks. The idea came originally after a pioneer research in this field [Brummel, 1984], referred in the manuscript.

Concerning duration, it is not arbitrary, as mentioned before. It essentially depends on value of parameter φ, which originally derives from the analysis of historical rainfall events identified in the registers used.

We share the belief with reviewer #1 that gamma function is an interesting pattern and appropriate for the simplified representation of convective temporal rainfall patterns. Specifically, Mediterranean convective rainfall episodes derived from the activity of individual convective cells, show particularly short durations and high intensities, unlike typical rainfall episodes in other parts of the world. On the other hand, there exist physical and empirical foundations for such election, as the pattern represented is consistent with activity life-cycle of a convective cell, described in terms of an initial rapid development until reaching a maturity stage during which maximum intensities are attained, and then followed by a stage of dissipation in time, typified by a progressive attenuation of rainfall intensities.

We also believe, in line with the comments expressed by reviewer #1, that the use of alternating blocks storm, along with the gamma-type design storm and other simple design storms, are not the best choice for certain, larger scale hydrological applications requiring a more quantitatively detailed and extensive representation of rainfall intensity process in space and time.

3. On the comparison with the alternating block method

Certainly, as reviewer #1 pointed out, the comparisons made with current methods used in hydraulic design are interesting, for example the Average Variability Method (AVM). In the draft we include a comparison with a method that is extensively used in Europe and especially in the Mediterranean countries. Section 5 of the manuscript, not being the most important one of the work, was included for illustrative purposes and for contrast with the best known method in the latter regions. Perhaps a further exhaustive comparison, not only with the AVM method, which is in itself very interesting, but with methods implemented in other parts of the world might be of interest for future research.

Line by line comments

Page 1, Line 8: Can probably remove the second "of"

We agree, it will be removed in the revised manuscript.

Page 1, Line 11: Remove “On the former work basis”

We agree, it will be removed in the revised manuscript.

Page 1, Line 13: “High” not “Highly”

We agree, “high” is the correct word.

Page 1, Line 23: “They experienced their major development . . . still unresolved” This sentence is overly vague. What was the development? What was left unresolved?

The sentence will be rewritten as follows in the revised manuscript:

“They experienced an important development during the 1970s and 1980s with more realistic approaches (Pilgrim and Cordery 1975; Walesh et al. 1979; Hogg 1980, 1982; Pilgrim 1987).”

Page 2, Line 6: “Widespread” – should this be “widely used”? “Widely known”?

Yes, the correct wording is “widely used”.

Page 2, Line 33: Again, this is a very vague sentence. What are the conceptual mistakes and unrealistic assumptions? Are you addressing these here in this paper?

The sentence will be rewritten as follows in the revised manuscript:

“Some authors point out that the design storm concept itself is fraught with conceptual error when used to simplify engineer analysis by unrealistic assumptions (Adams and Howard, 1986).”

Page 3, Line 5: I think you can argue that the temporal pattern has just as much of an influence (see the aforementioned http://arr.ga.gov.au/arr-guideline for a discussion on this as well references on this topic). For example, Ball (1994) (doi: 10.1016/0022-1694(94)90058-2).

Sentence in line 5 will be rewritten as follows:

"… the influence of storm duration and temporal pattern becomes critical (Ball, 1994)."

Page 3, Line 7: Stronger consequences than what?

The text has been improved, accordingly to this comment by reviewer #1.

In fact, "stronger" is not the correct word. It will be replaced by "strong" in the revised manuscript. In addition, the following sentence will be added at the end of this paragraph:

"The above mentioned uncertainties in IDF curves estimation can affect significantly the reliability of derived design storms, especially in the definition of its peak rainfall intensities, with undesirable consequences when used for hydrologic design purposes".

Page 3, Line 15 and 16: You have one thing being the most uncertain step and another thing being the most challenging task. This seems to be a contradiction and needs rewording.

Page 3, Line 17-23: This could be rewritten as one sentence: "As a design storm is composed of many variables (e.g. depth, duration, temporal pattern, and antecedent conditions) assigning a single return period may not be appropriate."

The sentence "Finally … challenging tasks" will be removed. Paragraph in lines 15-23 will be rewritten as follows in the revised manuscript:

"A storm event presents many characteristics so it cannot be fully described by the statistics of only one of them. For a return period definition, a common practice is to assign a given frequency to a specific event feature (i.e., its maximum intensity). But, given that a design storm is composed of many variables (depth, duration, temporal pattern, antecedent conditions), assigning a single return period may not be appropriate.

Page 3, Lines 23-30: These lines just state what was performed in this manuscript. This should be rewritten to state exactly the problems this paper is addressing and how it is building on previous work.

Lines 23-30 in page 3 have been replaced by the following text, which helps the reader to focus better on the problems studied herein, according to reviewer's comment:

The objective herein is formulating an analytical approach in order to describe rainfall intensities in time, as an alternative for practical design storm definition in Mediterranean areas. Also, developing all required analytical properties to ensure its applicability under usual criteria and requirements of design storm approaches for hydrological design. These include a methodology for return period assignment based on both, total depth and peak intensity of the storm. Also, a practical methodology to build the storm, applied to a given case-study to validate it. For illustrative purposes, a comparison with most extended design storm in Mediterranean areas will be developed and discussed.

Page 4: Could Line 8-24 be moved up and then Lines 1-7 follow. As it stands you state you use a gamma function in Line 3 and then don't actually introduce it till line 25.

We agree with reviewer comment. Text at initiation of section-2 (page 4) of the manuscript can be improved, for a clearer reading. The following changes in the text are introduced in lines 2-7, which make the exposition better organized and clearer:

"The temporal pattern of rainfall intensities representing the design storm is expressed in terms of a continuous analytical function, of the form given in eq. 1:

$$i(t) = i_0 \cdot f(t) \quad ; \; t \geq 0 \tag{1}$$

where t (min) is the elapsed time from the start of the rainfall episode (t=0), i(t) represents the rainfall intensity at instant "t", i_0 (mm/h) is the instantaneous peak rainfall intensity of the storm, and f(t) is a convenient non-dimensional, continuous and differentiable analytical function, which will be defined below."

Page 5: Not sure if another line can be added between equation 8 and 9 because I sort of missed this step.

Once again, we agree with reviewer comment, as minor changes in the text can help the reader to follow better the undergoing developments at that section.

LINES 7-11: (new re-written text):

“To do so, a final or residual value is established as a fraction η_1 of the maximum (eq. 7).

$$f(t_C) = \eta_1 \;\; ; \;\; 0 < \eta_1 < 1 \qquad (7)$$

where t_C (min) represents the total storm duration ($t_C > t_0$). Convenient η_1 values are shown in table 1. Introducing condition given in equation 7 into equation 2, yields to equation 8, which should be verified by $f(t_C)$.

Page 5, Line 24: I don’t like the use of the word “easily”.

The word “easily” will be removed in the revised manuscript.

Section 2.3: I understand the use of generic terms but I think you just use a delta t of 10 minutes so maybe it would make more sense to just employ that constant in this section (as you have in previous sections with eta1 of 0.05).

We understand comment by reviewer #1. In section 2.2 of the manuscript, as mentioned, the general expressions are obtained, and also particularized for the specific value $\eta_1 = 0.05$, which is later used in the application. This helps to illustrate the practical use of equations 14 and 19, with a very significant simplification of the expressions. But it should be remarked that this is not only done just for illustrative purposes, but also, and more importantly, to point out relevant properties (eq. 15 and 20). In particular, the latter one implies that the ratio i_0/P is directly proportional to the value of φ parameter.

In the same manner, in section 2.3 general expressions are obtained. But in this case, we consider that equations 22, 23 and 24 are clear enough as such, not being simplified in any way by substituting the particular value $\Delta t = 10$. Also, it should be noted that this substitution is not necessary at this point of the manuscript, and does not yield to any relevant property, as it was the case in previous section 2.2.

Page 8, Line 20: “not a” should be “no”.

Yes, the correct word is “no”.

Section 3.1.1 – A useful reference is Dunkerley, D. (2008), Identifying individual rain events from pluviograph records: a review with analysis of data from an Australian dryland site, Hydrol. Process., 22(26), 5024–5036, doi:10.1002/hyp.7122.

The following sentence will be added in the revised manuscript just before "Works by Restrepo-Posada…":

"Dunkerley (2008) presents an interesting review of the range of approaches used in the recognition of main events".

Page 9, Line 9: "Less" instead of "Lower".

Yes, the correct word is "less".

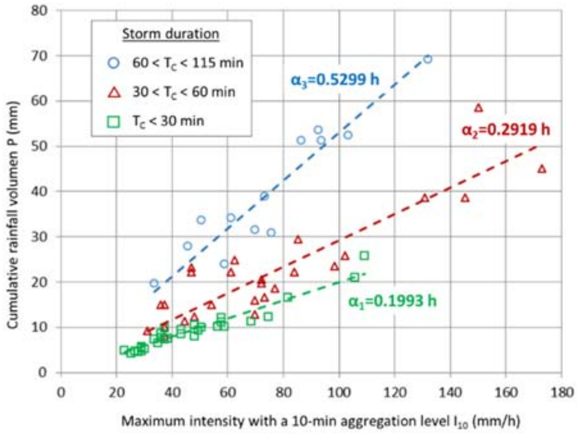
Section 3.2: I thought the relations were characterized by splitting the storms on critical duration (see Figure 2) not the ratio as stated in Line 5.

The first sentence of this section (page 10 – lines 4-5) will be rewritten as follows:

"Three different sets of events were identified, according to their duration. As shown in figure 2, each of them can be characterized in terms of a representative value of the ratio:"

Figure 2: I don't think the colours and symbols match.

We agree, there is a mistake. Triangles and squares are mixed up. Figure 2 will be replaced by the following one:



Section 3.2: It would be nice to discuss in one line what the different alpha’s mean in practice to the temporal pattern.

The following sentence will be added at the end of section 3.2. in the revised manuscript:

“Low α values typically correspond with storms with its peak intensity located short after the initiation of the storm, while higher α values are found for longer events and usually higher cumulative rainfall depths”.

Page 11, Line 5: I don’t like the use of the word “tackle” in general. I would prefer “undertaken” or something similar.

“tackle” will be replaced by “undertaking” in the revised manuscript.

Page 11, Lines 20-27: This seems to be just repeating the introduction. It also talks about storage not being important and then states it is important. I would probably just remove this paragraph.

We agree with reviewer #1. This paragraph will be removed in the revised manuscript.

Page 15, Line 10: You state the alternating block method overestimates the volume. But all these temporal patterns are statistical constructs anyway – so we don’t know which is the truth.

The sentence “It is demonstrated … in excess.” will be substituted in the revised manuscript by the following:

“Given a return period, the alternating block method combines in a single theoretical storm the most adverse statistics for several durations, which originally derive from different historical rainfall events. Conceptually, this is a worst-case storm ignoring actual rainfall patterns found in the rainfall registers, yielding to a volume overestimation.

Page 15, Line 19: “Most generally . . .” In Spain? In Europe? Around the world? This is not done Australia for example.

In the revised manuscript, “Most generally” will be replaced by “In many European and American countries”.

Page 16, Line 23: I am still undecided if this is an advantage – counting three storms for every return period. Is it more that the advantage is you have a more robust definition of the return interval in that the depth and temporal have been incorporated into one variable?

In the revised manuscript “…with the advantage of counting with…” will be replaced by “…resulting in…”

New references

Resulting from reviewer #1 comments, suggestions, and critics, the following references will be added to the revised version of the manuscript:

Ball, J. E. (1994). The influence of storm temporal patterns on catchment response. Journal of Hydrology, 158(3-4), 285-303.

Di Baldassarre, G., A. Brath, and A. Montanari (2006), Reliability of different depth-duration-frequency equations for estimating short-duration design storms, Water Resour. Res., 42, W12501, doi: 10.1029/2006WR004911.

Dunkerley D. (2008). Identifying individual rain events from pluviography records: a review with analysis of data from an Australian dryland site. Hydrological Processes, 22 (26), 5024-5036.

Frances, F., R. García-Bartual and G. Bussi (2012): High return period annual maximum reservoir water level quantiles estimation using synthetic generated flood events, in “Risk Analysis, Dam Safety, Dam Security and Critical Infrastructure Management”. Taylor and Francis, ISBN 978-0-415-62078-9. 185-190.

French, R., and Jones, M. (2012). Design rainfall temporal patterns in Australian Rainfall and Runoff: Durations exceeding one hour. Australian Journal of Water Resources, 16(1), 21-27.

Pilgrim, D. H. and Cordery, I. (1975). Rainfall temporal patterns for design floods. Journal of the Hydraulics Division, 101(1), 81-95.

Pilgrim D. H. (1987). Australian rainfall and runoff: a guide to flow estimation. Vol. 1. Institution of Engineers. Australia.

Walesh, S. G., Lau, D.H. and Liebman, M. D. (1979). Statistically based use of event models. Proceedings of the International Symposium on Urban Storm Runoff. University of Kentucky, Lexington, 75-81.

Response to Referee Comment 2016-644-RC2 – Anonymous Referee #2

The authors are grateful for the observations and comments made by reviewer #2

He suggests a comparative analysis using Δt=5 minutes, which was actually contemplated by the authors when dealing with section 5 of the draft. As described in our answer to the reviewer, the final choice of Δt=10 minutes has a scientific basis and is supported by the results of previous research.

1. On the number of blocks and the time level of aggregation

Regarding the number of blocks used to represent the design storm, we must make it clear that it is not arbitrary. On the contrary, it is completely defined by two factors, as it is also shown in the answer to reviewer #3 (minor remark #f):

a) On the one hand, the duration of the storm, which essentially depends on the value of parameter φ, so that the duration is pre-established before building the design storm. Parameter φ defines the temporal pattern of the rainfall, and originally derives from the original rainfall events of the historical registers used.
b) The time level of aggregation, Δt. On this point, the two natural choices for this study were Δt=5 minutes or Δt=10 minutes. Logically, in the first case, there would have resulted more blocks for the design storm, in line with the suggestion made by reviewer 2. From a practical point of view, the procedure does present any added difficulty. Nevertheless, for the purpose of comparison with the method of alternating blocks, the authors choice was Δt=10 minutes in favour of a greater reliability. Indeed, a thorough investigation has been done into the significant degree of uncertainty arising in IDF

curves for durations under 10 minutes, particularly for the Mediterranean area studied (Garcia-Bartual and Schneider, 2001; Vaskova, 2001). Both references are in the original manuscript. From our point of view, $\Delta t=10$ gives enough resolution to the storm definition, and provides a sufficient representation of the time pattern of the design storm, with more reliability.

This question from reviewer #2 helped to find two errors in the manuscript: Page 13, line 26: It should say 6 blocks, instead of 7 blocks. Table 4, storm 3, it should say 6 blocks instead of 7. Both errors are corrected in the new version of the manuscript.

Response to Referee Comment 2016-644-RC3 – Prof. A. Montanari

The authors are very grateful to Prof. Montanari for the work he has done on the draft and the observations and suggestions he has made. Thanks to his remarks we have been able to improve the content of the manuscript. We would particularly like to underline the new results and the discussion incorporated in the revised text, as a result of question number 4.

The rest of the questions have been also answered and all the minor remarks made by Prof. Montanari have been duly considered and incorporated into the new version of the manuscript.

1. On the principal component analysis

The principal component X_1 gives more weight to rainfall intensity than to cumulative rainfall depth, although both are considered in a weighted way. Any of the two variables (I_{10} or P) separately, explains less variance of the process than X_1, which is then introduced in the analysis exclusively with the goal of assigning a return period T to the storm.

Given the assignment of T, procedure essentially involves a single variable. X_1 was chosen for that purpose as it explains 92% of the variance. Thus, variable X_1 is an adequate quantification of the magnitude of the event, affected both by intensity and total rainfall depth.

In order to know the effect of ignoring 8% of the variance, it would be necessary to consider both variables simultaneously, either X_1 and X_2 or I_{10} and P , which is not compatible in practice with the usual univariate analyisis and a single-variable statistics linked to a given T.

2. On the uncertainty in determining equation 25

Equation 25 introduces the ratio between the total cumulative depth of the storm and its maximum intensity I_{10}, for a time level of aggregation $\Delta t = 10 \text{ min}$. This ratio has been assessed for the totality of the selected events, resulting in the cloud of points displayed in figure 2. In view of the former graph, and after splitting the sample in families of different duration, it was verified that the ratio α experienced small variations within each of them, with significant regression coefficients values for each of the families (longer, medium and short storm durations).

This fact enables the characterization of each family according to their ratio $\alpha = \frac{P}{I_{10}}$. If regressions had not been acceptable, such an empirical characterization would have not been acceptable either, and the proposal of three design storms i(t) with different values of the parameter α would have no empirical basis.

On this empirical basis, it is suggested to postulate the characteristic value of ratio α as a starting condition for building each design storm, one per family.

3. On the goodness of fit of the gamma function to explain the temporal pattern

The goodness of fit of a gamma-type pattern to represent rainfall intensity in time after convective rainfall events was studied in (Andres-Domenech et al, 2016). The index employed there was an objective function combining in a weighted way the squared differences between the empirical and the theoretical values of the following variables: rainfall intensities of each time interval, total cumulative depth, duration, maximum intensity and relative position of the peak intensity. Details can be found in (Andrés-Domenech et al, 2016), including illustrative examples for different rainfall events. After processing all the sample, the typical deviation of the error for the total cumulative rainfall depth was 6.4%, while the one corresponding to maximum peak intensity was 5%.

4. On the underestimation of the impact of extreme rainfall

Given that original storms of the sample have not an a priori assigned return period T, it becomes difficult to contrast accurately the potential overestimation derived from this method. Nonetheless, if we assume as valid the criteria for T assignment described in sections

3.3 and 3.4, it is feasible to assign an empirical value of T to the storms of the sample. In that case, it is possible to make a comparison with the theoretical storms resulting from the application of the procedure described in section 4, obtained for that same T value.

As an example, this task was performed for the most intense storm of the sample. It took place in Valencia, on June the 14th, 2004. This storm is a typical convective-type storm during warm season with high rainfall intensities. It presents a value of X_1=177.18, corresponding to a return period of T=26 years according to extreme value analysis of section 3.4. Its duration is equal to 40 min, thus, belongs to the intermediate duration family ($\alpha=\alpha_2$). The theoretical gamma-design storm for $\alpha=\alpha_2$ and T=26 years can be built following procedure in section 4. On the other hand, and using the traditional method for the construction of the alternating block design storm, a storm is built for T=26 years, using the ID curve for T=26 years.

The following table shows the resulting values of I_{10} and P.

Parameter	**Historical storm**	**Aggregated Gamma Storm**	**IDF Alternating Block Storm**
I_{10} (mm/h)	172.80	170.85	165.81
P (mm)	45.00	45.40	60.94

As shown in the table, the gamma shaped design storm reproduces very well the observed peak and volume, while the IDF Alternating Block storm reproduces also well the peak intensity (-4%), but overestimates the total depth (+35%). These results are obviously not conclusive, but indicate consistency of the method and are in accordance to previously found results in reference to IDF Alternating Block storm behaviour.

5. On the different outcome for the longest rainfall duration in Figure 4

The question raised by Prof. Montanari in regard to the comparison shown in figure 4, opens an interesting discussion.

In fact, as pointed out by the reviewer, the outcome for the longer duration is graphically similar, although the aggregated Gamma model storm gives a larger cumulative rainfall. On the contrary, for shorter durations the IDF alternating block design storm seems to be more pessimistic. From this point of view, the outcome for the longest duration is different, as the reviewer indicates.

It is important to notice that, conceptually speaking, there should be a duration limitation of any gamma-shaped design storm, imposed by the actual life cycle of the convective rainfall cell. In the sample studied (section 3.1), the average duration found is 38 minutes, with durations over 1 hour only in 15% of the rainstorms. In accordance to this fact, it should not be adequate to build representative design storms with the Gamma model exceeding the natural duration of the process, resulting in systematic overestimation of the total depth. The longer duration of the Gamma model storm in figure 4 lies in the limit of 1 hour.

This limitation is not really affecting to the IDF alternating block design storm procedure, as duration can be arbitrary chosen and the method can be applied anyway. In fact, it is perfectly possible to build IDF alternating block design storms with durations well over the actual historical durations of independent storm events for a given geographical point. This is not very realistic.

But going back to figure 4, it is interesting to point out that conclusions are inverted when variable I_{10} is taken as reference. That is, the aggregated Gamma model is more pessimistic for shorter durations, exhibiting higher peaks than the IDF alternating block design storm.

Finally, if variable X_1 is taken as reference for the analysis, both methods produce similar results for all durations. To improve clarity of results, and after the question raised by Prof. Montanari, table 5 has been modified, including a new column (variable X_1), and simplifying it for a clearer comparison. The following is the modified version of table 5 in the revised manuscript.

Table 5. Comparison of volume, peak intensity and magnitude of the Gamma aggregated and IDF alternating block design storms.

		Duration (min)	Maximum intensity (mm/h)	Volume (mm)	Magnitude (X_1)
Storm α_1	Gamma aggregated	20	175.0	34.8	175.45
	IDF alternating block	20	164.4	43.2	168.71
Storm α_2	Gamma aggregated	40	169.2	45.0	173.84
	IDF alternating block	40	164.4	60.3	175.05
Storm α_3	Gamma aggregated	60	156.0	80.9	174.87
	IDF alternating block	60	164.4	69.3	178.38

Regarding to this update in table 5, the following sentences will be added in Page 15, line 15 in the revised manuscript: “With regards to variable X1, results are very similar for both methods, as shown in table 2”.

Minor remarks

a) Please define the symbol i10. I understand it is the maximum rainfall intensity of a given storm, but I do not understand why the subscript 10 is used.

I_{10} is the maximum intensity for an interval aggregation of 10 minutes. Its general definition is given in equation (21).

b) Please make clear when introducing Figure 2 that the different patterns are identified basing on storm duration. When reading at the bottom of page 10 I had the feeling that patterns were identified by looking at the exponent of the regression lines. My doubt was resolved when reading the text at lines 22 and 23 at page 13. I think the authors should make clear at page 10 already that the regressions refer to different storm durations.

The first sentence of this section (page 10 – lines 4-5) will be rewritten as follows:

“Three different sets of events were identified, according to their duration. As shown in figure 2, each of them can be characterized in terms of a representative value of the ratio:”

c) I think the authors should define at page 11 what is meant by “magnitude” of the storm event.

In the revised manuscript, the following sentence will be added just after equation 26:

“According to the relationships between the cumulative rainfall depth and the storm maximum intensity, both variables are used together to define a new combined variable able to represent the storm magnitude in terms of volume and maximum intensity”.

d) In eq. 28 the symbol “i” looks like an exponent. I suggest changing the notation.

We agree. In the revised manuscript we will change the notation to $I_{i,10}$.

e) Please use the symbols IDF and ID coherently. I think both of them indicate the depth-duration-frequency curve.

In the revised manuscript all “IDF” and “ID” symbols will be reviewed and duly replaced.

f) Please clarify how the numbers of blocks at line 26 of page 13 were identified.

In the revised manuscript, the sentence “A continuous… blocks respectively” will be ended adding the following:

“… as once the truncation criterion is selected, the storm duration is established (equation 9), so that, for a given time level of aggregation (ΔT), the number of blocks can be derived”.

New references

Resulting from reviewer #3 comments, suggestions, and critics, the following reference will be added to the revised version of the manuscript:

Di Baldassarre, G., A. Brath, and A. Montanari (2006), Reliability of different depth-duration-frequency equations for estimating short-duration design storms, Water Resour. Res., 42, W12501, doi: 10.1029/2006WR004911.

A two parameter design storm for Mediterranean convective rainfall

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Abstract. The following research explores the feasibility of building effective design storms for extreme hydrological regimes, such as the one which characterizes the rainfall regime of the East and Southeast of the Iberian Peninsula, without employing IDF curves as a starting point. Nowadays and after decades of functioning hydrological automatic networks, there exist abundant high resolution rainfall data with a reasonable statistic representation, which enables the direct research of temporal patterns and inner structures of rainfall events at a given geographic location with the aim of establishing a statistical synthesis directly based on those observed patterns. The authors propose a temporal design storm defined in analytical terms, through a two parameter gamma-type function. The two parameters are directly estimated from 73 independent storms identified from rainfall records of high temporal resolution in Valencia (Spain). All the relevant analytical properties deriving from that function are developed in order to use this storm in real applications. In particular, in order to assign a probability to the design storm (return period), an auxiliary variable combining maximum intensity and total cumulated rainfall is introduced. As a result, for a given return period, a set of three storms with different duration, depth and peak intensity are defined. The consistency of the results is verified by means of comparison with the classic method of alternating blocks based on an IDF curve, for the above mentioned study case.

1 Introduction

Design storms are of paramount importance for hydrologic engineering and remain mainstream practice as they provide a simple and apparently appropriate tool for the design of hydraulic infrastructure. Design storms have been used for more than a century if we consider the block rainfall as input of the rational method (Watt and Marsalek, 2013). They experienced an important development during the 1970s and 1980s with more realistic approaches (Pilgrim and Cordery 1975; Walesh et al. 1979; Hogg 1980, 1982; Pilgrim 1987).

The need for design storms in hydrologic engineering must be analysed according to the spatial scale of the problem which might range from typical urban drainage designs to small and intermediate catchment basins. As reported by Watt and Marsalek (2013), one of the earliest applications of design storms to urban drainage took place in Rochester, New York (Kuichling, 1889). It followed the rational method which is still widely used today. In the urban context, the City of Los Angeles method (Hicks, 1944) and the Chicago Hydrograph Method (Keifer and Chu, 1957) represented an important step towards the development of hydrograph methods. At watershed scale, design storms are needed to obtain design floods when streamflow data are scarce or do not exist (Watt and Marsalek, 2013) for the design of culverts, bridges and small dams, drainage systems, drainage planning and flood management.

Design storms usually fall into two different categories. The first one considers models based on intensity-duration-frequency (IDF) relations. The second one corresponds to synthetic events where the temporal distribution is derived from observed storms.

Within the first category, the most widely used synthetic storms are probably the National Resource Conservation Service (NRCS, former SCS) dimensionless storms and the so-called alternating block method storms. Standard rainfall patterns for 24-h storms are available for four different geographic regions of the United States (Froehlich, 2009). The NRCS design storms are appropriate for catchments smaller than 250 km^2, and they are considered to be applicable to storms of any average return period. Temporal distributions within this method are based on depth–duration–frequency relations available for the US territory, divided into four different climatic regions (McCuen, 1989).

The alternating block method (Chow et al., 1988) is solely based on an IDF curve. These design storms display a maximum intensity block in the centre of the event and a total rainfall depth at any time that coincides with the total depth given by the IDF relation. The method is simple but has also been widely criticised because it does not represent any observed rainfall internal structure. Another noticeable weak point of the method, already pointed out by McPherson (1978), is the arbitrary selection of the storm duration, which causes total rainfall depth to be also arbitrarily selected. The Chicago design storm (Keifer and Chu, 1957) is a special case of an alternating block storm. In Spain, the use of this method is still today concretized through local or regional IDF curves like those proposed by Témez for all the Iberian Peninsula (Témez, 1978). Recent publications demonstrate that, generally, peak flow calculations using these design storms tend to overestimate the results (Alfieri et al., 2008).

The second category of design storms corresponds to temporal patterns derived from observed records. One of the first temporal distributions using this approach was developed by Huff (1967) in Illinois (US). The method determines in which time quartile the maximum intensity occurs. This work eventually became the Illinois State Water Survey Design Storm (Huff and Angel, 1989), extensively used by state and local agencies in the US Midwest. Following the same methodology, Hogg (1980) presented his findings on temporal patterns depending on the storm duration for different regions in Canada. Results led to the AES design storm (Hogg, 1982), widely used in urban drainage design. The former design storm reproduces the maximum intensity, the time of this maximum and the rainfall depth that occurs before the peak on the basis of observed records. Other works into this category are those developed in Australia (Pilgrim, 1987; French and Jones, 2012.) or the UK (Packman and Kidd, 1980). In Spain, García-Bartual and Marco (1990) studied hyetographs of extreme convective precipitation where the intensity resulting from the activity of each rainfall cell was represented by a gamma-type function with maximum intensity and volume as random variables.

Some authors point out that the design storm concept itself is fraught with conceptual error when used to simplify engineer analysis by unrealistic assumptions (Adams and Howard, 1986). Indeed, many of the concerns about classic design storms arise from the storm duration selection, the IDF concept limitations, the temporal distribution and the difficulties to relate the synthetic storm event to a specific return period.

The design storm duration is not a determining factor if the purpose is to determine a peak flow to design conveyance infrastructures. Consequently, it is common practice to fix it around the concentration time of the catchment basin. Nevertheless, when storage elements are to be analysed, the influence of storm duration and temporal pattern becomes critical (Ball, 1994).

As it has been shown in the past (Watt and Marsalek, 2013), uncertainties arising from existing IDF relations have strong consequences. First, record series used to fit IDF expressions are usually short for low frequency occurrences. Second, IDF curves are considered to represent worst maxima regardless of the physical nature of the storm. García-Bartual and Schneider (2001) exposed the inherent uncertainty in the process, which significantly affects the definition of the IDF curves shape in the interval 0-10 minutes. Finally, there is enough ground to deem data acquisition insufficiently accurate to provide robust data for IDF analysis, especially in urban areas (Hoppe, 2008). Moreover, as it is the case in Spain, outdated IDF curves are still used regularly as they are still found in guidance and regulations. The above mentioned uncertainties in IDF curves estimation can affect significantly the reliability of derived design storms, especially in the definition of its peak rainfall intensities, with undesirable consequences when used for hydrologic design purposes.

For the simplest applications (i.e., rational method), a temporal pattern is not required for the design storm. However, for most hydrologic engineering applications, a design hyetograph is necessary. Selecting this temporal trend is one of the most uncertain steps of the design storm definition since the physical nature of the process cannot be disregarded.

A storm event presents many characteristics so it cannot be fully described by the statistics of only one of them. For a return period definition, a common practice is to assign a given frequency to a specific event feature (i.e., its maximum intensity). But, given that a design storm is composed of many variables (depth, duration, temporal pattern, antecedent conditions), assigning a single return period may not be appropriate.

The objective herein is formulating an analytical approach in order to describe rainfall intensities in time, as an alternative for practical design storm definition in Mediterranean areas. Also, developing all required analytical properties to ensure its applicability under usual criteria and requirements of design storm approaches for hydrological design. These include a methodology for return period assignment based on both, total depth and peak intensity of the storm. Also, a practical methodology to build the storm, applied to a given case-study to validate it. For illustrative purposes, a comparison with most extended design storm in Mediterranean areas will be developed and discussed.

2 Design storm

The temporal pattern of rainfall intensities representing the design storm is expressed in terms of a continuous analytical function of the form given in equation (1).

$$i(t) = i_0 f(t) \qquad (1)$$

where $t \geq 0$ (min) is the time elapsed from the start of the rainfall episode (t=0), i(t) (mm/h) represents the rainfall intensity at instant t, i_0 (mm/h) is the instantaneous peak intensity of the storm and f(t) is a convenient non-dimensional, continuous and differentiable analytical function, which will be defined below.

The adopted function f(t) must reproduce the activity life-cycle of a convective cell, i.e., an initial development until reaching maturity stage during which maximum intensities are attained, followed by a stage of dissipation in time, typified by a progressive attenuation of rainfall.

Several recent studies characterize the physical dynamics of convective cells from radar-provided data. More precisely, these data correspond to relevant characteristics such as duration, spatial extension or the importance of the above-mentioned stages, (Capsoni et al., 2009; Rigo and Llasat, 2005). On the basis of high-resolution rainfall data, some authors report statistical evidence of the predominance of temporal patterns where the attenuation or temporal dissipation stage tend to last longer than the initial growing and development stage (Brummer, 1984). This characteristic supports the use of relationships like the gamma function, successfully employed in previous mathematical models of rainfall (García-Bartual and Marco, 1990; Salsón and García-Bartual, 2003) since it represents better the patterns observed in the temporal registers of convective rainfall events in the East and South-East of the Iberian Peninsula. Nonetheless, there exist other mathematical models where an analytic function f(t) is postulated, and where the maximum value is located precisely at half the total duration of the event produced by the convective cell (Northrop and Stone, 2005).

In terms of the proposed design storm, the adopted temporal pattern shows an evolution described in a parametrical way with a function f(t): a non-dimensional gamma type function with a single parameter which describes a fast initial growing stage of intensities until reaching the maximum value, followed by a slower diminishing stage, asymptotic in time and tending towards a null value when time growing to infinite.

$$f(t) = \varphi t e^{1-\varphi t} \tag{2}$$

where φ (min^{-1}) is a parameter.

This model proved to be an acceptable and consistent representation of the rainfall intensities from convective Mediterranean storms (Andrés-Doménech et al., 2016)

2.1 Analytical properties

Some interesting analytical properties of the f(t) function are revised, which will prove useful in subsequent development. As it can be deducted from equation (2),

$$f(0) = 0 \tag{3}$$

$$\lim_{t\to\infty} f(t) = 0 \tag{4}$$

In addition, as

$$f'(t) = \varphi(1-\varphi t)e^{1-\varphi t} \tag{5}$$

function f(t) displays a relative maximum at point $t = t_0 = \varphi^{-1}$. The corresponding value of this maximum is:

$$f(t_0) = 1 \tag{6}$$

Given that the duration t_C of the cell is finite, and in order to establish a finite duration of the process, a simple truncating criteria is adopted for the asymptote of this function. To do so, a final or residual value is established as a fraction η_1 of the maximum so that

$$f(t_C) = \eta_1 \tag{7}$$

where t_C (min) represents the total storm duration, with $t_C > t_0$ and $0 < \eta_1 < 1$. Convenient η_1 values are shown in table (1). Introducing condition given in equation (7) into equation (2), we obtain:

$$f(t_C) = \varphi t_C e^{1-\varphi t_C} = \eta_1 \tag{8}$$

Equation (8) admits the following solution

$$t_C = \frac{\eta_2}{\varphi} \tag{9}$$

and thus, verifying the condition

$$\eta_2 e^{1-\eta_2} = \eta_1 \tag{10}$$

Table 1 shows some of the solution values for this equation, for chosen values of the parameter η_1.

Table 1: Parameters η_1 and η_2 for different truncation criteria.

Truncation criterion as a % of the intensity peak value	η_1	η_2
1%	0.01	7.6386
5%	0.05	5.7439
10%	0.10	4.8897

In other words, once the truncating criteria is defined, for example 5%, the duration of the rainfall event is automatically defined as a function of parameter φ through equation (9) with η_2=5.7439.

2.2 Properties of the aggregated process

The suggested analytical function can be integrated, yielding to the following result:

$$F_{[t_1;t_2]} = \int_{t_1}^{t_2} f(t)dt = \int_{t_1}^{t_2} \varphi t e^{1-\varphi t} dt = \left(t_1 + \frac{1}{\varphi}\right) e^{1-\varphi t_1} - \left(t_2 + \frac{1}{\varphi}\right) e^{1-\varphi t_2} \tag{11}$$

where $0 \le t_1 < t_2 \le t_C$. In this way, the integrated value of $F_{[t_1;t_2]}$ is expressed in minutes. By applying equations (9) and (11) the following particular results are easily obtained:

$$F_{[0;t_C]} = \frac{e}{\varphi} - \left(t_C + \frac{1}{\varphi}\right) e^{1-\varphi t_C} = \frac{e}{\varphi}\left[1 - (1+\eta_2)e^{-\eta_2}\right] \tag{12}$$

$$F_{[0;\infty]} = \frac{e}{\varphi} \tag{13}$$

$$\frac{F_{[0;t_C]}}{F_{[0;\infty]}} = 1 - (1+\eta_2)e^{-\eta_2} \qquad (14)$$

It must be noted that result (14) is independent of parameter φ. For instance, if a truncating value of 5% is adopted (η_1=0.05) it automatically leads to η_2=5.7439 as shown in Table 1, and therefore:

$$\frac{F_{[0;t_C]}}{F_{[0;\infty]}} = 0.98 \qquad (15)$$

That is, the truncating criteria of 5% for f(t) is equivalent to establishing the total duration of the cell when 98% of the cumulative rainfall has already taken place with respect to the hypothetical 100% linked to a cell whose intensities are asymptotic to 0 and have infinite duration, according to the known analytical properties of the tail of f(t).

From equations (1) and (11), the total cumulative rainfall (mm) can be obtained, for a given time interval [t_1; t_2] as follows:

$$P_{[t_1;t_2]} = \int_{t_1}^{t_2} i(t)dt = \frac{i_0}{60}\int_{t_1}^{t_2} f(t)dt = \frac{i_0}{60}\left[\left(t_1+\frac{1}{\varphi}\right)e^{1-\varphi t_1} - \left(t_2+\frac{1}{\varphi}\right)e^{1-\varphi t_2}\right] \qquad (16)$$

The average rainfall intensity (mm/h) during such given time interval can be calculated as follows:

$$i_{[t_1;t_2]} = \frac{i_0}{t_2-t_1}\left[\left(t_1+\frac{1}{\varphi}\right)e^{1-\varphi t_1} - \left(t_2+\frac{1}{\varphi}\right)e^{1-\varphi t_2}\right] \qquad (17)$$

In the same manner, the total cumulative rainfall for the time interval [0; t] results

$$P_{[0;t]} = \frac{i_0}{60}\left[\left(\frac{e}{\varphi}\right) - \left(t+\frac{1}{\varphi}\right)e^{1-\varphi t}\right] \qquad (18)$$

Replacing t=t_C in equation (18) and substituting equation (9), we obtain the total rainfall for the theoretical storm, given by the following expression:

$$P_{[0;t_C]} = \frac{i_0}{60}\left[\left(\frac{e}{\varphi}\right) - \left(\frac{\eta_2}{\varphi}+\frac{1}{\varphi}\right)e^{1-\eta_2}\right] \qquad (19)$$

If we assume a truncating criteria of 5% (η_1=0.05) a straight forward expression is obtained for the total cumulative rainfall associated to the analytical storm:

$$P_{[0;t_C]} = 0.0443\,\frac{i_0}{\varphi} \qquad (20)$$

2.3 Maximum intensity for a given Δt

For practical applications, a given time interval of aggregation Δt is used, conveniently chosen depending on the type of hydrological application, the rainfall-runoff model to be used, and the characteristics of the urban hydrology application to be carried out.

Once selected a given Δt in minutes, it is convenient to locate the most intense rainfall interval along the time-axes, so that

$$I_{\Delta t} = \frac{i_0}{60} max\{F_{[t;t+\Delta t]}\} \qquad (21)$$

where $t < t_0 < t+\Delta t$ and $I_{\Delta t}$ is the maximum rainfall intensity (mm/h), for the most intense interval of the storm, as shown in figure 1.

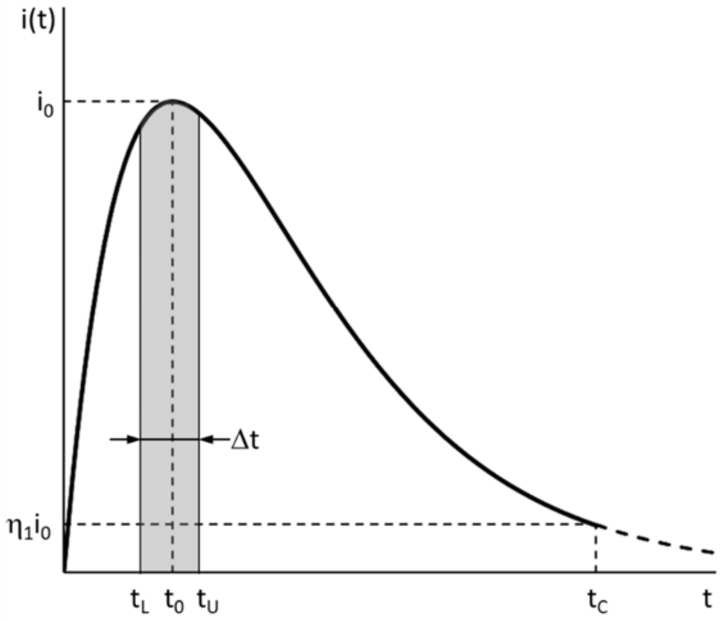

Figure 1. Most intense interval of the storm defined by [t_L; t_U] for a Δt time interval of aggregation.

If the above mention central interval is

$$[t_L;\ t_U] = \left[\frac{1}{\varphi} - \xi\Delta t;\ \frac{1}{\varphi} + (1-\xi)\Delta t\right] \tag{22}$$

as indicated in figure 1, the optimization problem has a solution in terms of the auxiliary variable ξ, being 0<ξ<1. Such solution is given by:

$$\xi = \frac{1}{\varphi\Delta t} - \frac{e^{-\varphi\Delta t}}{1-e^{-\varphi\Delta t}} \tag{23}$$

Consequently, according to equation (17), the maximum intensity of the storm, once it has been discretized in time intervals of Δt minutes, can be calculated as follows:

$$I_{\Delta t} = \frac{i_0}{\Delta t}\left[\left(t_L + \frac{1}{\varphi}\right)e^{1-\varphi t_L} - \left(t_U + \frac{1}{\varphi}\right)e^{1-\varphi t_U}\right] \tag{24}$$

In summary, the main derived properties of the chosen analytical shape of the storm are: total duration of the storm given a truncation criterion (equation (9)), total cumulative rainfall (equation (20)) and maximum intensity for a given time level of aggregation Δt (equation (24)). All these relations are uniquely expressed as functions of the two parameters of the storm, i_0 and φ.

3 Rainfall data processing

Valencia is a Mediterranean city, located on the eastern coast of the Iberian Peninsula. It presents a typical temperate Mediterranean climate (Csa, according to Köppen climate classification). This type of climate is characterized by mild temperatures (annual average of 17°C), without marked extremes and a rainfall about 450 mm/year. Rainfall is very unevenly distributed along the year, with very marked minima during the months of June, July and August and maxima happening along the months of September and October, these two months concentrating almost a third of the annual rainfall. Another important characteristic of the rainfall regime is its irregularity, alternating dry and more humid intervals. These dry or humid periods tend to last several years due to the Mediterranean climatic inertia. The torrential character of storms is also a main feature of the rainfall regime of the region, with frequent convective rainfall mesoscale episodes, most widely known as cut-offs, characterized by very localized high intensity storms.

The rainfall series used in this study were recorded by the Júcar River Basin Authority during the period 1990–2012. The rainfall gauge is installed in the city center and data time step is 5 minutes. Previous studies demonstrated the validity of this data set for similar purposes (Andrés-Doménech et al., 2010). The continuous rainfall series are processed to identify and extract convective storms. First, statistically independent rainfall events are identified. Then, amongst them, only convective events are extracted. Finally, convective storms are identified from convective events and finally selected to estimate model parameters.

3.1 Convective storms set

3.1.1. Identification of statistically independent rainfall episodes

Before undertaking the storm analysis, a preliminary step is required in order to separate the original continuous series of rainfall records in statistically independent rainfall events. There is no universal method for identifying the minimum interevent time of a rainfall regime and thus, independent storms. Dunkerley (2008) presents an interesting review of the range of approaches used in the recognition of main events. Early works by Restrepo-Posada and Eagleson (1982) are still in force and according to them the identification of independent events is based on considering events like statistically independent, so that the minimum interevent time must be an outcome of a Poisson process. Bonta and Rao (1988) bore out this theory, studying in depth some other aspects. Andrés-Doménech et al., 2010 completed the original methodology based on the coefficient of variation analysis and established for Valencia a minimum interevent time equal to 22 hours. The latter implies that if two rainfall pulses are separated more than 22 hours, then, they belong to different events. Under this premise, 987 statistically independent events are identified for the period 1990-2012.

3.1.2. Identification of convective episodes

The required rainfall episodes must have a certain convective character. Therefore, only storms that verify the following conditions can be taken into account: maximum intensity over 35 mm/h and convectivity index $\beta^* > 0.3$. The convectivity index introduced by Llasat (2001) reflects in an objective way the greater or lesser convectivity degree of a rainfall episode, on the sole basis of the registered 5-min data, with no additional meteorological information being required. β* depends on a convectivity threshold which depends itself on the record time-step. This convectivity threshold was estimated for the Spanish Mediterranean coastline by Llasat (2001). For a 5-min resolution data series, the threshold was set to 35 mm/h. Consequently, this index represents the proportion of total rainfall fallen with an intensity higher than 35 mm/h. Events with β* >0.3 represent convective storms at this location. Thus, according to this additional criterion, only 64 convective events from the complete set are selected.

3.1.3. Selection of convective storms

Some of the independent convective events selected above can correspond to long or very long episodes with important dry intra-periods (always less than 22 hours). Concatenation of some convective cells can lead to this situation, resulting in long episodes of some days.

Often, these rainfall cells (storms) can be linked by very slight background intensity (around 2 mm/h). Usually, these convective cells only correspond to a small duration within the whole episode. Nevertheless, they can represent more than 80% of the total rainfall amount. According to this fact, the convective events set is classified as follows:

a) Type I events. These storms consist of a single convective cell. They are characterized by a moderate duration and a considerable average intensity. They can present low intensity intervals before and/or after the larger part of rainfall.

b) Type II events. Long lasting rainfall events consisting of two or more storms separated in time.

Following this classification, 58 events are type I and 6 events are type II. These 6 type II events are carefully examined and analysed to extract storms within them. The following criteria to select individual storms are adopted:

a) Identify the event peak intensity, always over 35 mm/h and its near range.

b) The first storm time interval corresponds to the prior interval to 9.6 mm/h intensity (3 times the rain gauge sensitivity).

c) The last storm time interval is defined by a shift in the sign of the hyetograph derivative, always around intensities lower than 9.6 mm/h.

Finally, and according to this methodology, 73 storms are defined for the period 1990-2012. Table 2 shows a basic report of the empirical statistics of this sample. Andrés-Doménech et al., 2016 also pointed out a strong correlation between the storm volume and duration (0.839) and also an evident correlation between storm volume and its maximum intensity (0.369).

Table 2. Storm univariate statistics (adapted from Andrés-Doménech et al., 2016).

	Rainfall volume P (mm)	**Maximum intensity I_{10} (mm/h)**	**Storm duration T_C (min)**
Mean	20.0	76.4	38.0
Maximum	69.2	206.4	115.0
Minimum	4.2	36.0	10.0
Median	15.0	64.8	30.0
Standard deviation	15.9	37.3	21.9
Bias	1.39	1.46	1.21
Kurtosis	1.36	2.09	1.18

3.2 Relations between cumulative rainfall and maximum intensity of the storm

Three different sets of events were identified, according to their duration. As shown in figure 2, each of them can be characterized in terms of a representative value of the ratio:

$$\alpha_i = \frac{P}{I_{10}} \qquad (25)$$

Figure 2 shows the three different ratios empirically found: $\alpha_1 = 0.1993$ h, $\alpha_2 = 0.2919$ h and $\alpha_3 = 0.5299$ h.

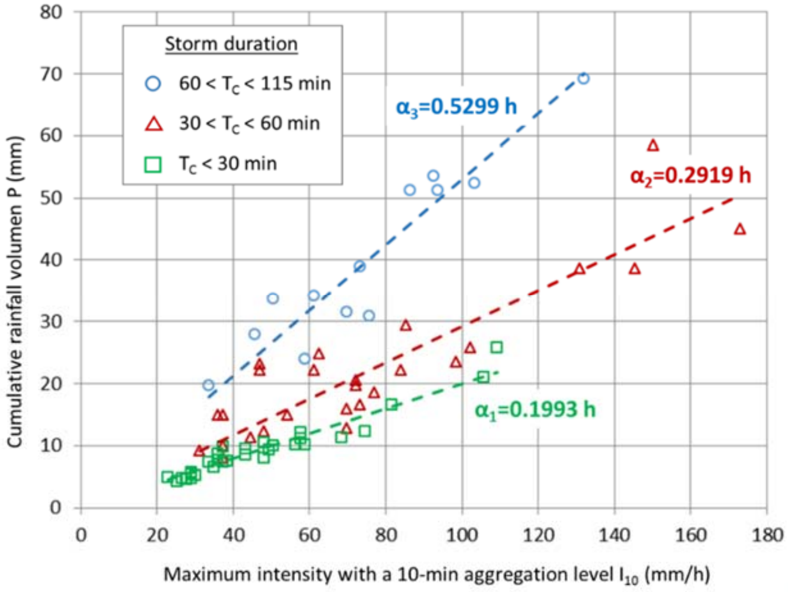

Figure 2. Relations between cumulative rainfall and maximum intensity of the storm depending on the storm duration.

Such distinction allows to identify three different families, depending on α_i. Each of them is characterized by its corresponding storm pattern. In accordance to this, a given return period T should yield to three storms, one per family all of them with equivalent magnitude, but with different time patterns. Low α values typically correspond with storms with its peak intensity located short after the initiation of the storm, while higher α values are found for longer events and usually higher cumulative rainfall depths.

3.3 Storm magnitude

The question of determining the magnitude of a given storm is undertaken through a principal component analysis (PCA), over the observed sample (I_{10}; P). This strategy is based on the fact that both maximum intensity and cumulative rainfall are directly related to the magnitude of the event, and thus, relevant to it, while the preliminary statistical analysis showed a significant correlation among them as stated before (Andrés-Doménech et al., 2016).

Table 3 shows the results of the principal components analysis, resulting in the two new variables X_1 and X_2.

Table 3. Principal components eigenvectors resulting from the PCA analysis.

Original variable	Principal component X_1	Principal component X_2
P	0.3704	0.9289
I_{10}	0.9289	-0.3704

It can be noted that the first main component, X_1, explains 92.1% of the variance observed in the sample. This main component is defined as

$$X_1 = \beta_P P + \beta_I I_{10} = 0.3704P + 0.9289I_{10} \tag{26}$$

According to the relationships between the cumulative rainfall depth and the storm maximum intensity, both variables are used together to define a new combined variable able to represent the storm magnitude in terms of volume and maximum intensity. X_1 can be considered a measurement of the magnitude of the rainfall event, as both initial variables, P and I_{10}, contribute to it. This new variable after the PCA analysis, in statistical terms, contains more information by itself than either P or I_{10}, and thus, represents an adequate variable in order to establish a return period T linked to a given design storm.

3.4 Return period

The process of assigning a return period T to a given design storm should be based on a previous statistical analysis of the selected variable, X_1. To do so, an appropriate extreme value distribution function is sought. For the given set of rainfall episodes, several distribution functions were tested, including Gumbel, TCEV, SQRT-ETmax and GEV. In all cases, maximum likelihood was used to estimate the corresponding parameters. Figure 3 shows the results of this extreme value function analysis. Best fit was obtained with SQRT-ETmax distribution, with the advantage of being more parsimonious than TCEV and GEV functions. This result is in accordance with what usually occurs in the Eastern coastline of Spain.

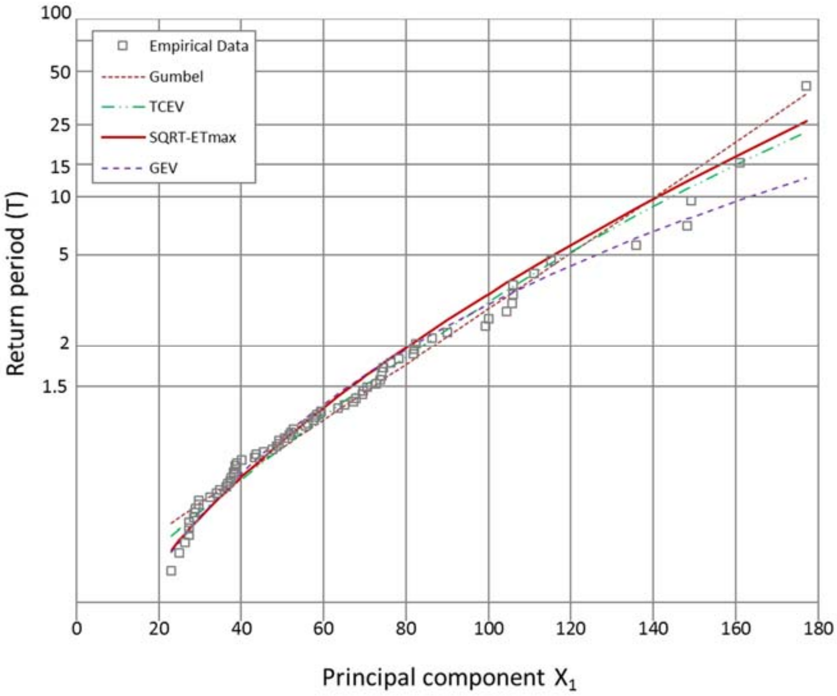

Figure 3. Extreme value distribution analysis for principal component X₁.

4 Construction of the design storm

If $X_1(T)$ is the quantile of the extreme value distribution corresponding to a given return period T, the two variables P and I_{10} which define the design storm for that given return period, are obtained by solving equations (25) and (26) for each family i=1, 2 and 3. That is,

$$\begin{cases} I_{10,i}(T) = \dfrac{X_1(T)}{\beta_I + \beta_P \alpha_i} \\ P_i(T) = \dfrac{\alpha_i X_1(T)}{\beta_I + \beta_P \alpha_i} \end{cases} \quad (28)$$

In order to define, in practice, the design storm associated to $I_{10,i}$ and P_i values, and once chosen a convenient time level of aggregation (i.e. Δt=10 min), it is necessary to previously obtain the two parameters i_0 and φ which define analytically the design storm. To do so, equations (20) and (24) are used, and it results, for each i=1, 2 and 3:

$$P_i(T) = 0.0443 \frac{i_{0,i}}{\varphi_i} \quad (29)$$

$$I_{10,i}(T) = \frac{i_0}{\Delta t}\left[\left(t_L + \frac{1}{\varphi_i}\right)e^{1-\varphi_i t_L} - \left(t_U + \frac{1}{\varphi_i}\right)e^{1-\varphi_i t_U}\right] \tag{30}$$

where t_L and t_U are calculated according to equations (22) and (23).

5 Comparison with the alternating block design storm

After formulating the practical steps to build a synthetic storm, a comparison of the former with the most widely used storm (built with alternating blocks obtained from an IDF curve), is performed. In order to carry out this comparison, storms corresponding to a return period of 25 years are built. The choice of 25 years corresponds to the requirements set by the Municipality of Valencia regulations for the design of urban drainage hydraulic infrastructures.

Before obtaining the alternating block design storm, an ID curve for 25 years must be determined, from the very same sample of storms previously used for the development of the Gamma storm and described in section 3. To do this, the usual procedure for obtaining IDF curves is followed, adjusting the empirical sample to the following IDF relation:

$$i(t) = \frac{a}{(b+t)^c} \tag{31}$$

where i (mm/h) is the maximum intensity corresponding to a rainfall duration t (min), while a, b and c are the parameters of the IDF curve. Vaskova (2001) demonstrated the fitness of this expression to adjust local IDF curves in Valencia. With the data employed in the present paper, the following coefficients result for the 25-year return period ID curve: a=8198 mm/h, b=29.8 min and c=1.06. Then, for each case, the alternating block design storm is built from the ID curve defined by equation (31), following the usual methodology (Chow et al., 1988). To allow for a proper comparison with the Gamma storm, the same number of blocks is kept for every case.

To perform the comparison, first, the three synthetic storms corresponding to each of the families defined by α_1 (short storms), α_2 (medium duration storm) and α_3 (long storms) are built. In order to do this, once the truncating level has been set η_1 (0.05 in the present paper), the method summarized in section 4 is followed. For a return period of 25 years it results a storm magnitude X_1=175.5 (Figure 3). A continuous storm for each of the 3 families is obtained and, after being discretized in blocks of Δt=10 min, generates, for each family, a storm of 2, 4 and 6 blocks respectively, as once the truncation criterion is selected, the storm duration is established (equation 9), so that, for a given time level of aggregation (ΔT), the number of blocks can be derived. Table 4 summarizes the essential parameters of each of the 3 storms.

Table 4. Parameters for the three synthetic storms.

Storm parameters	Storm 1 (short)	Storm 2 (intermediate)	Storm 3 (long)
X_1	175.5	175.5	175.5
α (h)	0.1993	0.2919	0.5299
P^i (mm)	34.9	49.4	82.7
I_{10}^i (mm/h)	175.0	169.2	156.0
φ (min^{-1})	0.3047	0.1699	0.0862
i_0 (mm/h)	239.8	189.3	160.8
t_c (min)	18.85	33.81	66.61
ξ	0.2783	0.3648	0.4290
Number of blocks	2	4	6

Figure 4 represents for each family, both the continuous and the aggregated Gamma storms along with the alternating block one obtained from the ID curve.

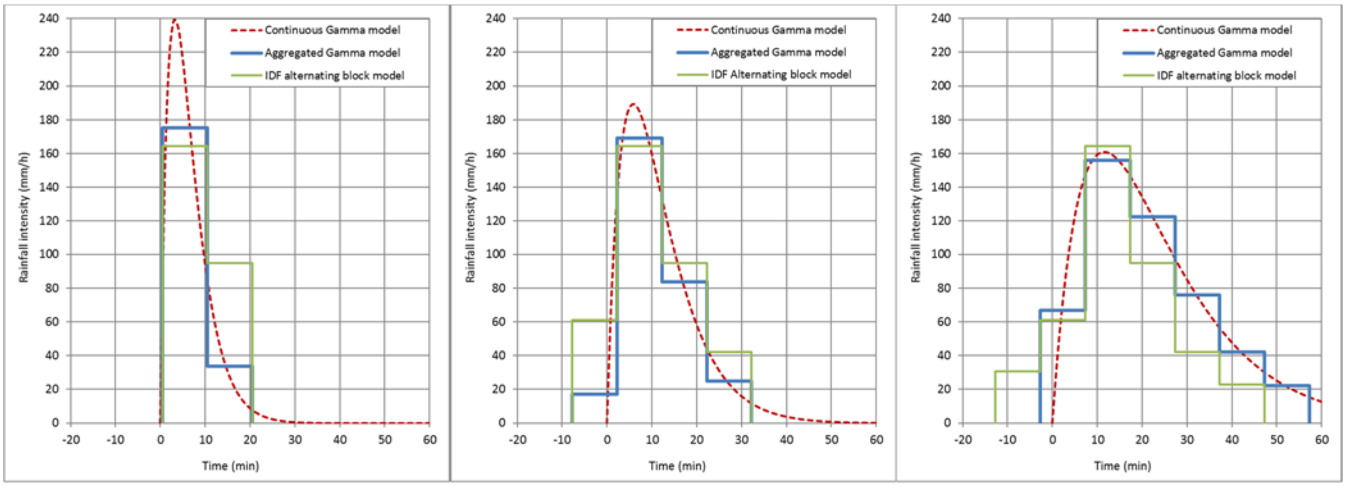

Figure 4. Comparison of the continuous and aggregated Gamma model with the IDF alternating block model for the three families $\alpha_1 = 0.1993$ (left), $\alpha_2 = 0.2919$ (center) and $\alpha_3 = 0.5299$ (right) and for T=25 years.

Both methods lead to consistent and relatively similar results, those being particularly alike for the longer storms. However, for short and medium duration storms, it becomes clear that the classic method offers significantly more pessimistic results. In other words, the common method displays higher intensities. This result is coherent with the very own process of defining the storm. Indeed, given the alternating block method assumes the simultaneous occurrence of maximum intensities for different durations, even when those values had not been encountered historically in the same rainfall event, overestimated intensities seem to be an unsurprising outcome. On the contrary, the Gamma storm is built directly from the temporal pattern observed in real episodes. That is, as demonstrated by Andrés-Doménech et al. (2016), the Gamma storm is coherent with the temporal structure of the rain process and that is why the proposed synthetic storm reproduces the observed rainfall more accurately. Table 5 gathers the quantitative differences found for each of the three storms.

Table 5. Comparison of volume, peak intensity and magnitude of the Gamma aggregated and IDF alternating block design storms.

		Duration (min)	**Maximum intensity (mm/h)**	**Volume (mm)**	**Magnitude X_1**
Storm α_1	Gamma aggregated	20	175.0	34.8	175.45
	IDF alternating block	20	164.4	43.2	168.71
Storm α_2	Gamma aggregated	40	169.2	45.0	173.84
	IDF alternating block	40	164.4	60.3	175.05
Storm α_3	Gamma aggregated	60	156.0	80.9	174.87
	IDF alternating block	60	164.4	69.3	178.38

As expected, the higher the duration of the storm, the lesser the difference between the maximum instant intensity of the continuous storm and the one of the maximum block. Furthermore, differences between the maximum block intensities between the aggregated Gamma storm and the alternating blocks one are also reduced as the duration of the storm increases. Nonetheless, the most remarkable differences lie on rainfall volumes. Given a return period, the alternating block method combines in a single theoretical storm the most adverse statistics for several durations, which originally derive from different historical rainfall events. Conceptually, this is a worst-case storm ignoring actual rainfall patterns found in the rainfall registers, yielding to a volume overestimation (Di Baldassare et al., 2006). For the aggregated Gamma storm, differences with regard to the continuous model are more limited, in all cases, which supports the conclusion of having generated a synthetic storm that not only reproduces peak intensities properly but also respects the observed temporal patterns and, consequently, reproduces better storm volumes. Concerning variable X_1, results are very similar for both methods, as shown in table (5).

6 Conclusions

The use of design storms has been a worldwide common practice for many years, employed to solve a range of hydrologic engineering problems in a direct way. These synthetic storms represent an appropriate statistical synthesis of historical rainfall records and therefore, are of maximal utility in their application to problems of urban drainage infrastructure design. In many European and American countries, they are directly obtained from intensity-duration-frequency curves (IDF), which are usually pre-established for a given area. This simplifies notably the setting of the design storm, making this a straightforward and fast process. Moreover, it presents the huge advantage of being applicable to places where there exists little or no rainfall information, inasmuch as it is possible to assume as a starting point certain IDF curves, deemed to be sufficiently reliable or representative of the maximum rainfall of that location.

One of the downsides of this process is the fact that it ignores in its approach aspects relative to the actual duration and structure -or inner pattern- of intensities of rain, visible in high resolution rainfall registers. In some countries, automatic pluviometer networks have been working for decades and thus, detailed information is now available, allowing engineers to undertake such matters with statistical representativity (De Luca, 2014).

On the other hand, the diversity of hydraulic elements of nowadays drainage systems (e.g., storm tanks, SuDS) causes that the most conditioning storm parameters for the design are not only rain intensities but also duration, total cumulated rainfall and temporal structure of the storm. This makes particularly interesting the exploration of new strategies for building design storms, starting directly from the observed patterns in the high resolution registers, instead of using IDF curves. This research explores the possibilities in this sense, for the case of convective type Mediterranean storms and proposes a case study from the automatic pluviometer register of the city of Valencia.

The design storm is defined in an analytical way through a two parameter function (i_0 and φ), already substantiated by previous studies for the Mediterranean area. The former parameters are estimated directly from independent rainfall events, identified in the original temporal series. The assignment of a return period is done through an auxiliary variable which describes the magnitude of the event, and incorporates simultaneously both the total cumulated rainfall and the maximum intensity. In practice, this criterion leads to three different design storms for each return period, of a similar magnitude but with different temporal patterns and durations. Those storms, exclusively defined in terms of the two pointed parameters, are easily discretized in time intervals Δt, in view of their application to practical cases.

For illustrative purposes, the construction of these storms for Valencia is developed and then compared with the classical alternating block storm, obtained by the usual methods from the same records. This enables the verification of the consistency of the proposed method, resulting in three storms for every return period, with temporal patterns derived from the observation and direct analysis of high resolution rainfall series. Besides they are exclusively defined through the value of their only two parameters in each case. While it is true that the process is clearly more laborious than the alternating block method, the feasibility of the process in a real case is verified, starting from the principle of direct determination of the storm without using IDF curves. Naturally, it has the important limitation of being only applicable in geographic locations where there is high resolution rainfall information, of sufficient quality and appropriate length of historical record series. In the future, for a higher statistical representativity it will become necessary to count with a longer register.

The proposed method herein, as well as other simple design storm approaches, present some inherent limitations for certain hydrological engineering applications, as they are not suitable for case studies where a more detailed or comprehensive description of the rainfall process is required. Some examples are continuous time hydrological systems evaluation, hydrological applications in large catchments or applications where ensembles or stochastic generation of events are needed to account for a number of possible scenarios (Frances et al., 2012).

Despite that, the proposed analytical definition defines a feasible work framework to provide the design storm with the space-temporal dimension of the event, through the addition of a component that considers the decline of intensities from the centre of the cell. By following the practical strategy contained in the present paper, the characterization and estimation of parameters of such a component must be founded on the direct observation of radar data for the most significant storms, with the goal of parametrizing the most characteristic spatial patterns (Barnolas et al., 2010).

Acknowledgements

This work was supported by the Regional Government of Valencia (Generalitat Valenciana, Conselleria d'Educació, Investigació, Cultura i Esport) through the project "Formulación de un hietograma sintético con reproducción de las relaciones de dependencia entre variables de evento y de la estructura interna espacio-temporal" (Reference GV/2015/064).

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