

Climate and hydrological variability: the catchment filtering role

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Final Response

On behalf of co-authors, I am grateful to the Editor Prof. Sabine Attinger 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 the analysis performed and improved the manuscript accordingly. All the items highlighted by the referees have been taken into account in order to revise the original manuscript, with one exception, concerning the graph at the end of the paper, which could optionally be presented in a higher dimensional space, as suggested by Ref. #3. In the end, we did not modify it, as we believe that the lower dimensional space graph is clearer and more illustrative to the reader.

Basically, the most important changes and/or corrections done in the paper refer to:

- a) A more concise statement of the assumptions, scope and limitations of the modelling approach, have been included, as well as new discussions of these points in the INTRODUCTION and ANALYTICAL MODEL sections.
- b) The estimation of annual maximum peak flood quantiles with the AMS method has replaced the POT approach. The affected figures were consequently modified.
- c) Nine new references have been included in the new version of the manuscript.
- d) Conclusions are presented in more detail, stating more clearly the applicability, limitations and potentials of the modelling approach presented.

Besides, all the editorial remarks and other minor corrections have been addressed in the revised manuscript, submitted for its possible publication in HESS.

Below we provide a detailed summary of the changes made in the paper. The numbered items refer to each topic answered during the open discussion to each referee.

The original and detailed replies to the referees' review comments are reported right after.

REFeree#1

1. On the variability of the land uses/watershed properties.

A discussion of this point has been included in the INTRODUCTION. Also it is now mentioned as future research line in the CONCLUSIONS section of the revised manuscript.

2. The analysis related to the number of events per year.

Sections 2.3 and 3 of the paper have been modified in accordance with this point. The AMS approach substitutes the POT approach. Consequently, figures 1, 2 and 3 have been modified.

3. On the variability induced by initial abstraction and concentration time.

A discussion of this point has been included in section 4.1, accompanied by two additional references in the revised manuscript.

REFeree#2

1. About a more complicated scenario where climate change also brings about changes to the landscape filtering attributes.

A discussion of this point has been included in the INTRODUCTION, with additional references being given.

2. On the assumption that each rainfall event, thus runoff event, can be treated as an independent event, with no “memory” of previous events.

This assumption has been discussed. New text has been added in the revised manuscript at the beginning of section 2- ANALYTICAL MODEL.

3. On how heterogeneity in catchment properties (soil properties, vegetation, storage, etc.) can influence the results.

This point is now explicitly mentioned in the new version of the INTRODUCTION section, helping to clarifying the scope of the research. Additional references have been included to sustain the analytical approach with a lumped rainfall-runoff model.

4. About considering the entire range of stream discharge and its non-stationarity effects.

New text has been added referring to this point, both in the INTRODUCTION and ANALYTICAL MODEL sections, and new references have been added.

5. On the limitations of the approach.

Limitations of our approach have been highlighted and clarified both in the INTRODUCTION and CONCLUSIONS.

REFEREE#3

1. About the transferability of the results.

A discussion of this point has been included in the INTRODUCTION, and later mentioned in the CONCLUSIONS of the revised manuscript.

2. About seasonality in the rainfall model.

A new discussion of this point has been included in section 2.1.

3. On the accuracy of the model for other places.

The question is treated together with the previous point of “transferability” of the results, both in the INTRODUCTION, and CONCLUSIONS of the revised manuscript.

4. About the sensitivity analysis,

This point has been addressed in the CONCLUSIONS.

5. On the interactions between parameters/inputs

This point has been also addressed in the CONCLUSIONS, as a future line of research.

6. Showing in a higher dimensional space how input and storage parameters interact.

As mentioned before, we decided to keep the original version of the figure in the revised manuscript. The higher dimensional space graph suggested by the Referee was generated, but is only shown in the specific response to the Referee regarding this point.

Response to Referee Comment RC-C4407-2014 – Anonymous Referee #1

The authors firstly want to thank gratefully Anonymous Referee #1 for the time spent in our research work, his constructive and useful comments, and for the interesting suggestions that will be helpful for an improved version of the paper.

Here are our responses for the specific referred issues. Please note that point 3 suggests also additional references in the paper for a better response, as indicated.

1. On the variability of the land uses/watershed properties

It is clear that some relevant aspects in the hydrological analysis have not been included in our analysis, and should guide further research on the topic.

As correctly indicated by anonymous Referee #1, certain dominant drivers of the hydrological response like variability of watershed properties or land use changes have not been considered in the research, although the proposed modeling framework has the potential to incorporate it to certain extend, and thus, allow to assess the relative effect of such variability as compared to climatic variability. The latter question is out of the initial scope of the paper, as the modeling efforts were basically centered on the role of climatic variability and its effects, on catchments were the rainfall statistical properties and its future trends represent the major factor controlling flood frequency distribution.

Following the interesting comment by Referee #1, the scope of the paper (INTRODUCTION) will be explained in more detail in the reviewed version of the paper. Also, an emphasis will be placed in the final conclusions of the paper, with an explicit mention of the interest of extending the investigation to the effect of watershed properties and role of land use change using a similar modeling framework.

2. The analysis related to the number of events per year

This useful comment of Referee#1 has led us to reconsider the method used for return period estimation in the paper. According to the main purpose of the paper, i.e., the analysis of maximum peak flows, we have reconsidered that it is much more accurate and robust to use the Annual Maximum Series (AMS) method rather than the Peak Over Threshold (POT).

Given the distribution function of all peak flows derived from the rainfall series,

$$F_Q(q_p) = \begin{cases} 1 - (1 - \kappa I_a / \alpha)^{1/\kappa} & q_p = 0 \\ 1 - \left\{ 1 - \frac{\kappa}{\alpha} \left[I_a + \frac{t_c q_p}{2\lambda_p} \left(1 + \sqrt{1 + \frac{4\lambda_p S}{t_c q_p}} \right) \right] \right\}^{1/\kappa} & q_p > 0 \end{cases} \quad (1)$$

the distribution function of maximum annual floods can be expressed as (see for instance, Viglione and Blöschl, 2009)

$$F_{Qmax}(q_{Pmax}) = e^{-\beta(1-F_Q(q_P))} \quad (2)$$

Where β is the annual number of rainfall events.

The former equation can be expressed in terms of return period (years) as:

$$T_{Qmax} = \frac{1}{1-F_{Qmax}} \quad (3)$$

Combining equations (1) and (2) and replacing them in (3), we can express the T-years maximum peak flow as:

$$q_{Pmax,T} = F_Q^{-1} \left[\frac{1}{\beta} \ln \left(1 - \frac{1}{T} \right) + 1 \right]$$

Provided this new expression for the T-years maximum peak flow estimation, numerical results have been recalculated and Figures 1, 2 and 3 updated accordingly (see at the end of this document the new figures).

As expected, the variations are very slight and only affect quantiles associated to low return periods. Indeed, both estimation methods (POT and AMS) converge for large return periods.

Nevertheless, we consider that in order to increase the robustness and appropriateness of the paper, quantiles should be estimated according to the AMS method.

As it can be deduced from the new figures, the sense and strength of the conclusions is absolutely the same. In the revised version of the manuscript, the end of section 2.3 will be modified to replace the estimation method for T.

In section 3, the sentence “According to Eq. (8), a 20% increase in β implies a 16.7% decrease in the flood return period” has also to be replaced. Now, considering the AMS estimation method for T, if we consider a 20% increase in β this implies a decrease of the flood return period ranging from 0% (for low T values) to 16.7% (for high T values). In the

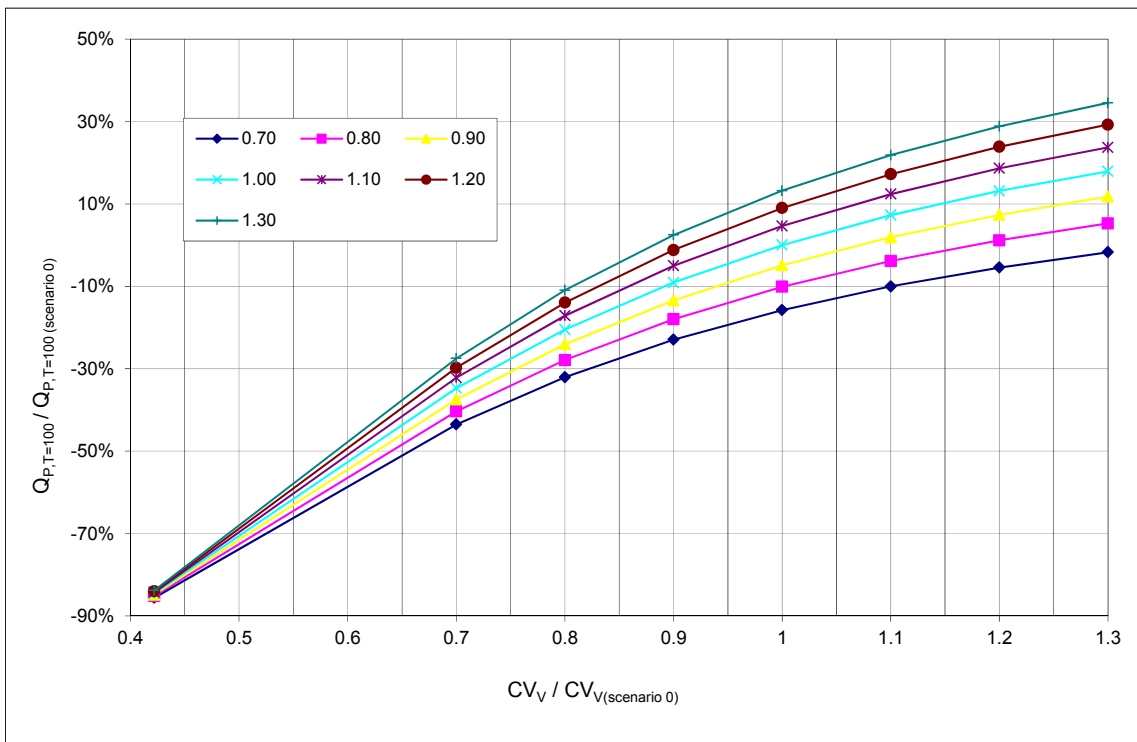
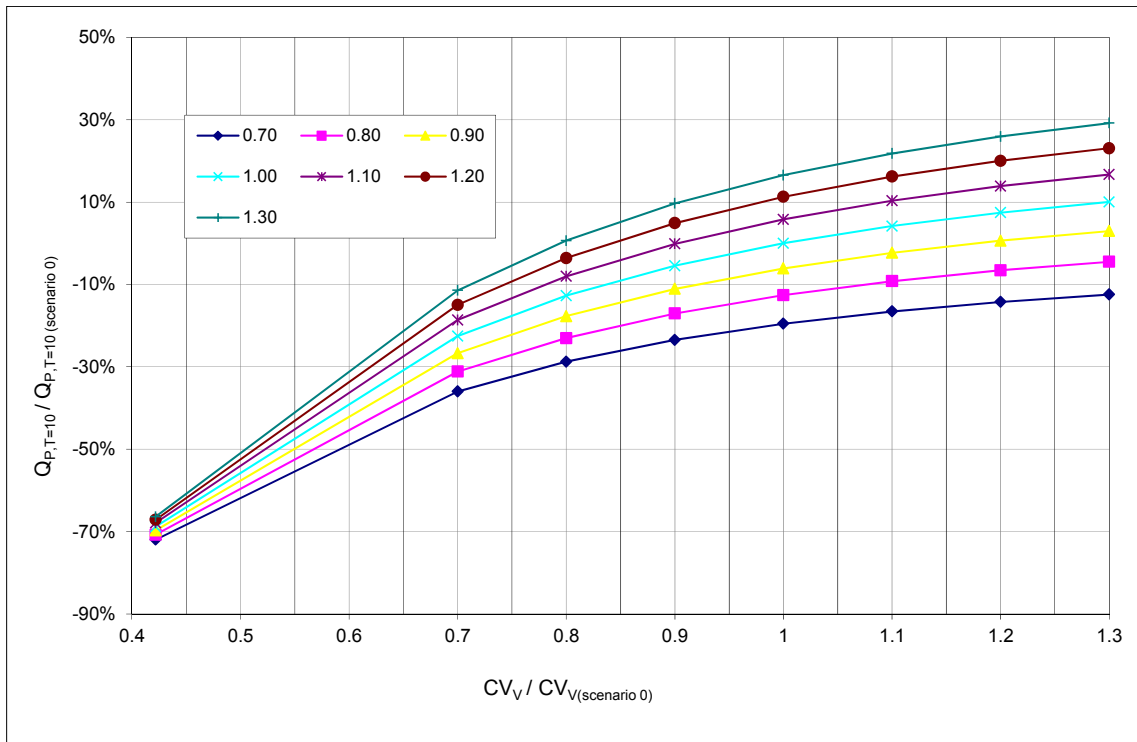
revised version of the manuscript, this issue will be better addressed as suggested by Referee#1.

3. On the variability induced by initial abstraction and concentration time

Initial abstraction value is directly obtained using a factor $k=0.2$, which is taken from practical recommendations (Ferrer, 1993). Concentration time value has been taken after a wide hydrological experience in many small catchments of rapid response in the Mediterranean East and South East coast of Spain (Olivares, 2004; Camarasa, 1990). It can be considered a realistic, representative value for a typical ephemeral river of the region. The main idea is to define a set of parameters for the hydrological conditions considered, which can essentially be representative and typical of fast responding catchments in semi-arid Mediterranean regions. As stated before, the effect of the variability of such parameters is beyond the scope of the paper, although will be underlined in the reviewed version of the paper as a main research line to be continued under the proposed modelling framework, according to suggestion of Referee #1.

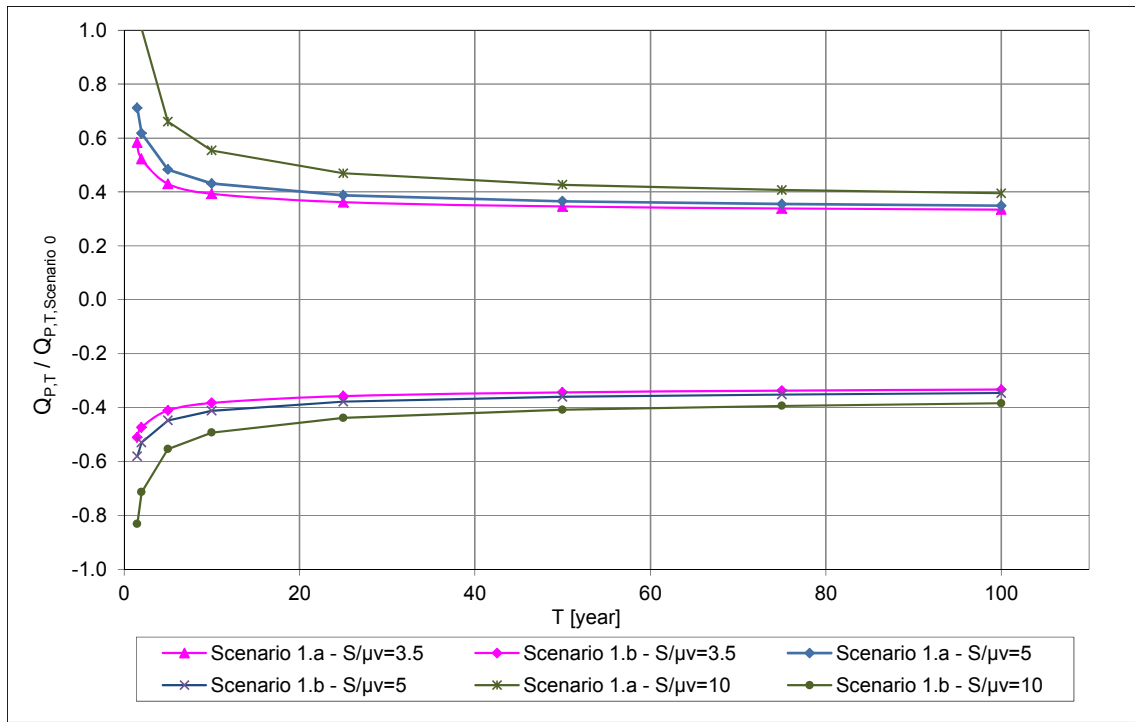
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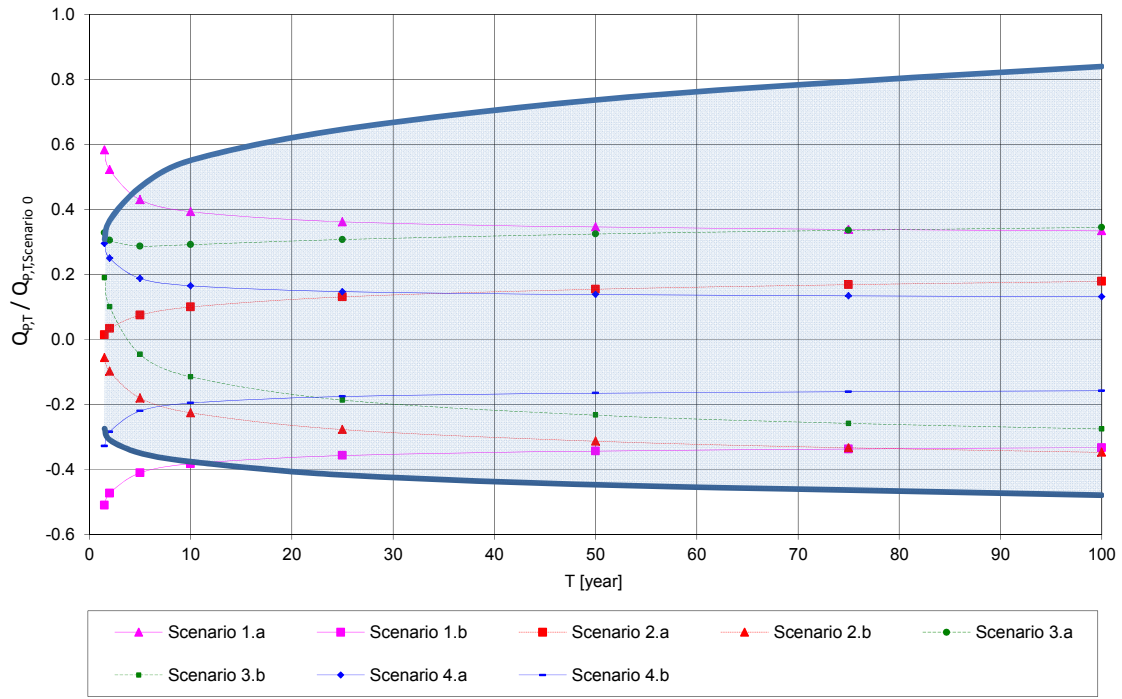
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2 Figure 1. Flood quantile variations for changes in β and CV_V . Catchment parameters are set to
 3 $S/\mu_V=3.5$ and $t_C=1$ h. Cases $T=10$ years (top) and $T=100$ years (bottom).



1

2 Figure 2. Flood quantile variations for scenarios 1.a (+30% μ_V) and 1.b (-30% μ_V) and for
 3 $S/\mu_V=3.5, 5$ and 10 .



1

2 Figure 3. Flood quantile variations for scenarios defined in Table 1 and $\xi=0.05$ confidence
 3 interval for scenario 0 peak flow distribution (shaded area). Catchment parameters are set to
 4 $S/\mu_V=3.5$ and $t_C=1$ h.

Response to Referee Comment RC-C4448-2014 – Anonymous Referee #2

The authors firstly want to thank gratefully Anonymous Referee #2 for the time spent in our research work, his constructive and useful comments, and for the interesting suggestions that will be helpful for an improved version of the paper. In particular, paper by Botter et al. (2013) was revealing, containing material and results of maximum interest. It will obviously be referenced in the reviewed version of the paper.

Here are our responses for the specific referred issues by Referee #2.

1. About a more complicated scenario where climate change also brings about changes to the landscape filtering attributes

Yes, we absolutely agree with Referee #2 about this issue. There exist clear interactions at the catchment scale between landscape characteristics (soils, vegetation, geology ...) and climatic properties. As Referee #2 states, no possible climate-vegetation-soil feedbacks are either considered or investigated in our research. The initial scope of the proposed modeling scheme and further simulations performed was in fact significantly more limited, as they basically centered in the variability of rainfall patterns, and to which extend such variations can be actually buffered by a given standard hydrological catchment, with typical response parameters of a semi-arid Mediterranean region. We observe that this same question was also outlined by anonymous Referee #1. Accordingly, the reviewed version of the paper will include a more detailed description of the scope of the paper (INTRODUCTION). Being clear the particular interest of this point, our suggestion would be to emphasize the topic in the discussion/final conclusions of the paper, with an explicit mention of the interest of extending the investigation in future, in order to incorporate the effect of watershed properties variations and role of land use changes, using a similar modeling framework.

2. On the assumption that each rainfall event, thus runoff event, can be treated as an independent event, with no “memory” of previous events

The analysis presented in the paper is an “event based” approach, where, indeed, each rainfall event, thus runoff event, is treated as an independent event, with no “memory” of previous events. For the type of catchments fulfilling the scope of the paper, there are some arguments supporting this assumption. In the Valencia Region, as in other many semi-arid locations

around the Mediterranean, ephemeral rivers are quite related to small and fast-responding catchments. These stream flow regimes could also be named as “erratic regimes” according to the classification provided by Botter et al. (2013). Such regimes occur when rainfall interarrival times are quite larger than the typical duration of the resulting flow pulses, as it is the case in the presented case study. As stated in Andrés-Doménech et al. (2010), antecedent dry periods for the rainfall pattern analyzed are exponentially distributed with a 22 hours low bound and an 8 days expected mean value. With such a sporadic rainfall regime, antecedent moisture conditions are mainly related to the own event, so that the assumption of independence from the previous one is quite plausible. Moreover, for this type of hydrological events, direct runoff is the dominant component of the hydrograph, and in any case, this is especially true during the peak flow stage. All these assumptions will be included in the reviewed version of the manuscript to clearly state the hypotheses which support the subsequent development and its applicability.

3. On how heterogeneity in catchment properties (soil properties, vegetation, storage, etc.) can influence the results

Again, we agree with Referee #2 about this particular concern. Investigations about this question have been contrasting and sometimes contradictory (Sangati et al., 2009), as a result of the inherent complexity of the problem. In any case, it is clear that runoff statistics sensitivity to spatial heterogeneity is in principle less significant as catchment area is smaller and more homogeneous. In our case, the assumption of a concentration time of 1 hour for the hypothetical catchment under consideration is actually limiting the catchment area. Thus, the lumped modelling assumption can be considered reasonable, at least for the purpose of comparing in quantitative terms the resulting confidence intervals width for peak flows distribution, resulting from either climatic input variations or known asymptotic properties of the Pareto distribution MLE estimators. Such comparison is rigorously done under a simple, popular, well defined and identical catchment rainfall-runoff lumped operation.

4. About considering the entire range of stream discharge and its non-stationarity effects

This point of the discussion is in accordance to what has already been stated in item #2. As highlighted by Referee #2, the focus of the paper is on peak flows. Indeed, peak flow characterization is of major importance to assess hydrological and hydraulic response and impacts of these small and fast-responding catchments. We absolutely agree with Referee #2 on the importance the entire range of stream discharge could have, but it is not the main issue within the scope of the analyzed catchments. Anyway, and as explained before in item #2, all these assumptions will be added to the reviewed.

5. On the limitations of the approach

We totally agree with Referee #2. For the aim of the research and in benefit of the analytical simplicity and practical applicability, as mentioned by Referee #2, a very simply modelling approach is assumed, which necessarily involves very important limitations, as was also outlined by Referee #1. These limitations are clearly identified, and will be correspondingly explained in detail to improve the paper. In fact, the research presented herein can constitute a first stepping stone towards a more complex analysis after relaxation of some of the initial assumptions, for instance, incorporating seasonality of rainfall stochastic properties or an extended sensitivity analysis due to variations of catchment response parameters. These aspects, among others already mentioned, should guide further research lines.

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Response to Referee Comment RC-C4466-2014 – Anonymous Referee #3

On behalf of co-authors, I thank gratefully Anonymous Referee #3 for his constructive and useful comments, and in particular for the very interesting questions pointed out, concerning limitations of the modelling approach and future research topics linked to the paper results.

Here are our responses for specific referred issues by Referee#3.

1. About the transferability of the results

The results presented in the paper derive from a set of strong simplified assumptions, especially concerning the rainfall-runoff process. Such assumptions and in particular, the values adopted for the parameters involved, constitute a severe limitation of the range of hydrological catchments where the approach is representative. Results cannot be transferred to other catchments and/or hydrological regimens different from those mentioned in the paper.

In this respect, and according to Referee#3 comment, the text of the paper is to be improved with some additional description of the type of Mediterranean catchments under consideration, including a couple of additional research references centered on case-studies that are good examples illustrating the geomorphology, climate and type of hydrological context under investigation [Olivares 2004; Camarasa, 1990].

Reference cited by Referee#3 (Troch et al, 2013) is to be included also in the new version of the paper, more precisely to clarify the scope of our research, which is not aiming to investigate the interactions at the catchment scale between landscape characteristics and climatic properties. It will be also emphasized in the reviewed version of the paper the interest of the methodology presented as basis for future analysis where more complex cases could be examined, as well as a contribution to better understand and quantify the interplay of runoff controlling factors in semi-arid regions, in particular the role of climatic variability.

2. About seasonality in the rainfall model

We agree with Referee#3 observation. As he states, the rainfall properties and nature change with season. Convective storms usually occur during fall, more particularly in September and October months, while events of frontal type take place mostly during winter and spring seasons. This issue is now being investigated by the authors under a framework modeling of a

non-homogeneous point process in time, including different intensity-duration-volume statistical relationship for different seasons. Accordingly, the analysis and mathematical incorporation of seasonality in the rainfall stochastic properties is going to be examined in a follow up paper.

3. On the accuracy of the model for other places

As previously mentioned, results reported in the paper cannot be transferred to other catchments and/or hydrological regimens different from the ones referred in the paper. We will try to improve the text of the paper at this point, to clarify the applicability range of the analysis performed, adding some additional description of the type of Mediterranean catchments under consideration. As mentioned before, some more references will be added concerning this point.

4. About the sensitivity analysis

This is a very interesting point, to be remarked in the following version of the text. In particular, and following Referee#3 suggestion, conclusions of the paper will emphasize the importance of the research as a first stepping stone towards a more complex analysis after relaxation of some of the initial assumptions. More particularly, the potential extension of the sensitivity analysis due to variations of catchment response parameters is to be mentioned as a future research line.

5. On the interactions between parameters/inputs

We do not completely agree with this comment. Interactions between parameters and inputs are not ignored in the paper, but analysed in a simplified way to outline the main results we are looking for. We indeed agree that the analytical sensitivity analysis could be performed in a much more complex way. Nevertheless, the paper aims at highlighting the main factors which influence the filtering role operated by the catchment so that our conclusions should be considered as a first stage of a much more complex analysis, where other interactions (for example the one between the concentration time and the storage capacity) even other more

complex rainfall-runoff transformations should be considered. Those simplifying assumptions will be better underlined in the reviewd version of the manuscript.

6. Showing in a higher dimensional space how input and storage parameters interact

As mentioned by Referee#3, in a former version of the paper we considered 2D surfaces to better presents results shown in Figures 1 and 2. Nevertheless, we finally decided to submit these bi-variased analyses into simple 1D graphs including the second component of the analysis (β/β_0 in the case of Figure 1 and S/μ_V in Figure 2) by mean of different 1D curves. Definetely we support the 1D representation as much more simple and understandable than the pure 2D one. As an example, see below the 2D representation of results from Figure 2 for scenario 1.a. In our opinion, the graph does not ease the interpretation of results nor brings added value to them.

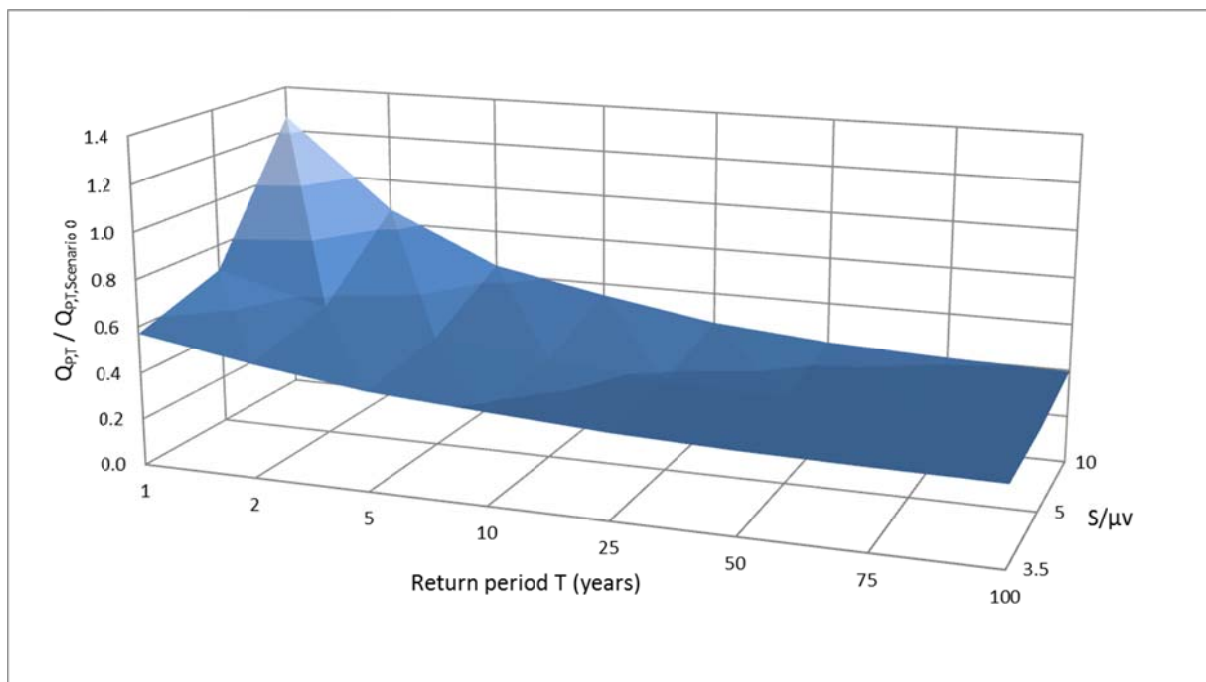


Figure. Flood quantile variations for scenarios 1.a (+30% μ_V) for $S/\mu_V = 3.5, 5$ and 10 .

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- 5 soil interactions and long-term hydrologic partitioning: signatures of catchment co-evolution,
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Climate and hydrological variability: the catchment filtering role

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Abstract

Measuring the impact of climate change on flood frequency is a complex and controversial task. Identifying hydrological changes is difficult given the factors, other than climate variability, which lead to significant variations in runoff series. The catchment filtering role is often overlooked and thus may hinder the correct identification of climate variability signatures on hydrological processes. Does climate variability necessarily imply hydrological variability? This research aims to analytically derive the flood frequency distribution based on realistic hypotheses about the rainfall process and the rainfall-runoff transformation. The annual maximum peak flow probability distribution is analytically derived to quantify the filtering effect of the rainfall-runoff process on climate change. A sensitivity analysis is performed according to typical semi-arid Mediterranean climatic and hydrological conditions, assuming a simple but common scheme for the rainfall-runoff transformation in small-size ungauged catchments, i.e. the CN-SCS model. Variability in annual maximum peak flows and its statistical significance are analysed when changes in the climatic input are introduced. Results show that depending on changes in the annual number of rainfall events, the catchment filtering role is particularly significant, especially when the event rainfall volume distribution is not strongly skewed. Results largely depend on the return period: for large return periods, peak flow variability is significantly affected by the climatic input, while for lower return periods, infiltration processes smooth out the impact of climate change.

1 Introduction

Many of the concerns about climate change are related to its effects on the hydrological cycle (Kundzewicz et al., 2007, 2008; Koutsoyiannis et al., 2009; Bloeschl and Montanari, 2010), and more specifically, its impact on freshwater availability and flood frequency (Milly et al., 2002; Kay et al., 2006; Allamano et al., 2009). However, results from recent studies about climate change impacts on flood frequency have not been conclusive (Kay et al., 2006). Indeed, detecting changes in flood frequency is not easy, because there are factors other than climate variability that may lead to significant changes, for instance, spatial variability of watershed properties or changes in the channel network geometry and land-use change (Milly et al., 2002). In particular, river bed geometry alterations, even if localized, can significantly affect flood magnitude. Therefore, to better identify climate impacts, one should focus on catchments that are close to pristine conditions (Di Baldassarre et al., 2010).

This research addresses an issue that is often overlooked and which may hinder the proper identification of climate variability effects on hydrological processes, namely, the filtering role played by catchment. In fact, runoff can be interpreted as a smoothed convolution of past and current rainfall, where smoothing is operated over the catchment contributing area and along the concentration time. Depending on the catchment's physical characteristics and meteorological conditions, smoothing may average out changes in rainfall distribution in space and time and hence cancel out climate variability. This is a key reason why climate variability effects might not be clearly visible in the hydrology response. In other words, climate variability does not necessarily imply hydrological variability. This issue has been also investigated for an urban hydrology context. For example, Andrés-Doménech et al., (2012) analysed storm tank resilience to changes in rainfall statistics, proving that the effect of climate variability on storm tank efficiency is likely to be smoothed out by the filtering effect caused the urban catchment.

In the present study, modelling efforts are basically centred on the role of climatic variability and its effects on catchment hydrological response, with rainfall statistical properties and their future trends representing the major factors controlling flood frequency distribution. It should be noted that other factors, such as land use change, might have a more significant impact than climate change itself under certain hydrological conditions. The present research focuses on climatic impacts alone: interactions at the catchment scale between landscape characteristics (soils, vegetation and geology, for instance) and climatic properties (Troch et

al., 2013), or possible climate-vegetation-soil feedbacks are not considered as they may hinder the assessment of climatic effects.

The modelling framework and simulations performed in this study focus on rainfall patterns variability, using a suitable modelling framework to investigate the extent to which such rainfall variations can actually be buffered by a given standard hydrological catchment, with typical response parameters of a small catchment in a semi-arid Mediterranean region. Thus, heterogeneity in catchment physical properties, which has provided contrasting and sometimes contradictory results (Sangati et al., 2009), is not considered in the presented approach. Runoff statistics sensitivity to spatial heterogeneity is in principle less significant as the catchment area is smaller and therefore more homogeneous. In our case, we assume that the concentration time is short, therefore implying that the catchment area is small. Thus, the lumped modelling assumption can be considered reasonable for the purpose of the study.

To assess climatic impacts, the frequency of occurrence of peak flows is estimated by means of a derived distribution approach, which is particularly useful to obtain probability distributions of peak flows in ungauged or poorly observed basins. In such cases design floods are calculated from a hydrological model, which is driven by historical or synthetic rainfall data (Haberlandt and Radtke, 2014). The derived flood frequency analysis was also used by Gaume (2006) to investigate asymptotic behaviour of flood peak distributions from rainfall statistical properties, highlighting the strong dependence of peak flow distribution on rainfall statistical properties, and considering a limited and reasonable hypothesis on the rainfall-runoff transformation.

Accordingly, a stochastic process is used here to model rainfall and a simple deterministic lumped model is proposed to simulate the rainfall-runoff transformation. Such an analytical approach, which has a long history of application in hydrology (see, for instance, Eagleson (1972) and Papa and Adams (1997)), presents several advantages. The most relevant is the opportunity to analytically assess the cause-effect relationships that take place in the rainfall-runoff transformation.

However, the analytical approach requires the use of models that lend themselves to analytical developments, which are obtained by using simplified representations. Therefore our analysis, being based on the use of an analytical model, cannot account for the overall complexity of catchment processes. Consequently, a simplified representation of hydrological processes is considered herein, without including detailed effects.

Under such assumptions, the aim of this research is to quantify the actual extent to which the rainfall-runoff process actually filters the impact of rainfall variability on runoff annual maximum peak flow series. The flood frequency distribution is analytically derived for a hypothetical catchment based on plausible assumptions about the rainfall process and the rainfall-runoff transformation. Once derived the peak flow probability distribution, one may quantify the smoothing brought on by the rainfall-runoff process. A hypothetical case study is developed according to climatic and hydrological conditions typical of the Valencia region (Spain), described in section 2.2. As also described later, the rainfall-runoff model proposed assumes a simple but common scheme for small, fast-responding, ungauged catchments, subjected to erratic hydrological regimes (Ferrer Polo, 1993; Soulis and Valiantzas, 2012).

2 Analytical model

We set up an analytical model to describe the river flow regime for a hypothetical catchment, based on analytical descriptions of rainfall and rainfall-runoff transformation. Under suitable assumptions which are described below, this model allows us to derive the annual maximum flood frequency distribution, depending on climate and catchment behaviour.

The analysis presented herein is an event-based approach, where each rainfall-runoff event is treated as an independent event. In the Valencia region, as in other many semi-arid locations around the Mediterranean, ephemeral rivers are closely related to small and fast-responding catchments. Such regimes, also named as “erratic regimes” according to the classification provided by Botter et al. (2013), occur when rainfall inter-arrival times are somewhat longer than the typical duration of the resulting flow pulses, as the case presented in this study. As pointed out by Andrés-Doménech et al. (2010), antecedent dry periods for the considered climate can be assumed to be exponentially distributed with a 22-hour low bound and an 8-day expected mean value. With such a sporadic rainfall regime, antecedent moisture conditions are mainly related to the event itself and rainfall intensities during the initial stages of the storm, so that the assumption of independence for subsequent events is plausible. Moreover, for this type of hydrological events, direct runoff is the dominant component of the hydrograph.

To carry out this analysis, we assume that the rainfall forcing in the present climate can be modelled by a stationary model. Thus, non-stationarity can be accounted for by changing the parameters of the rainfall model at a given time when climate variability is supposed to occur.

Such a change in the rainfall model parameters implies a corresponding deterministic change of rainfall statistics and therefore non-stationarity (Koutsoyiannis and Montanari, 2014; Montanari and Koutsoyiannis, 2014). Non stationarity in the river flow is assumed to occur for the presence of the above non-stationarity in rainfall and thus is quantified through the proposed approach.

2.1 Rainfall description

A rainfall analytical model is used to describe the occurrence of the rainfall process over time. We adopt a stochastic rectangular pulses model that simulates rainfall dynamics by assuming that rainfall events occur as independent rectangular pulses over time. Events are assumed to occur according to a Poisson process (Madsen and Rosbjerg, 1997; Madsen et al., 1997) and thus the probability of experiencing n rainfall event in the time span $[0, t]$ is given by

$$P[n] = \frac{(\beta t)^n}{n!} e^{-\beta t} \quad (1)$$

where β is the mean number of rainfall events per unit time. Event rainfall depth (v) is assumed to be independent and the result of a generalized Pareto distribution (Andrés-Doménech et al., 2010). This model provided a good fit for the rainfall series of Valencia (Spain), recorded with 5-minute resolution by the Júcar river basin hydrological service (SAIH) during the period 1990-2006. Andrés-Doménech et al. (2010) also found the model to be accurate for other locations in Spain. Other authors have also reported good results in other Mediterranean locations (Tzavelas et al., 2010).

The distribution function of the generalized Pareto distribution is given by

$$F_V(v) = 1 - \left(1 - \kappa \frac{v}{\alpha}\right)^{1/\kappa} \quad v \geq 0, \quad (2)$$

where $\kappa < 0$ and $\alpha > 0$ are the shape and scale parameters, respectively.

For the region that is considered in the study, convective storms usually occur during Autumn, particularly in September and October, while frontal events mostly occur during Winter and Spring. Thus, maximum rainfall peaks occur systematically during Autumn. The rainfall model that we use can potentially reproduce both frontal and convective events (see, for instance, Andrés-Doménech et al., 2010). Consequently, seasonality is not specifically accounted for. We assume that climatic variability may occur through an intensification of

rainfall events, and we investigate the conditions under which it may imply or not an amplification of annual maximum floods, that is, to what extent the rainfall-runoff transformation may filter out or amplify the effects of climate variability.

2.2 Rainfall-runoff description

To conceptualize rainfall-runoff transformation, the SCS-CN event-based model was adopted. This model has been widely used in Spain (Ferrer Polo, 1993) and other Mediterranean countries (Soulis and Valiantzas, 2012). In this model, runoff volume, $r(v)$, is related to event rainfall volume v by the following relationship:

$$\begin{cases} r(v) = 0 & \text{if } v \leq I_a \\ r(v) = \frac{(v - I_a)^2}{v - I_a + S} & \text{if } v > I_a \end{cases}, \quad (3)$$

where $I_a = kS$ is the initial rainfall abstraction, S is the catchment storage capacity and k is the initial abstraction coefficient. By assuming the dimensionless SCS unit hydrograph (SCS, 1971), each rainfall event produces a single-peak triangular hydrograph. The specific peak river flow can be expressed as

$$q_p(v) = \lambda_p \frac{r(v)}{t_C}, \quad (4)$$

where $r(v)$ is the runoff event volume computed by (3), t_C is the concentration time of the catchment and λ_p is a dimensionless peak factor.

The original SCS model recommends a standard value $\lambda_p = 9/8$, implying that 3/8 of the total runoff volume occurs before the peak, being the time to peak equal to $2t_C/3$ from the beginning of net rainfall. For the particular case of semiarid regions in Spain, a value $\lambda_p = 5/3$ is recommended (Ferrer Polo, 1993) to take into account the faster hydrological response.

2.3 Deriving the peak flow probability distribution

The rainfall and rainfall-runoff analytical descriptions allow for the analytical derivation of the probability distribution function (PDF) of **all events** peak flow. Assuming that no runoff occurs if $v < I_a$,

$$F_{Q_p}(0) = F_V(I_a) = 1 - (1 - \kappa I_a / \alpha)^{1/\kappa}, \quad (5)$$

where Q_P indicates the stochastic process whose outcome is the event peak flow $q_P(t)$. On the other hand, when initial abstraction I_a is exceeded then $Q_P > 0$, and the related cumulative probability distribution is

$$F_{Q_P}(q_P) = \int_0^{q_P} f_{Q_P}(q_P) dq_P = F_{Q_P}(0) + \int_{I_a}^{q_P} f_V(v) dv = 1 - (1 - \kappa v / \alpha)^{1/\kappa} \quad (6)$$

Combining these expressions with equations (3) and (4) provides equation (7).

$$F_{Q_P}(q_P) = \begin{cases} 1 - (1 - \kappa I_a / \alpha)^{1/\kappa} & q_P = 0 \\ 1 - \left\{ 1 - \frac{\kappa}{\alpha} \left[I_a + \frac{t_C q_P}{2\lambda_P} \left(1 + \sqrt{1 + \frac{4\lambda_P S}{t_C q_P}} \right) \right] \right\}^{1/\kappa} & q_P > 0 \end{cases} \quad (7)$$

As previously explained, it should be noted that these rainfall and rainfall-runoff models assume statistical independence of peak river flow over time. Therefore, the distribution function of maximum annual floods Q_{Pm} can be expressed as (see, for instance, Viglione and Blöschl, 2009):

$$F_{Q_{Pm}}(q_{Pm}) = e^{-\beta(1-F_Q(q_P))} \quad (8)$$

where β is the annual number of rainfall events. In terms of return period, the T-year maximum peak flow can be expressed as:

$$q_{Pm,T} = F_{Q_P}^{-1} \left[\frac{1}{\beta} \ln \left(1 - \frac{1}{T} \right) + 1 \right] \quad (9)$$

This analysis is equivalent to an Annual Maximum Series analysis of flood flows, as the flood events are assumed to be independent (Andrés-Doménech et al., 2010).

2.4 Confidence intervals of peak flow PDF

Asymptotic properties of the maximum likelihood estimators (MLE) of the generalized Pareto distribution (2) such as consistency, normality and efficiency were obtained by Smith (1984). The MLE (κ, α) are asymptotically normal (De Zea Bermudez and Kotz, 2010) with a variance-covariance matrix given by

$$\begin{bmatrix} \sigma_{\kappa}^2 & \sigma_{\kappa\alpha} \\ \sigma_{\kappa\alpha} & \sigma_{\alpha}^2 \end{bmatrix} = \frac{1}{n} \begin{bmatrix} (1-\kappa)^2 & \alpha(1-\kappa) \\ \alpha(1-\kappa) & 2\alpha^2(1-\kappa) \end{bmatrix}, \quad (10)$$

where n is the sampling size. Consequently, the correlation coefficient is

$$\rho_{\kappa\alpha} = \frac{1}{\sqrt{2(1-\kappa)}} \quad (11)$$

Monte Carlo simulations are performed to generate 1000 pairs (κ, α) normally distributed according to (10) and also to the MLE of (2). Thus, 1000 discrete probability functions are obtained according to (7) and (8). For a specific value q_{Pmi} , 1000 normally distributed values F_{Qpmi} are calculated so that for each q_{Pmi} , percentiles $F_{Qpmi}(\xi)$ and $F_{Qpmi}(1-\xi)$ corresponding to ξ and $1-\xi$ probabilities are derived. These values are then transformed with equation (9) into their corresponding return periods, T_ξ and $T_{1-\xi}$, which represent the confidence interval limits for a ξ significance level.

3 Qualitative sensitivity analysis for peak flows to climate change

Based on the previously established assumptions, the analysis shows that the following parameters affect the magnitude of the annual maximum peak river flow $q_{Pm,T}$:

- (a) Expected number of rainfall events per year, β [yrs⁻¹];
- (b) shape and scale parameters, κ [-] and α [mm], respectively, of the generalized Pareto distribution for event rainfall depth;
- (c) storage capacity of the catchment, S [mm];
- (d) initial abstraction of the catchment, I_a [mm];
- (e) concentration time of the catchment t_C [h];
- (f) SCS peak factor λ_P [-];
- (g) return period, T [yrs].

Parameters (a) and (b) are directly related to climate input; parameters (c) and (d) are related to the runoff production process in the catchment; parameters (e) and (f) affect the temporal catchment response; finally, parameter (g) is conditioned by the scope of the analysis.

The dependence of $q_{Pm,T}$ on these eight parameters is dictated by equations (7), (8) and (9). In particular, equation (9) dictates the dependence of $q_{Pm,T}$ on the return period and β . An increase in the annual number of rainfall events implies an increase in the mean annual rainfall if all other climatic behaviours remain unchanged. Consequently, an increase in β does not affect the distribution of flood peaks as long as the events remain distant enough in time and therefore independent, but only affects the number of flood peaks sampled per unit of time. This implies a relevant effect on the flood return period. According to equation (9), a 20% increase in β implies a decrease in the flood return period ranging from 0% (for low T

values) to 16.7% (for high T values). This result is counterintuitive, but one should note that a relevant change in the return period does not necessarily imply a significant change in the flood quantile. As a matter of fact, changes in $q_{Pm,T}$ can be negligible after a change in β , especially if the Pareto distribution for event rainfall depth is not strongly skewed. The hypothetical case study presented herein will prove this first conclusion, as shown later. Therefore, it can be concluded that the filtering role of the catchment with regard to changes in β is particularly significant when the distribution of event rainfall volume is not strongly skewed.

The sensitivity to the other climatic and catchment parameters is to be analysed through equation (7). Specifically, an increase in the flood quantile is induced by an increase in parameters α and t_c . The latter is raised to a power less than 1 and therefore is less effective than α . Conversely, an increase in k , S , I_a and λ_p leads to a decrease in the flood quantile value. These considerations are somewhat intuitive, but it is interesting to quantitatively analyse the sensitivity of the flood quantile to production parameters (c) and (d) to quantify the actual filtering role of the catchment on climate variability. The case study is developed with data from Valencia (Spain) presented as a quantitative sensitivity analysis.

4 Quantitative sensitivity analysis for peak flows to climate variability: a hypothetical case study

Rainfall model parameters are estimated by maximum likelihood for the 1990-2006 data series in Valencia. Resulting values are $\beta=27.29 \text{ yrs}^{-1}$, $\alpha= 8.46 \text{ mm}$ and $\kappa= -0.411$. Consequently, the average event depth per event is $\mu_V=14.36 \text{ mm}$ and the coefficient of variation is $CV_V=2.37$. Further details regarding the rainfall model can be found in Andrés-Doménech et al. (2010). This climate scenario constitutes the reference situation (scenario 0) to perform the sensitivity analysis.

Parameters defining the catchment are adopted in a dimensionless form. This analysis focuses on how the production parameters influence the peak flow statistics. Thus, the storage capacity is considered through the ratio S/μ_V , with an initial abstraction coefficient $k=0.2$ (as in the original version of the SCS-CN model and also mentioned by Ferrer Polo (1993)).

Peak flows are expressed per unit area (mm/h), so no particular catchment area is assumed.

4.1 Sensitivity to β and to the skewness of the rainfall depth distribution

The first quantitative analysis performed corresponds to flood quantile sensitivity to β and to the skewness of the Pareto distribution governing event rainfall depth. Catchment parameters are set to $S/\mu_V=3.5$ and $t_C=1$ h, corresponding to typical values for small catchments in the Valencia region. Concentration time has been set to a representative value, based on a wide hydrological experience in many small catchments of rapid response in the eastern Mediterranean and south east coast of Spain (Olivares Guillem, 2004; Camarasa Belmonte, 1990). It can be considered a realistic and representative value for a typical ephemeral river in fast responding small catchments in semi-arid Mediterranean regions.

Relative changes in 10-year and 100-year flood quantiles compared to scenario 0 are evaluated for different situations, combining variations in β and CV_V . It should be noted that changes in β mean that μ_V should be scaled accordingly. Lowering CV_V brings the Pareto event rainfall depth distribution close to the exponential distribution (Koutsoyiannis, 2005), while increasing CV_V progressively increases skewness. Given CV_V variations, the κ parameter of the Pareto distribution, as well as its skewness, vary (Singh and Guo, 1995). Pareto parameters (κ, α) for the modified scenarios can be analytically derived from their relationships with CV_V (Andrés-Doménech et al., 2012).

Figure 1 summarises the results obtained and shows that changes in β do not lead to significant flood quantile variations, unless the distribution of rainfall event depth is highly skewed (higher CV_V values). As stated in the previous section, the less skewed the rainfall regime is, the less significant the filtering role of the catchment. Conversely, changes in CV_V are not filtered at all.

4.2 Sensitivity to the runoff production process

Catchment production is highly influenced by the balance between rainfall depth and the catchment storage capacity. Thus, sensitivity to the production process should be analysed by introducing variability in rainfall event depth for different S/μ_V situations.

Arbitrary variations in $v(t)$ statistics from the reference situation (scenario 0) are considered as plausible climate variability scenarios for rainfall event depth. Instead of evaluating the effects of changes on the distribution parameters, changes in the rainfall statistic μ_V of rainfall event depth are considered. The analysis is now performed by changing μ_V in the range $\pm 30\%$ of its reference value (scenarios 1.a, +30% and 1.b, -30%). This is in accordance with the

maximum expected variability in annual amounts of rainfall for the predicted climate change scenarios in Spain (Brunet et al., 2009). In this scenario CV_V remains unchanged. It follows that both the κ parameter of the Pareto distribution and its skewness also remain unchanged (Singh and Guo, 1995). The modified α values for the modified scenarios can be derived from α dependence on μ_V (Andrés-Doménech et al., 2012). As stated before, physical parameters defining the catchment are adopted in a dimensionless form. To analyse the filtering role of the catchment depending on production parameters, three realistic storage capacity scenarios are considered, namely, $S/\mu_V=3.5, 5$ and 10 .

For each S/μ_V scenario, Figure 2 depicts flood quantile variations for scenarios 1.a (+30% μ_V) and 1.b (-30% μ_V). Unchanged climatic conditions (scenario 0) yield a flow quantile decrease as S/μ_V increases. Hence, considering scenario 1.a and 1.b leads to quantile increments associated to S/μ_V increments. In fact, flood quantile reductions caused by higher S/μ_V values (scenario 0) are more relevant than the variation resulting from μ_V changes (scenarios 1.a and 1.b).

Another point to be noted is the magnitude of relative variations depending on the return period T . For higher return periods, relative changes in flood quantiles tend to be very close to those imposed by the climatic input (mean rainfall event depth μ_V). This result reinforces the thesis supported by Gaume (2006) who demonstrated that, for large return periods, the rainfall PDF behaviour is decisive on the catchment response and determines the asymptotic behaviour of the flood peak distribution. On the other hand, for low return periods, catchment infiltration parameters strongly influence the derived peak flows for each scenario considered. This result is in accordance with typical Mediterranean catchment behaviour (Gioia et al., 2008; Preti et al., 2011).

4.3 Peak flow confidence intervals

Confidence interval limits for a $\xi=0.05$ significance level are obtained for annual maximum peak flow quantiles corresponding to climatic scenario 0. In order to quantify the statistical significance of peak flow variations after considering various scenarios, eight different climatic scenarios are selected from amongst those previously analysed. These account for climatic variations induced by changes in μ_V , β and CV_V (Table 1). Annual maximum peak flow quantiles are evaluated for each scenario and variations with regard to scenario 0 are

calculated. Figure 3 summarises the results obtained for each scenario and for the confidence interval limits for scenario 0. As observed, all results corresponding to β and/or CV_V variations (scenarios 2.a to 4.b) lie within the 90% confidence interval for scenario 0. Therefore, results show that there is no concluding evidence from the statistical point of view concerning the significance of peak flow variability induced by these parameters. Nevertheless, when considering peak flow variations due to changes in μ_V (scenarios 1.a and 1.b), our results confirm the conclusions already drawn in section 3. For low return periods, changes are significant because they are strongly influenced by the runoff production process in the catchment. For larger T, the significance of peak flow variations drastically decreases.

5 Conclusions

The research presented herein highlights the filtering role brought on by catchment processes through a simple rainfall-runoff transfer function. The peak flow distribution is analytically derived from a rainfall model using the CN-SCS hydrological conceptualisation. Variability of annual maximum peak flows is quantitative analysed when changes in climatic input are introduced.

Such a modelling approach involves certain limitations, and yet it benefits from the analytical simplicity and practical applicability. Consequently, numerical results obtained after simulations cannot be transferred to hydrological regimes that differ from the type of Mediterranean catchments specified here. Nevertheless, the proposed methodology represents a useful modelling framework for further studies, and may constitute a first step forward towards a more complex analysis after relaxing some of the initial assumptions. Although certain dominant drivers of the hydrological response, like variability of watershed properties or land use changes, have not been explicitly considered in this study, the proposed modelling framework has the potential to incorporate those drivers to a certain extent, and thus, allow for the effect of such variability to be assessed and compared in future studies.

The results obtained from the sensitivity analysis can be summarised as follows:

- a) The filtering role of the catchment with regard to changes in the annual number of rainfall events is particularly significant when the rainfall event volume distribution is not strongly skewed.
- b) Sensitivity to the runoff production parameters in the catchment is highly influenced by the balance between rainfall depth and catchment storage capacity. For higher return

1 periods, relative changes in **annual maximum** flood quantiles tend to be asymptotically
2 similar to those imposed by the climatic input. For low return periods, the infiltration
3 process **strongly influences** the derived peak flow distribution, which is in accordance
4 with typical Mediterranean catchment hydrological behaviour.

- 5 c) In the range of low return periods (1 to 10 years), the only parameter of the rainfall model
6 which actually affects significantly peak flows is the mean **rainfall event** depth. The other
7 parameters involved in the rainfall modelling approach play a negligible role in this case,
8 mainly due to the threshold based conceptualization used in the CN-SCS model.

9 Although these conclusions were derived under simplified assumptions, results correspond to
10 a rigorous sensitivity analysis performed for realistic hydrological conditions **of typical**
11 **ephemeral, fast-responding rivers**, and thus provide indications of general validity for small
12 Mediterranean catchments responding under these simple rainfall-runoff models. Further
13 research should focus on the limitations of such a simple model for high and very high return
14 periods and on the dependence of peak flow variability on time-dependent parameters of the
15 rainfall-runoff transformation. **On the other hand, the research could be extended by including**
16 **in the rainfall-runoff deterministic model additional climatic perturbations and land use**
17 **changes, as well as by exploring possible parameter interaction effects.**

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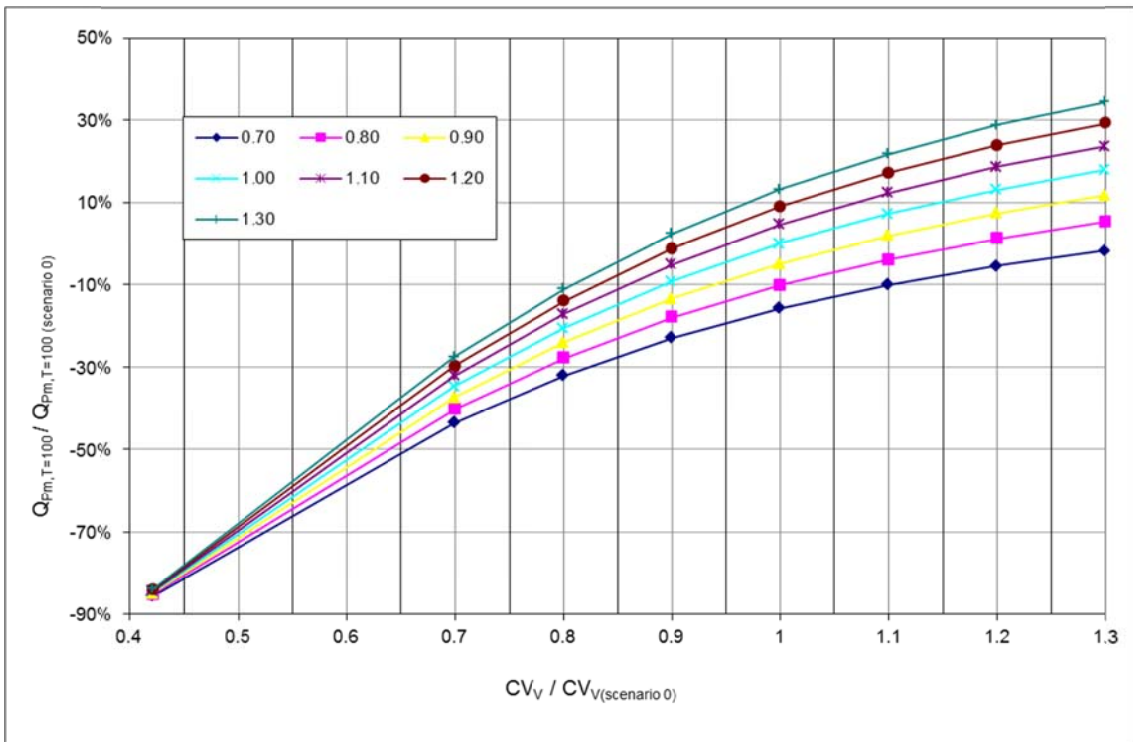
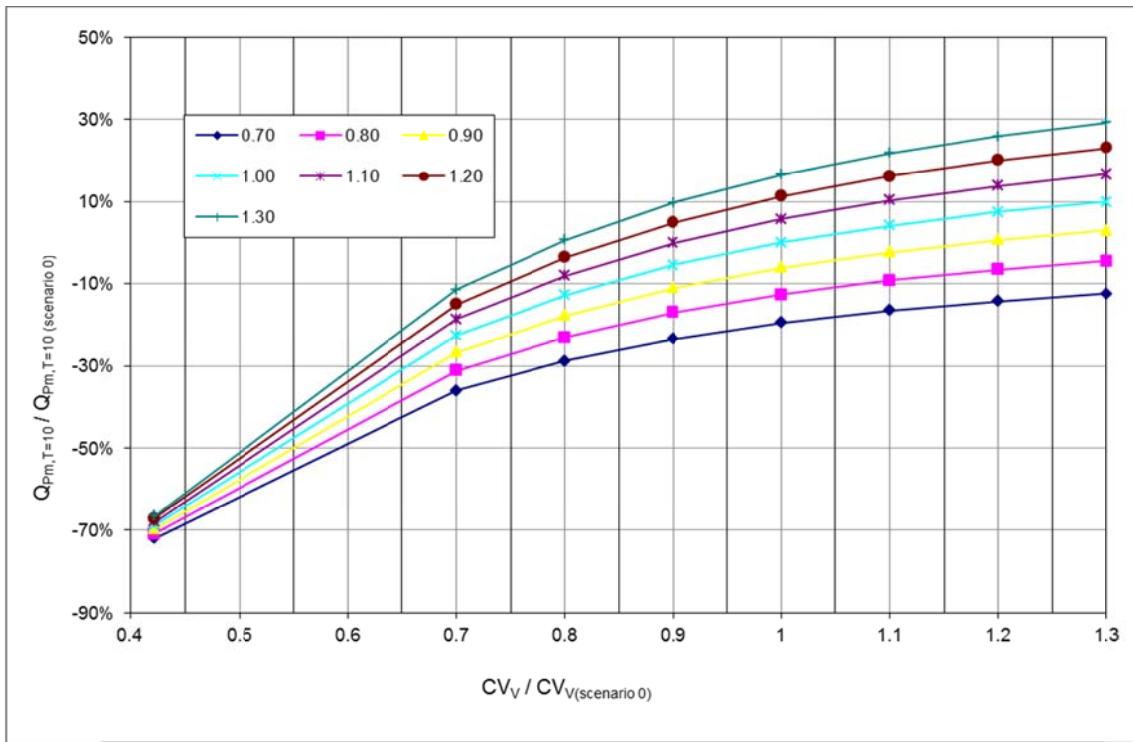
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Table 1. Climate scenarios considered for significance analysis.

Climatic Scenario	μ_v Hypothesis	CV_v Hypothesis	β Hypothesis	μ_v [mm]	CV_v	α [mm]	κ	β
0	Reference scenario	Reference scenario	Reference scenario	14.36	2.37	8.46	0.411	27.29
1a	30% Increase in μ_v	Reference scenario	Reference scenario	18.67	2.37	11.00	0.411	27.29
1b	30% Decrease in μ_v	Reference scenario	Reference scenario	10.05	2.37	5.92	0.411	27.29
2a	Reference scenario	30% Increase in CV_v	Reference scenario	14.36	3.08	7.94	0.447	27.29
2b	Reference scenario	30% Decrease in CV_v	Reference scenario	14.36	1.66	9.79	0.318	27.29
3a	Reference scenario	30% Increase in CV_v	30% Increase in β	14.36	3.08	7.94	0.447	35.48
3b	Reference scenario	30% Decrease in CV_v	30% Increase in β	14.36	1.66	9.79	0.318	35.48
4a	Reference scenario	Reference scenario	30% Increase in β	14.36	2.37	8.46	0.411	35.48
4b	Reference scenario	Reference scenario	30% Decrease in β	14.36	2.37	8.46	0.411	19.11

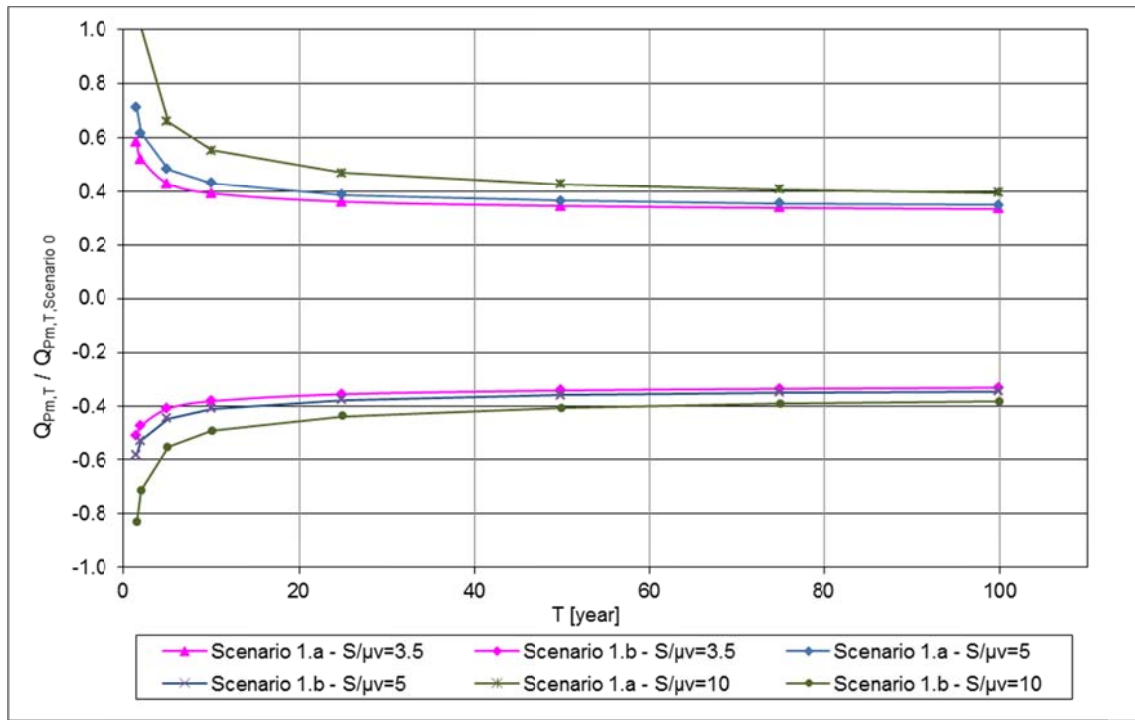


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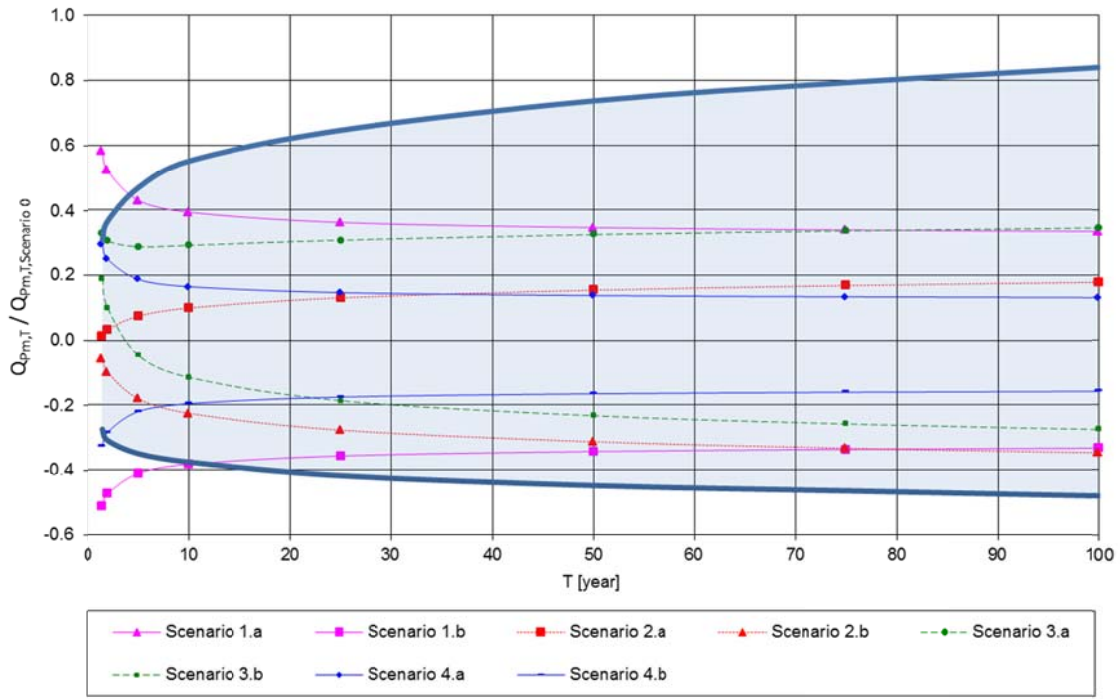
Figure 1. Annual maximum flood quantile variations for changes in β and CV_V . Catchment parameters are set to $S/\mu_V=3.5$ and $t_C=1$ h. Cases $T=10$ years (top) and $T=100$ years (bottom).

3



1

2 Figure 2. **Annual maximum flood** quantile variations for scenarios 1.a (+30% μ_V) and 1.b (-
3 30% μ_V) and for $S/\mu_V=3.5, 5$ and 10 .



1

2 Figure 3. Annual maximum flood quantile variations for scenarios defined in Table 1 and
 3 $\xi=0.05$ confidence interval for scenario 0 peak flow distribution (shaded area). Catchment
 4 parameters are set to $S/\mu_V=3.5$ and $t_C=1$ h.