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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 in fact, this may hinder the correct identification of climate variability signatures on hydrological processes. Does climate variability necessarily imply hydrological variability? The research herein presented aims to analytically derive the flood frequency distribution basing on realistic hypotheses about the rainfall process and the rainfall–runoff transformation. The peak flow probability distribution is analytically derived to quantify the filtering effect operated by 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 peak flows and its statistical significance are analysed when changes in the climatic input are introduced. Results show that in regard to changes in the annual number of rainfall events, the catchment filtering role is particularly significant 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 impacted by the climatic input, while for lower return periods, infiltration processes smooth out the effects 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

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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, 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 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 by the urban catchment.

Derived flood frequency analysis is 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. The problem arises when quantifying the actual

extent to which the rainfall–runoff process is actually filtering the impact of rainfall variability on runoff peak flow series.

This research aims to analytically derive the flood frequency distribution for a hypothetical catchment based on plausible assumptions about the rainfall process and the rainfall–runoff transformation. The peak flow probability distribution is analytically derived, allowing us to 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) assuming a simple but common scheme for small ungauged catchments (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 flood frequency distribution, depending on climate and catchment behaviours.

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 accordingly to a Poisson process (Madsen and Rosbjerg, 1997; Madsen et al., 1997) and thus the probability of experiencing n rainfall events 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

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(Andrés-Doménech et al., 2010). This model provided a good fit for the rainfall series of Valencia (Spain), recorded with 5 min 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.

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 Eq. (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 event 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

$$F_{Q_p}(q_p) = \int_0^{q_p} f_{Q_p}(q_p) dq_p = F_{Q_p}(0) + \int_{I_a}^v f_V(v) dv = 1 - (1 - \kappa v / \alpha)^{1/\kappa}. \quad (6)$$

Combining these expressions with Eqs. (3) and (4) provides Eq. (7).

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

It should be noted that these rainfall and rainfall–runoff models assume statistical independence of peak river flow over time. Therefore, T year peak flow can be directly computed as

$$q_{P,T} = F_{Q_p}^{-1} \left(1 - \frac{1}{\beta T} \right) \quad (8)$$

where β is the expected rainfall events per year. This analysis is equivalent to a peak over threshold analysis of flood flows (Önöz and Bayazit, 2001), where the threshold is set to zero 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 Eq. (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

$$\begin{bmatrix} \sigma_{\kappa}^2 & \sigma_{\kappa\alpha} \\ \sigma_{\kappa\alpha} & \sigma_{\alpha}^2 \end{bmatrix} = \frac{1}{n} \begin{bmatrix} (1-\kappa)^2 & \alpha(1-\kappa) \\ \alpha(1-\kappa) & 2\alpha^2(1-\kappa) \end{bmatrix}, \quad (9)$$

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

$$\rho_{\kappa\alpha} = \frac{1}{\sqrt{2(1-\kappa)}} \quad (10)$$

Monte Carlo simulations are performed to generate 1000 pairs (κ, α) normally distributed according to Eq. (9) and also to the MLE of Eq. (2). Thus, 1000 discrete probability functions are obtained according to Eq. (7). For a specific value q_{P_i} , 1000 normally distributed values $F_{Q_{P_i}}$ are calculated so that for each q_{P_i} , percentiles $F_{Q_{P_i}}(\xi)$ and $F_{Q_{P_i}}$

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$(1 - \xi)$ corresponding to ξ and $1 - \xi$ probabilities are derived. These values are then transformed with Eq. (8) 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

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

- a. Expected number of rainfall events per year, β [yr^{-1}];
- b. shape and scale parameters, κ [-] and α [mm], respectively, of the generalized Pareto distribution for event rainfall depth;
- 10 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 [yr].

15 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 $q_{P,T}$ on these eight parameters is dictated by Eqs. (7) and (8).
20 In particular, Eq. (8) dictates the dependence of $q_{P,T}$ 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

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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 time. This implies a relevant effect on the flood return period. According to Eq. (8), a 20 % increase in β implies a 16.7 % decrease in the flood return period. 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 $q_{P,T}$ 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 Eq. (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 $\beta = 27.29 \text{ yr}^{-1}$, $\alpha = 8.46 \text{ mm}$ and $\kappa = -0.411$. Consequently, average event depth per event is $\mu_V = 14.36 \text{ mm}$ and the coefficient of variation is $CV_V = 2.37$. Further details on 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 in Ferrer Polo, 1993). Peak flows are expressed per unit area (mm h^{-1}), 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. Relative change 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. As a consequence of CV_V variation, the κ parameter of the Pareto distribution and its skewness vary (Singh and Guo, 1995). Pareto parameters (κ, α) for the modified scenarios can be analytically derived from relationships between them and CV_V (Andrés-Doménech et al., 2012).

Figure 1 summarises the results obtained and shows that changes in β do not produce significant flood quantile variations, unless the distribution of event rainfall depth is highly skewed (higher CV_V values). As mentioned 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.

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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 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 event rainfall depth. Instead of evaluating the effects of changes on the distribution parameters, changes in the rainfall statistic μ_V of event rainfall 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 predicted climate change scenarios in Spain (Brunet et al., 2009). In this scenario CV_V is kept unchanged. It follows that both the κ parameter of the Pareto distribution and its skewness 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, Fig. 2 depicts flood quantile variations for scenarios 1.a ($+30\% \mu_V$) and 1.b ($-30\% \mu_V$). Unchanged climatic conditions (scenario 0) yield a flow quantile decrease as S/μ_V increases. Hence, consideration of 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 issue to be highlighted 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

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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 behaviours (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 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. They consider climatic variations induced by changes in μ_V , β and CV_V (Table 1). Peak flow quantiles are evaluated for each scenario and variations with respect to scenario 0 are calculated. Figure 3 summarises the observed 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 intervals 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 Sect. 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.

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5 Conclusions

The research presented herein explores 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 by using the CN-SCS hydrological conceptualisation. Variability of peak flows is quantitative analysed when changes in climatic input are forced. The results obtained from this sensitivity analysis can be summarized as follows:

1. The filtering role operated by the catchment with regard to changes in the annual number of rainfall events is particularly significant when the event rainfall volume distribution is not strongly skewed.
2. 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 periods, relative changes in flood quantiles tend to be asymptotically similar to those imposed by the climatic input. For low return periods, the infiltration process has a strong influence on the derived peak flow distribution, which is in accordance with typical Mediterranean catchment hydrological behaviour.
3. In the range of low return periods (1 to 10 years), the only parameter of the rainfall model which actually affects significantly peak flows is the mean event rainfall depth. The other parameters involved in the rainfall modelling approach play a negligible role in this case, mainly due to the threshold based conceptualization used in the CN-SCS model.

Although these conclusions were derived under simplified assumptions, results correspond to a rigorous sensitivity analysis performed for realistic hydrological conditions, and thus provide indications of general validity for small Mediterranean catchments responding under these simple rainfall–runoff models. Further research should focus on the limitations of such a simple model for high and very high return periods and on the

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dependence of peak flow variability on time-dependent parameters of the rainfall–runoff transformation.

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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	Increase 30 % in μ_V	Reference scenario	Reference scenario	18.67	2.37	11.00	0.411	27.29
1b	Decrease 30 % in μ_V	Reference scenario	Reference scenario	10.05	2.37	5.92	0.411	27.29
2a	Reference scenario	Increase 30 % in CV_V	Reference scenario	14.36	3.08	7.94	0.447	27.29
2b	Reference scenario	Decrease 30 % in CV_V	Reference scenario	14.36	1.66	9.79	0.318	27.29
3a	Reference scenario	Increase 30 % in CV_V	Increase 30 % in β	14.36	3.08	7.94	0.447	35.48
3b	Reference scenario	Decrease 30 % in CV_V	Increase 30 % in β	14.36	1.66	9.79	0.318	35.48
4a	Reference scenario	Reference scenario	Increase 30 % in β	14.36	2.37	8.46	0.411	35.48
4b	Reference scenario	Reference scenario	Decrease 30 % in β	14.36	2.37	8.46	0.411	19.11

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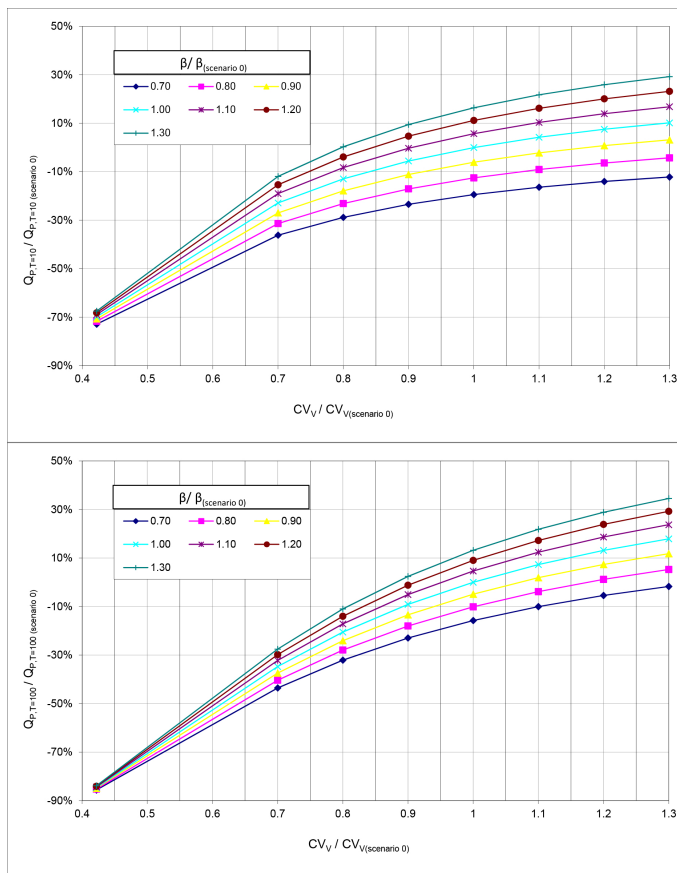


Figure 1. Flood quantile variations for changes in β and CV_V . Catchment parameters are set to $S/\mu_V = 3.5$ and $t_C = 1$ h. Cases $T = 10$ years (top panel) and $T = 100$ years (bottom panel).

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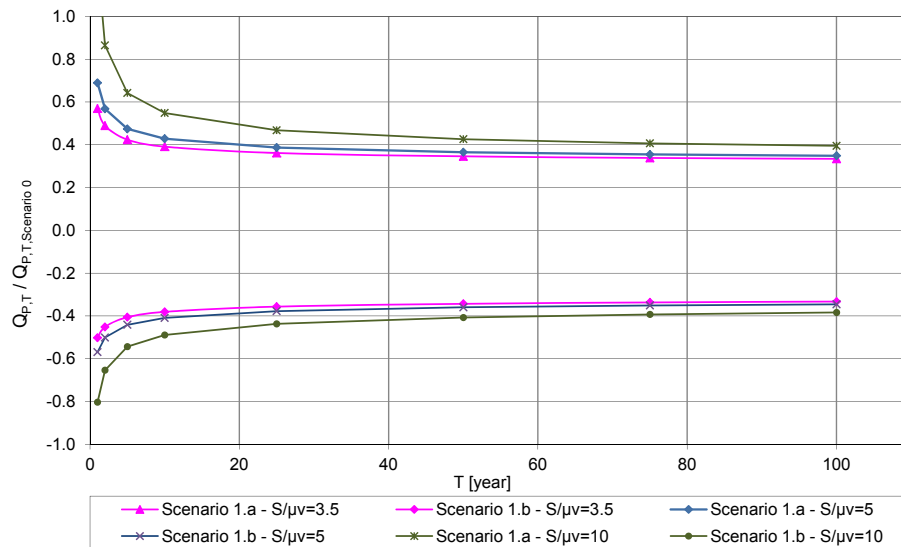


Figure 2. Flood quantile variations for scenarios 1.a ($+30\% \mu_V$) and 1.b ($-30\% \mu_V$) and for $S/\mu_V = 3.5, 5$ and 10 .

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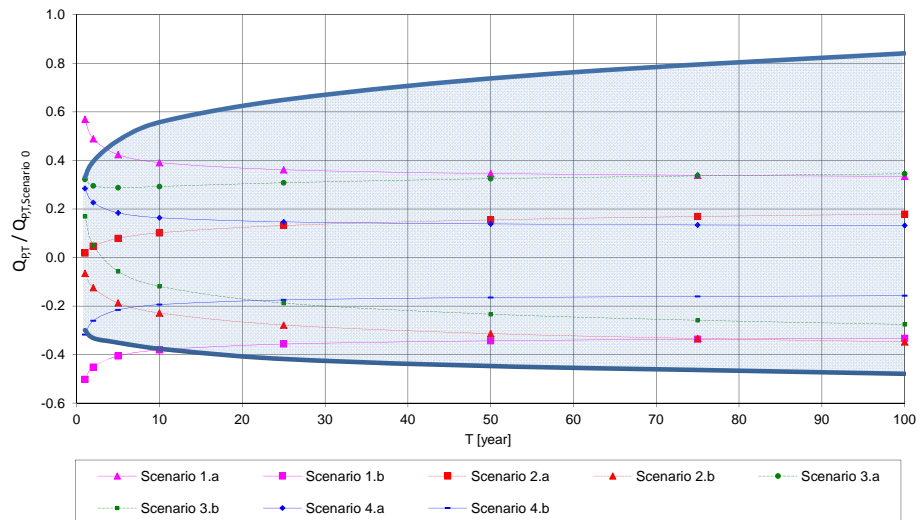



Figure 3. Flood quantile variations for scenarios defined in Table 1 and $\xi = 0.05$ confidence interval for scenario 0 peak flow distribution (shaded area). Catchment parameters are set to $S/\mu_V = 3.5$ and $t_C = 1$ h.

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