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A stochastic design rainfall generator based on copulas and mass curves

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Abstract

The use of design storms can be very useful in many hydrological and hydraulic practices. In this study, the concept of a copula-based secondary return period in combination with the concept of mass curves is used to generate design storms. The analysis is based on storms selected from the 105 year rainfall time series with a 10 min resolution, measured at Uccle, Belgium. In first instance, bivariate copulas and secondary return periods are explained, together with a focus on which couple of storm variables is of highest interest for the analysis and a discussion of how the results might be affected by the goodness-of-fit of the copula. Subsequently, the fitted copula is used to sample storms with a predefined secondary return period for which characteristic variables such as storm duration and total storm depth can be derived. In order to construct design storms with a realistic storm structure, mass curves of 1st, 2nd, 3rd and 4th quartile storms are developed. An analysis shows that the assumption of independence between the secondary return period and the internal storm structure could be made. Based on the mass curves, a technique is developed to randomly generate an intrastorm structure. The coupling of both techniques eventually results in a methodology for stochastic design storm generation. Finally, its practical usefulness for design studies is illustrated based on the generation of design storm ensembles and rainfall-runoff modelling.

1 Introduction

Engineers involved in the design of hydraulic structures in river systems are often confronted with a lack of available data regarding the phenomenon under study, e.g. peak discharges at a specific point in a catchment. As rainfall data are often readily available, they often serve as an indispensable source of information for the further analysis. A variety of point rainfall data products can be used in such design studies: the historical time series, a synthetically generated time series, intensity-duration-frequency

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(IDF) relations and design storms.

A method for generating design storms should be flexible enough to entail the variability of several rainfall characteristics. To that end, design storms are mostly characterized by a specific return period, a rainfall volume or intensity, and a duration, which are related to the extremity of the storm, and a temporal rainfall pattern or an internal storm structure (Chow et al., 1988).

The internal storm structure (Bernardara et al., 2007; Thompson et al., 2002; Koutsoyiannis, 1994, 1993) is often the most important characteristic and several methods exist for its characterization (see e.g., Prodanovic and Simonovic, 2004; Veneziano, 1999; Chow et al., 1988; Pilgrim and Cordery, 1975, and references therein): the use of an arbitrary (symmetrical) pattern in combination with an average intensity derived from the IDF curves, the construction of a pattern out of the complete IDF curves, using simulations of stochastic models, or by using standardized profiles (summation curves) derived from an empirical probabilistic analysis of the rainfall. The method of Huff (1967), which falls in the latter category, will be used in this study. Mass curves, often referred to as Huff curves, are representations of the non-dimensional cumulative time vs. the non-dimensional cumulative storm depth since the beginning of a storm. For specific time intervals, i.e. a 5% time interval, the empirical distribution of the normalized cumulative storm depth is then considered and often the 10%, 50% and 90% percentile of that distribution is then visualized. Furthermore, a classification of storms into quartile groups can be made.

Besides the internal storm structure, also the duration and mean storm intensity or storm depth should be calculated for a specific design storm. In practice, this is often done by fixing a specific design return period. Subsequently, a certain storm duration is fixed, which could be based on the concentration time of the catchment under study, and the corresponding mean storm intensity or storm depth for that design return period is then retrieved from previously established IDF relations. In this study, the recently proposed framework for a multivariate copula-based frequency analysis (Salvadori et al., 2007; Salvadori and De Michele, 2004) is used to establish a direct link

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between a physical storm duration, its depth or mean intensity, and the corresponding return period. The work of Ellouze et al. (2009), Gargouri-Ellouze and Chebchoub (2008), Kao and Govindaraju (2008) and Grimaldi and Serinaldi (2006) already considered the use of copulas in the modelling of design storms.

All analyses in this work are based on a 105 year rainfall time series with a 10 min resolution, measured at Uccle (Brussels), Belgium. These rainfall measurements have already been the subject of several studies, generally focusing on either the construction of IDF relations (Willems, 2000; Demarée, 1985; Laurant, 1976) or, more recently, on climate change and the detection of trends in rainfall observations (Ntegeka and Willems, 2008; De Jongh et al., 2006; Blanckaert and Willems, 2006; Vaes et al., 2002; Gellens, 2000). Also some work on scaling behaviour of the Uccle rainfall has been reported by Schmitt and Nicolis (2002) and Schmitt et al. (1998). In the context of design storms, the development of composite storms for Flanders based on the Uccle rainfall has been of great importance for Flemish water managers and engineers involved in urban drainage or river design (Vaes et al., 2000, 2001; Vaes and Berlamont, 2000, 2001; Vaes, 1999).

This work proposes a stochastic design rainfall generator by combining the traditional concept of Huff curves for the analysis of the internal storm structure with the concept of a copula-based secondary return period of a storm. In the following, firstly a copula-based secondary return period is assigned to each Uccle storm and some remarks on the choice of the couple of storm variables and the importance of a good fit are made (Sect. 2). Secondly, the internal storm structure of the observed storms and its independence of the return period is analyzed and an algorithm for a random internal storm structure generation is proposed (Sect. 3). Section 4 then illustrates how the design storm generator could be used for water management purposes. Finally, conclusions and recommendations for future research are given in Sect. 5.

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2 Assignment of return periods to Uccle storms

2.1 Storm selection

A first step is the delineation of individual and statistically independent storms in the 105 year time series of 10 min rainfall. Therefore, a minimal dry period, or critical dry duration, should be defined. All dry periods which are shorter than this criterion are considered to belong to the same storm (Bonta and Rao, 1988). Here, a 24-h dry period criterion is chosen, based on the method of Restrepo-Posada and Eagleson (1982), which assumes that the arrival times of statistically independent storms follow a Poisson distribution. However, from a design perspective, one could consider to use another independence criterion dictated by the application in which the storms are to be used, e.g. storms should be separated by a dry period at least as long as the concentration time of the catchment under study. For reasons of consistency, the same storm selection procedure as applied by Vandenberghe et al. (2010a,b) is used.

For each storm, several variables are calculated, such as the total storm depth D (mm), the storm duration W (h) and the mean storm intensity I (mm/h). In order to be able to analyze Huff curves (see Sect. 3), for each storm, the rainfall depth in every 10 min interval is made cumulative and the time lapse within the storm is expressed as a fraction of the total duration of the storm. Then cumulative rainfall depths in each 5% interval of the storm duration, which do not correspond with the normalized 10-min intervals, are assigned using a linear interpolation of the cumulative 10-min rainfall amounts. Subsequently, each storm is assigned to a specific quartile group, depending on which quarter of the storm has the highest rainfall depth, where storms with equal rainfall amounts in different quarters are not further considered. Because of the assumption of stationarity, the further analysis is based on a seasonal division of storms: winter is defined as December, January and February. March, April and May make up the spring season. June, July and August are then considered as the summer months, while September, October and November are assigned to autumn. Eventually, this results in 1777 winter, 1652 spring, 1647 summer and 1697 autumn

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storms (Table 1).

2.2 Copulas and secondary return periods

In order to assign a return period to each storm in the data set, bivariate copulas and secondary return periods are used (Salvadori et al., 2007; Salvadori and De Michele, 2004; Salvadori, 2004). This means that a storm is described by two variables, which can be dependent, and that a copula is used to construct their bivariate cumulative distribution function, which on its turn is used to calculate specific probabilities of occurrence of each storm. Section 2.2.1 shortly explains the concepts of a copula and the secondary return period. Section 2.2.2 provides some reflections on which couple of storm variables is best used in the present context, whereas Sect. 2.2.3 illustrates the impact of the quality of the copula fit on the interpretation of the secondary return period.

2.2.1 Concepts

A 2-copula C models the dependence structure between two random variables X and Y , which can in the present context be thought of as the total storm depth D , the mean storm intensity I or the storm duration W . It is a function that couples the marginal cumulative distribution functions (CDFs) $F_X(x)$ and $F_Y(y)$ in order to construct the bivariate CDF $F_{X,Y}(X,Y)$, as expressed by the theorem of Sklar (1959):

$$P(X \leq x, Y \leq y) = F_{X,Y}(x,y) = C(F_X(x), F_Y(y)) = C_{UV}(u,v) \quad (1)$$

A 2-copula is thus a bivariate cumulative distribution function with uniform marginals U and V on the unit interval. One can also determine U and V non-parametrically as the normalized ranks (Genest and Favre, 2007). With the use of the inverse marginal CDFs the corresponding x and y for specific values u and v can be calculated: $x = F_X^{-1}(u)$ and $y = F_Y^{-1}(v)$.

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In order to come to the definition of the secondary return period, let us consider a storm for which either X or Y (or both) exceed a respective threshold x and y . This is called the OR-case: $\{X > x \text{ or } Y > y\}$ (Salvadori et al., 2007). In a marginal-free context this event is given as $\{U > u \text{ or } V > v\}$. The probability of occurrence of a storm in the

5 OR-case can then be calculated as follows:

$$\mathbb{P}(F_X(x) > u, F_Y(y) > v) = 1 - C(u, v) \quad (2)$$

With the knowledge of the mean storm interarrival time ω_T , the so-called primary return period in the OR-case T_{OR} can then be calculated:

$$T_{OR} = \frac{\omega_T}{1 - C_{UV}(u, v)} = \frac{\omega_T}{1 - t} \quad (3)$$

10 It should be clear that different combinations of u and v can result in the same T_{OR} , as long as they have the same probability t .

Eventually, the secondary return period was proposed as being very useful for design purposes (Salvadori and De Michele, 2004; Salvadori, 2004; Salvadori et al., 2007). Unfortunately, this type of return period did not yet find its way to engineering applica-

15 In engineering applications, one usually chooses a design storm with a certain (primary) return period for which the design should hold. Consider now the storms in the OR-case. By fixing a certain design return period T_{OR}^* , a certain level t^* of the copula is fixed. In Fig. 1 this is indicated with the thick contour line (for $t=0.4$). A storm that lies on this curve has a return period T_{OR}^* and is called a critical storm (Salvadori et al., 2007). In Fig. 1 S^* is such a critical storm and is defined by the critical thresholds u^* and v^* . A more extreme storm with a higher return period, and thus on a higher contour line, is called a super-critical storm, e.g. S_1^+ and S_2^+ . On the other hand, the storms S_1^- and S_2^- have lower return periods and are called sub-critical storms. The
20 secondary return period is now defined as the average time between the occurrence
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of two super-critical storms and is expressed as follows:

$$T_{\text{SEC}} = \frac{\omega_T}{1 - K_C(t^*)} = \frac{\omega_T}{\overline{K_C(t^*)}} \quad (4)$$

The function K_C is the distribution function of the random variable $Z=C(U,V)$, i.e. $K_C(z)=\mathbb{P}\{Z \leq z\}$. For Archimedean copulas this function can easily be calculated:

$$K_C(t) = t - \frac{\varphi(t)}{\varphi'(t^+)} \quad \text{with } 0 < t \leq 1 \quad (5)$$

where $\varphi'(t^+)$ is the right derivative of the additive generator φ (Nelsen, 2006).

Similar to the equation used for calculating the primary return period (Eq. 3), the denominator in Eq. (4) expresses a probability, as $\overline{K_C(t^*)}$ can be interpreted as the probability that a super-critical storm will occur at any realisation of a storm (Salvadori et al., 2007). This probability mass is given in dark grey in Fig. 1a.

In the calculation of the primary return period in the OR-case, one uses the probability that X or/and Y will exceed a respective threshold x and y . This probability can be expressed as $1 - C_{UV}(u, v)$ (see Eq. 3). However, this probability is not the same as the probability of the occurrence of a super-critical storm that is used for the calculation of the secondary return period, i.e. $1 - K_C(t)$. Figure 1b gives the area in dark grey on which the probability mass, i.e. $1 - C(u^*, v^*)$, is calculated. The primary return period T_{OR} will then be the average time between the occurrence of two successive storms in this region, which is defined by the critical thresholds u^* and v^* . It is obvious that the probability mass corresponding to the dark grey area in Fig. 1a is smaller than the probability mass of the dark grey area in Fig. 1b, for the same critical thresholds. In practice, it is advised to use this probability of super-critical events, as these are in fact dangerous for the design, and hence the secondary return period is a more realistic concept. Note that the function K_C has recently been applied in the work of Kao and Govindaraju (2010) as it is a compelling univariate summary of multivariate information.

An additional comment should be made with regard to the seasonal analysis as carried out in this paper. To calculate the return period (primary and secondary) of

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e.g. summer storms one should incorporate the probability of occurrence of a summer storm. This probability can easily be calculated by dividing the number of summer storms by the total number of storms (see Table 1, i.e. $1647/6773=0.24$). For winter, spring and autumn storms this is 0.26, 0.24 and 0.25, respectively. Intuitively, one should expect a probability of 0.25 for each season in a climate without dry and wet regimes. When a different copula is fitted for each season, the probability of occurrence of an extreme event given by the denominators in Eqs. (3) and (4) should thus be multiplied by the probability of occurrence of a storm in the considered season. The mean interarrival time is that of the storms in the considered season. The general equation for calculating a seasonal return period T_s is then:

$$T_s = \frac{\omega_{T,s}}{\mathbb{P}_{\text{seasonal storm}} \cdot \mathbb{P}_{\text{survival}}} \quad (6)$$

where $\omega_{T,s}$ is the mean interarrival time of the storms in the specific season, $\mathbb{P}_{\text{seasonal storm}}$ the probability of occurrence of a storm in that season and $\mathbb{P}_{\text{survival}}$ the survival probability as given by the denominators of Eqs. (3) and (4).

On the contrary, when the probability of occurrence of a storm in a specific season would not be taken into account, the length of the data set should be considered to be $105/4=26.25$ years, which of course would influence the further interpretation of the results (i.e., the most extreme summer storm within the 105 year series would be assigned a return period of 26.25 year instead of 105 year).

2.2.2 Choice of the couple to fit a copula

To calculate the primary and secondary return periods of each storm, a copula should be fitted to the dependence structure between two rainfall characteristics on a seasonal basis. Three different couples of storm variables can be used: (I, W) , (W, D) and (I, D) . A way to visualize this dependence structure is by making a normalized rank scatter plot, which is in fact the support of the empirical copula (Genest and Favre, 2007). Figure 2 shows these plots for the three couples of summer storm variables. As the

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secondary return period focuses on storms in the upper-right quadrant of the copula, it only makes sense to consider two random variables that are positively associated. Therefore, it would be an irrational choice to consider the couple (I, W) for the further analysis.

In what follows, the couple (W, D) will be considered for several reasons. Firstly, for (W, D) more storms are located in the upper-right quadrant compared to the other couples, which will contribute to the reliability of the further analysis. Secondly, it still allows for the calculation of I and resembles the approach of traditional frequency analyses where the distribution of rainfall amounts for different aggregation levels is considered (Willems, 2000). Thirdly, no problems with asymmetrical empirical copulas occur for this couple (Vandenberghe et al., 2010a).

An A12 copula (Vandenberghe et al., 2010a,b; Nelsen, 2006) is fitted to (W, D) for each season separately, resulting in four parameters. Table 2 gives more detailed information on these fits which are evaluated in the same way as done by Vandenberghe et al. (2010a). The performance of the test statistics S_n and T_n is studied by Genest et al. (2009) (therein denoted by $S_n^{(K)}$ and $T_n^{(K)}$). The S_n statistic is considered to be very powerful, especially in the case of Archimedean copulas, such as the A12 copula family. It should be noted that the reported p-values of the S_n statistics indicate that the null hypothesis, which states that the fitted A12 copula is an adequate model for the data, should be rejected for the winter and autumn storms when considering a significance level of 1% (i.e., the p-values are smaller than 0.01). For the spring and summer storms, this hypothesis cannot be rejected, indicating a significant fit. Because of the large data sample the performed tests are relatively severe. Therefore, the p-values for the spring and summer storms are in fact very promising as they would become even larger when only subsamples of the data were to be considered. The fits of the winter and autumn storms are more doubtful, and their complications will be considered in Sect. 2.2.3.

For the calculation of the mean storm interarrival time ω_T , one needs to consider that the original data set of 105 years is split up into four periods of each 26.25 years

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because of the seasonal division. For a specific season, ω_T is thus calculated as 26.25 years divided by the total number of storms in that season. The primary and secondary return period can then be calculated: ω_T (in years) divided by the product of the probability of occurrence of storm in a specific season and the respective probabilities as given in Fig. 1, which are easily calculated with the fitted copulas (see also Sect. 2.2.3).

It should be noted that the overall distribution function of (W, D) is considered here. It would also be interesting to consider e.g. annual maxima, which can be defined in several ways in a multidimensional setting (Kao and Govindaraju, 2007), in combination with extreme value copulas. In combination with marginal extreme value distributions of these annual maxima, a multivariate extreme value distribution would be obtained (Salvadori et al., 2007). Also, with an appropriate construction of the extreme value copula, the asymmetry of the data could be taken into account (Durante and Salvadori, 2009). This will be considered in future research.

2.2.3 Importance of a good fit

In this section, two different ways of calculating the secondary return period are matched with the intuitive interpretation of the secondary return period. On the one hand, T_{SEC} can be calculated theoretically with Eq. (4). For the A12 copula family, which is an Archimedean copula family, K_C can be calculated as follows:

$$K_C(t) = \frac{t(\theta + 1 - t)}{\theta} \quad (7)$$

Thus for each storm, the corresponding level t can be calculated, after which T_{SEC} can be obtained easily. On the other hand, T_{SEC} can also be calculated empirically. Therefore, the empirical copula C_n is considered, which can be defined as follows (Genest and Favre, 2007):

$$C_n(u, v) = \frac{1}{n} \sum_{k=1}^n \mathbf{1}\left(\frac{R_k^W}{n+1} \leq u, \frac{R_k^D}{n+1} \leq v\right) \quad (8)$$

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where R_k^W and R_k^D are the ranks of W and D , n is the number of data points and $\mathbf{1}(A)$ is the indicator function of the set A . If for all n storms the corresponding empirical copula values $c_i = C_n(u_i, v_i)$, with $i=1, \dots, n$, are now treated as random values of the variable C_n , these values can be ranked and the corresponding empirical CDF can be calculated. This empirical CDF is in fact the empirical function K_{C_n} :

$$K_{C_n}(i) = \frac{R_i^{C_n}}{n+1} \quad (9)$$

where $R_i^{C_n}$ is the rank of the empirical copula value c_i .

The secondary return period can intuitively be derived as the mean interarrival time of super-critical storms. For a specific season, the empirical copula is constructed. The storm with the largest empirical copula value (the highest point in a 3-D-representation of the empirical copula) is thus the most extreme storm in the considered season out of a data set of 105 years. Subsequently, its intuitively derived return period is thus 105 years. For the second highest point in the empirical copula, the intuitively derived secondary return period of the corresponding storm is 52.5 (=105/2) years, and so on.

Figure 3 shows an evaluation considering the winter storms. Note that according to the goodness-of-fit test based on S_n in Sect. 2.2.2, the fitted A12 copula was rejected for the winter storms. The upper-left panel shows the empirical copula C_n . The upper-right panel shows a good visual correspondence between the theoretical function K_C and the empirical function K_{C_n} . The lower-left and lower-right panel illustrate the correspondence between the intuitively derived secondary return period in abscis and, respectively, the theoretical and empirical secondary return period in ordinate, plotted in a double logarithmic scale. The full line corresponds with the 1:1 line. It is clear that the theoretical T_{SEC} underestimates the intuitively derived return period, whereas the empirical T_{SEC} almost perfectly matches it. This points out that one should always be very cautious when interpreting theoretically calculated secondary return periods: very small shortcomings in the fitted copula (which may e.g. not accurately enough model the tail dependence) can already induce large deviations from what would intuitively

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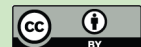
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be expected. In the case of summer storms, for which the fitted A12 copula was not rejected, a much better correspondence between the intuitively derived, the empirical and the theoretical return period exists (not shown here). More research on this topic is certainly recommended, but is beyond the scope of setting the methodology for generating design storms as presented in this paper.

2.3 Marginal distribution functions

To be able to perform the transformation from U and V to W and D , the marginal cumulative distribution functions of W and D need to be known. For the further analysis in this paper, a kernel smoothed version of the empirical cumulative distribution functions will be used for this purpose (provided by the Matlab distribution fitting toolbox). As no extrapolations of W and D out of the available data range will be made throughout this paper, these non-parametrical CDFs provide sufficient information. When extrapolations would be needed, marginal distribution functions that are able to accurately model the tail behaviour of W and D should be used instead.

3 Analysis of Huff curves

Each storm in the time series is classified as a first, second, third or fourth quartile storm, based on the occurrence of the largest rainfall amount in, respectively the first ([0,0.25]), second ([0.25,0.50]), third ([0.50,0.75]) or fourth ([0.75,0.5]) quarter of the total storm duration (see also Sect. 2.1). If such classification cannot be made (e.g. a storm shorter than four 10-min intervals) or the maximum is observed in two or more quartiles, then the storm is removed from further analyses. The construction of Huff curves is then based on the distribution of normalized cumulative rainfall amounts in 5% time intervals of the normalized storm duration. Here, the 10%, 50% and 90% percentile curves are analyzed, considering storms of different quartile groups and with specific secondary return periods.

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Figure 4 shows different Huff curves which are constructed considering all storms in a specific season and quartile group, regardless of their return period. The number of storms considered is given in Table 1.

3.1 Independence of return periods

In order to study the influence of the extremity of a storm on its internal storm structure, Huff curves can be constructed considering only storms having a return period larger than a specific threshold. To obtain reliable Huff curves a sufficient number of storms is needed. Therefore, these thresholds on the secondary return period should not be too large, as most secondary return periods are small (see Fig. 3). Figure 5 shows Huff curves for third quartile storms in summer, with thresholds on the secondary return period of 0.04, 0.08, 0.12, 0.16, 0.20 and 0.24 year. Note that these thresholds are not extreme, however, 68% of all 3rd quartile summer storms have a secondary return period smaller than 0.24 year (88 days). For these thresholds, respectively 299, 259, 185, 147, 117 and 97 storms are considered. As the percentile curves are very similar, this might indicate the independence of the internal storm structure and the extremity of a storm.

As Huff curves are constructed based on empirical distribution functions of the normalized cumulative storm depth at a specific percentage of the total storm duration, from which the 10, 50 and 90% percentiles are calculated, a statistical test could be used to assess whether these distributions differ significantly when different thresholds of the secondary return period are considered. To assess whether the total Huff curves are identical, this statistical test can be performed at several percentages of the total storm duration. For example, for testing the significance of the differences between the six Huff curves considered in Fig. 5 obtained with six different thresholds of T_{SEC} , three different non-parametrical Anderson-Darling six-sample tests are considered to compare the empirical distribution functions of the normalized cumulative storm depth at 25%, 50% and 75% of the total storm duration. This test is also able to account for ties, which is preferable as e.g. the most extreme storms are six times considered for

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the analysis of all six Huff curves. When the three resulting p-values are larger than the significance level of 1%, the null hypothesis of equal Huff curves is not rejected. These tests can then be performed for all configurations of seasons and quartile storms and the results are given in Table 3. The internal storm structure, expressed by Huff curves, of 2nd, 3rd and 4th quartile storms on the one hand are not influenced by the extremity of the storms in winter, spring, summer and summer. On the other hand, 1st quartile storms seem to be influenced. When the storms are considered, regardless of their season, significant differences are present for all quartile storms.

It should be noted that the comparison as proposed here is somewhat subjective and could have a different outcome using other thresholds of the return period (resulting in different sample sizes) and other percentages of the total storm duration at which the empirical distributions are compared (i.e., 25%, 50% and 75%). Nevertheless, the independence between the return period of a storm and its internal storm structure is assumed for the further analysis in this study in which storms will be treated seasonally.

3.2 Random generation of the internal storm structure

In order to obtain a random design storm generator, an algorithm for a random generation of a cumulative internal storm structure is developed. In first instance, the cumulative storm depths at the 25%, 50% and 75% of the total storm duration are randomly generated, constrained by the fact that these cumulative storm depths should lie between the 10% and 90% percentile Huff curve and that the cumulative storm depths may not decrease in time. Also, to assure that the design storm will respect the desired quartile, the maximum increase in cumulative storm depth should occur in that chosen quartile. Once the cumulative storm depths are chosen for each quartile, the rainfall in each quartile is further refined to each 5% time interval, based on the same Huff curves. Therefore, a random generator selects cumulative rainfall depths that fall within the 10% to 90% percentile curves, assuring that the total preset cumulative rainfall depth during the chosen quartile, as determined before, is obtained. Again, the algorithm respects the non-decreasing nature of the cumulative rainfall depth in time.

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Figure 7 shows the outcome of the random generation of such a cumulative internal storm structure, together with the 10% and 90% percentile curves which serve as boundaries in the random generation.

4 Practical use of the random design storm generator

4.1 Simulation of one design storm

The developed algorithm for the generation of an internal storm structure and the concept of the copula-based secondary return period can now be used to generate design storms. Firstly, a secondary return period should be defined. With this return period the corresponding copula level t can be defined. Then, a random couple (u, v) can be selected having the predefined probability of occurrence, i.e. on the t -contour line of the copula. With the use of the inverse of the marginal cumulative distribution functions, (u, v) is then transformed to values for, respectively the storm duration W and the total storm depth D . Then a random dimensionless internal storm structure is generated based on the Huff curves, which is superimposed on W and D .

For example, a 2nd quartile storm in winter with a secondary return period of 0.4 year corresponds to a copula level of 0.7618 and a random couple $(u, v) = (0.8439, 0.8047)$. Then, non-parametrical distribution functions are fitted to W and D considering all winter storms (see Sect. 2.3), regardless of their return period. By using the inverse CDFs, the couple (u, v) results in $W = 87.4$ h and $D = 18.6$ mm. Imposing a randomly generated dimensionless internal storm structure on these values results in the design storm given in Fig. 8.

4.2 Ensemble generation of storms: a practical example

This section explains one possible way in which the stochastic design storm generator could be used in practice.

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In hydraulic design studies, one often uses a hydrological model to generate a discharge input for a hydraulic model based on a point rainfall series. Very often, only one extreme storm event is used because of computational reasons. This storm event is most likely a historical storm that caused problems within the river system. Through a simulation with a hydrological model, a discharge event corresponding to this historical storm can be obtained. However, there is no information on the uncertainty of this simulated discharge. When several statistically equal extreme storm events could be used, an ensemble of hydrological discharges would be generated, yielding a distribution of the simulated discharges at a specific point of interest in the catchment under study. In this way, one could design a hydraulic structure in such way that it has only 1% of failure for storms with similar extreme statistics as the specific historical storm event that caused problems in the past.

The usefulness of the ensemble generation of storm events is demonstrated here at the level of the hydrological model. The probability distributed moisture (PDM) model (Moore, 2007) is considered, as it is a rainfall runoff model which is widely used in Flemish water management practices (Ferket et al., 2010; Cabus, 2008). The model is used with the calibrated parameters for the catchment of the Demer river (area: 96.64 km², Belgium). First of all, a specific storm is selected from the historical data set. The storm starting on the 21 August 1908, more specifically a 2nd quartile summer storm, is chosen and has a secondary return period of 2.79 year. Based on this storm, several statistically identical storms can be generated with the method as described above. A number of 10 000 storms is taken for the ensemble. To be sure that the antecedent soil moisture conditions of the catchment are the same for each storm of the ensemble, the same number of preceding historical storms, i.e. the preceding 100 days, is used in the rainfall runoff simulations. Figure 9 shows the series of rainfall used.

Subsequently, this series forces the PDM model yielding a discharge series from which the last discharge event corresponding to the selected historical storm is selected (indicated in black in Fig. 9). For this discharge event, the maximum peak dis-

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charge Q_{\max} and its relative timing t_{\max} (time to peak divided by total event time) are then calculated: $7.9 \text{ m}^3/\text{s}$ at 36.8% of the total event duration. However, it would be interesting to know what the distributions of Q_{\max} and t_{\max} look like, in order to obtain information on their uncertainty. Therefore, the PDM model is re-run 10 000 times with the rainfall series of Fig. 9 as input in which the historical storm considered is replaced by a randomly generated 2nd quartile summer storm having the same secondary return period. Again, the discharge event corresponding to the design storm is selected and Q_{\max} and t_{\max} are calculated.

Figure 10 shows the resulting distributions of Q_{\max} and t_{\max} , which give an indication of the uncertainty of the discharge and could provide valuable information for a further hydraulic study. The peak discharge generated by the historical storm is already in the upper-tail of the distribution, which has a non-Gaussian form. The distribution function of t_{\max} is most dense in the interval [25%, 50%] and no peak discharge occurs in the first quarter of the discharge event. This is of course due to the fact that a 2nd quartile storm is considered. Nevertheless, some storms generate a peak discharge more towards the end of the discharge event. This results from the fact that, depending upon the properties of the catchment, the discharge does not behave linear with respect to the rainfall (see a discussion in Willems, 2000). Because of this non-linearity of the system, discharge will not have the same frequency of occurrence as the rainfall event. It should thus be noted that it would make no sense to perform a frequency analysis of the discharge and define a return period of a specific discharge event and then to generate storms with the same return period to use this information in a design study.

The above only concerns the hydrological part of a design study. To come to an eventual design of hydraulic structures, the ensemble of the 10 000 hydrological discharge time series should be routed through a hydraulic model. This allows then for an evaluation of the distribution of hydraulic discharges or water levels at a specific hydraulic structure. The latter could then be designed having a predefined probability of failure for a specific historical storm event.

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5 Conclusions

This paper demonstrated that by combining the copula-based concept of a secondary return period together with a random internal storm structure generation based on Huff curves, a fairly simple stochastic design storm generator can be constructed. Storms were selected from the 105 year 10 min rainfall time series at Uccle based on a minimum dry period criterion of 24 h between two storms. Although this independence criterion is based on the assumption that storms arrive according to a Poisson process, one could select another criterion which, for instance, could be based on the concentration time of the watershed under study. Based on a seasonal copula-based frequency analysis, each storm, defined in terms of its storm duration and total depth, was assigned a secondary return period. Some remarks were also given on which couple of storm variables is of highest interest, both from a practical as well as a theoretical point of view. It was also shown that the choice of the copula and its goodness-of-fit influence the calculation of the return period. Eventually, for a chosen season and for a specific return period, the fitted copulas allowed for generating several storms in terms of their storm duration and depth, all having the same secondary return period and belonging to the same season and quartile group. After the underpinning of the assumption of independence between the internal storm structure and the return period, an algorithm to randomly generate such storm structure was proposed. The proposed methodology was then put into the context of hydrological design. An ensemble generation of statistically identical design storms, with respect to the return period and the internal storm structure, in combination with a hydrological rainfall-runoff model showed the usefulness of the proposed generator in obtaining information on the distribution of peak discharge and its relative timing of specific historical storm events. These distributions could provide valuable information on uncertainty in design studies.

The main aim of this paper was to provide a methodology for a copula-based design storm generator and to illustrate its potential for applied hydrological research in a comprehensible way. Therefore, less attention was paid to theoretical issues and con-

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straints. Nevertheless, the fitting of copulas is a constantly evolving topic and it would also be possible to address asymmetrical or/and extreme value copulas for capturing the dependence between storm variables. The use of only extreme storms instead of all storms would also affect the interpretation of the return period and would further limit the number of available storms for the analysis of the internal storm structure.

The practical example as proposed concerns only one possible application. A more detailed analysis of this concept in several different hydrological and hydraulic settings is preferable. For example, the advantages and disadvantages of the proposed design storm generator compared to the composite storm approach of Vaes (1999) could be evaluated in the design of urban drainage systems.

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Table 1. Number of storms, considering different seasons and quartile-groups.

Season	Quartile group				All
	1st	2nd	3rd	4th	
Year	2662	1397	1237	1477	6773
Winter	664	335	324	454	1777
Spring	659	356	307	330	1652
Summer	679	327	299	342	1647
Autumn	660	379	307	351	1697



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Table 2. Kendall's tau τ_K and the estimated A12 copula parameter θ with 95% confidence bounds (lower bound LB and upper bound UB) and corresponding S_n and T_n goodness-of-fit measures with their p-values for the storms per season.

	Winter	Spring	Summer	Autumn
τ_K	0.6420	0.6068	0.5695	0.6252
θ	1.8622	1.6953	1.5485	1.7786
LB	1.7955	1.6309	1.4767	1.7036
UB	1.9289	1.7597	1.6202	1.8536
RMSE	0.0055	0.0043	0.0044	0.0064
S_n	0.1453	0.0842	0.0907	0.2719
$p(S_n)$	0.0019	0.0640	0.0648	0.0000
T_n	0.7834	0.7885	0.8989	1.0088
$p(T_n)$	0.0461	0.0543	0.0192	0.0019

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Table 3. Statistical comparison of Huff curves for different thresholds of T_{SEC} (0.04, 0.08, 0.12, 0.16, 0.20 and 0.24 year) and different seasons. The p-values for the different non-parametrical Anderson-Darling 6-sample tests are given. Significant differences of Huff curves at a significance level of 1% are indicated in bold.

	1st quartile			2nd quartile			3rd quartile			4th quartile		
	Percentage of storm duration									25%	50%	75%
	25%	50%	75%	25%	50%	75%	25%	50%	75%			
Year	0.00	0.00	0.00	0.00	0.00	0.48	0.68	0.00	0.48	0.34	0.00	0.00
Winter	0.00	0.02	0.74	0.07	0.83	0.97	0.83	0.15	0.87	0.89	0.30	0.03
Spring	0.00	0.00	0.93	0.68	0.55	0.93	0.98	0.03	0.93	0.97	0.11	0.22
Summer	0.00	0.00	0.07	0.10	0.63	0.90	0.91	0.85	0.97	0.92	0.34	0.27
Autumn	0.00	0.00	0.24	0.28	0.63	0.91	0.94	0.01	0.92	0.68	0.34	0.08

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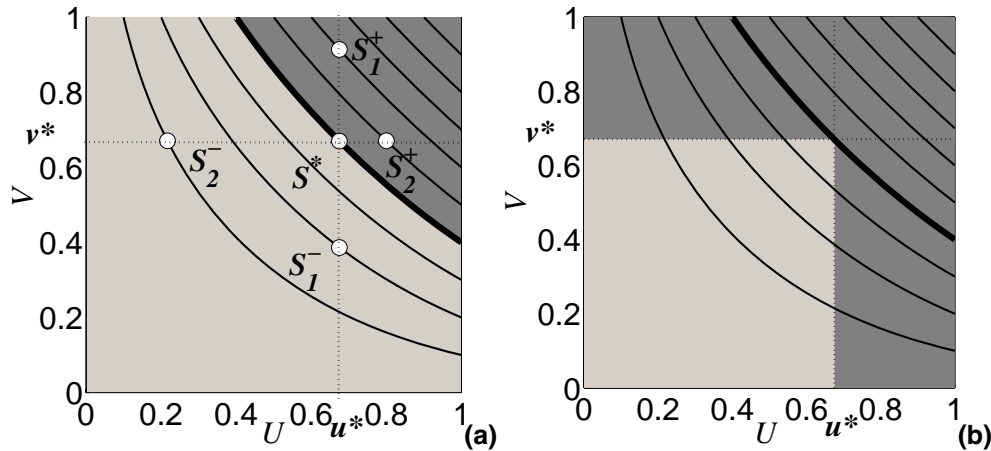


Fig. 1. Illustration of sub-, super- and critical storms **(a)**. Difference in probability used for secondary and primary return periods (dark gray area **(a)** vs. **(b)**). (After Salvadori et al., 2007).

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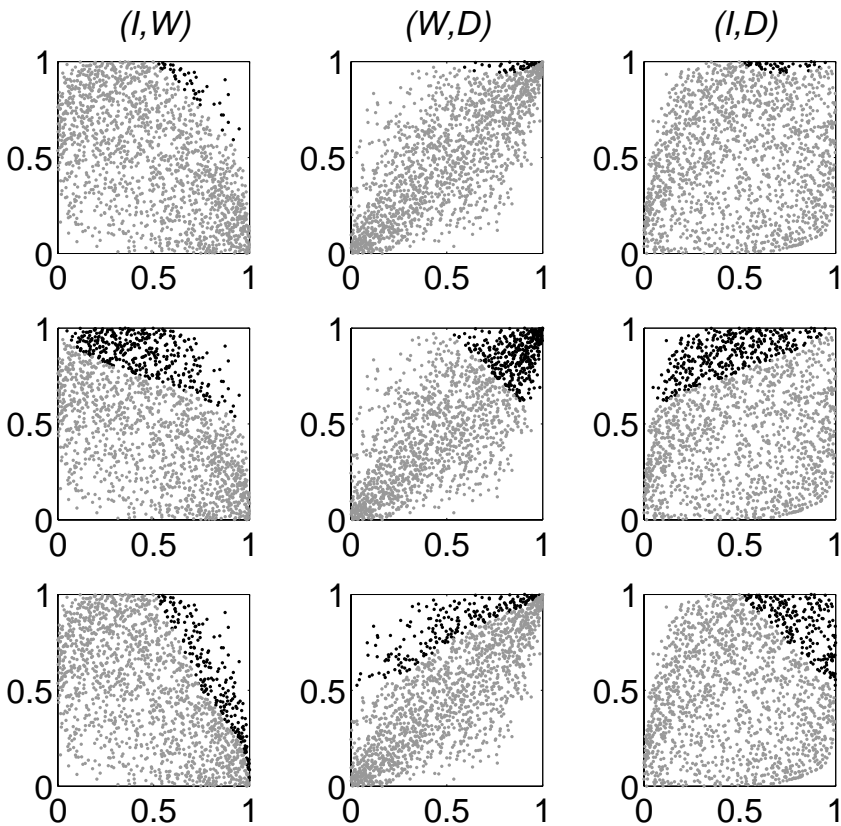


Fig. 2. Normalized rank scatter plots of three different couples of storm variables (per column). Each row shows the same plots, with different storms highlighted within each row. In the first row, the extreme storms with respect to I and W are selected (i.e., storms found in the upper-right corner of the (I,W) plane), and are indicated in black in each of the plots of the first row. For the second and the third row, extreme storms with respect to, respectively (W,D) and (I,D) are selected, and marked in black.

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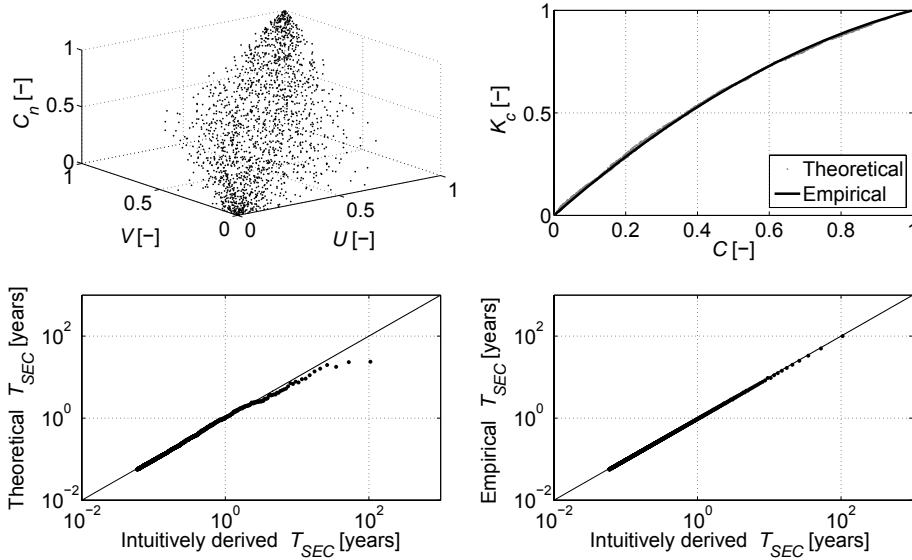


Fig. 3. Importance of a good fit for the interpretation of the secondary return period, considering the winter storms.

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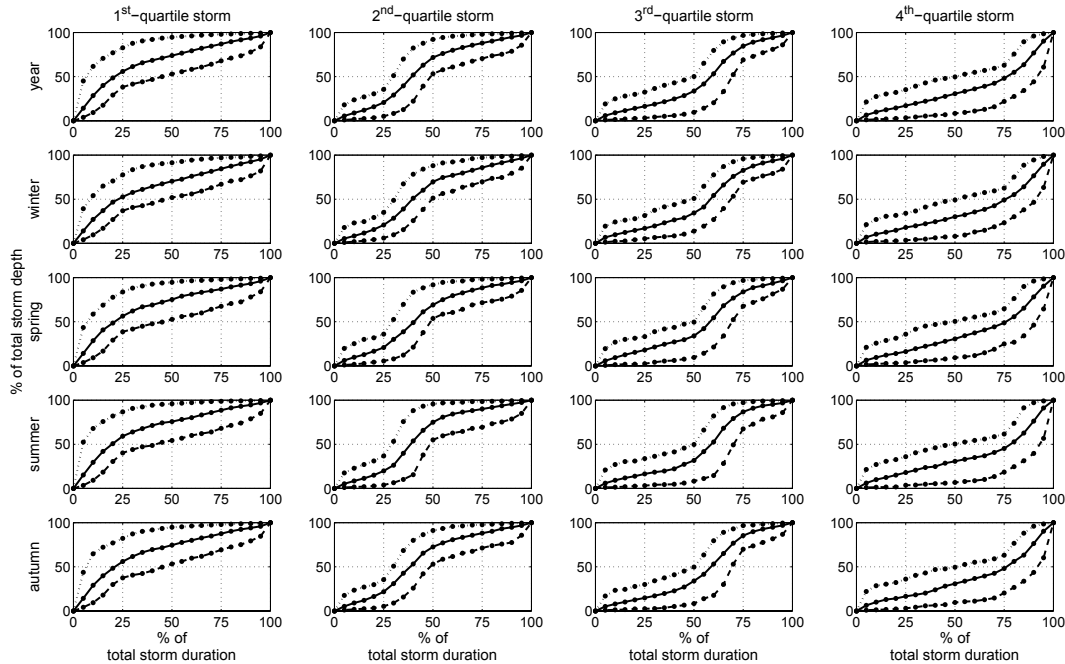


Fig. 4. Huff curves for different quartile storms and different seasons. The 10%, 50% and 90% percentile curves are given by, respectively the dashed, full and dotted line.

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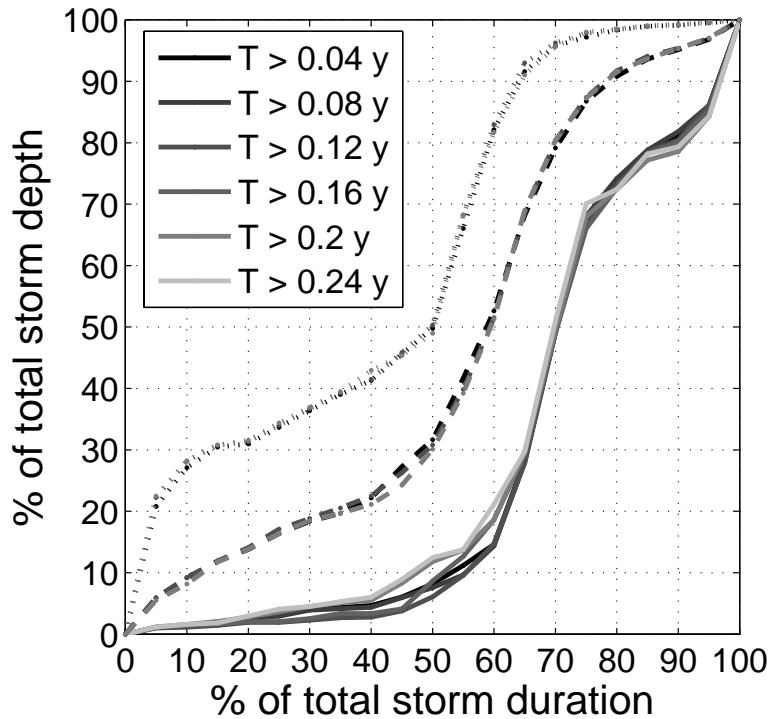


Fig. 5. Comparison of Huff curves, considering 3rd quartile summer storms for different thresholds on the secondary return period T .

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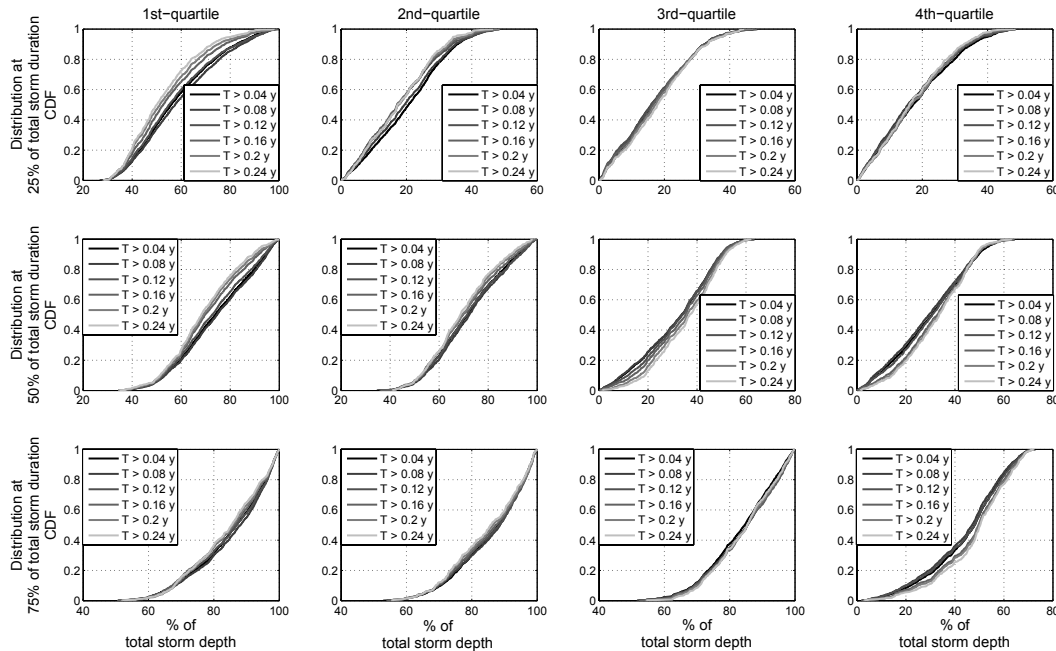


Fig. 6. Comparison of the empirical distribution functions (CDFs) of the percentage of total storm volume (normalized cumulative storm volume) at 25%, 50% and 75% of the total storm duration, considering summer storms for different thresholds on the secondary return period T .

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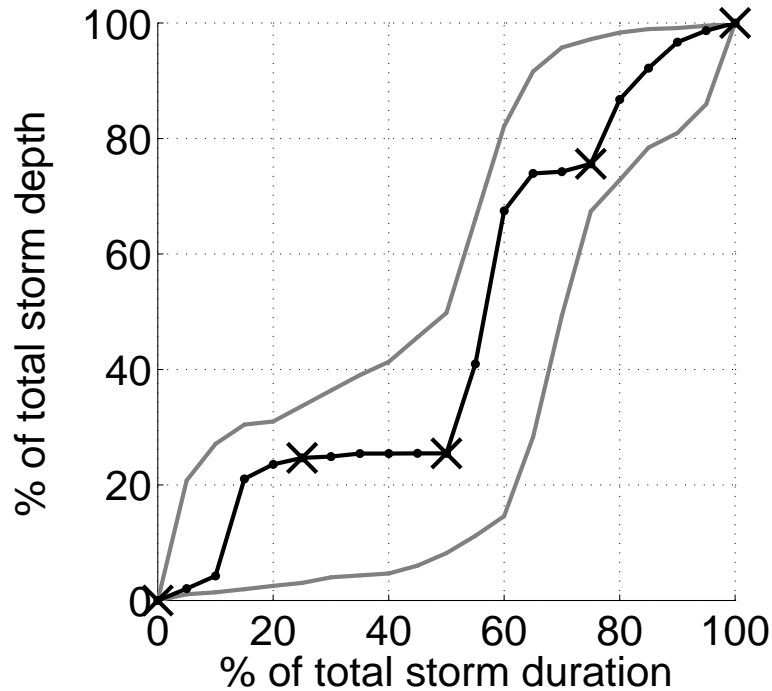


Fig. 7. A cumulative randomly generated storm structure of a third quartile storm in summer. For each 5% time interval, a percentage of the total storm depth is assigned in the range of the 10% and 90% percentiles. The grey lines form the 10% and 90% percentile curves of the Huff curves. The points marked by x are the randomly chosen cumulative storm depths at 25%, 50% and 75% of the storm duration. The black line is the random generation using the 5% interval data.

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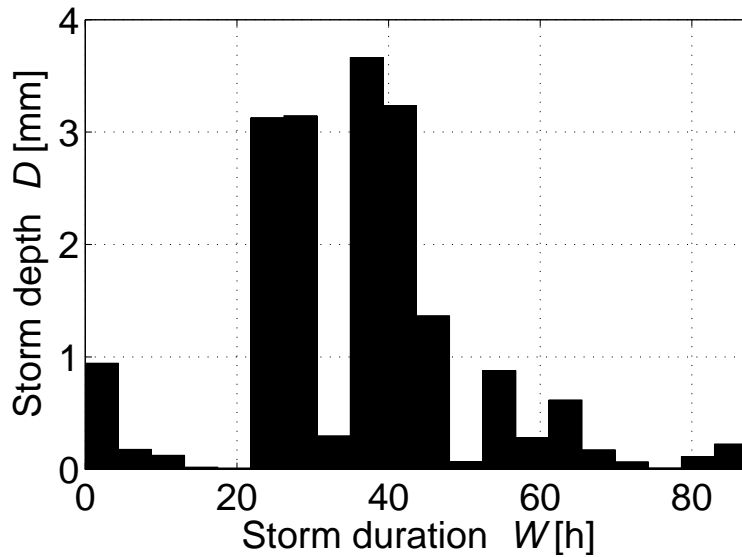


Fig. 8. A 2nd quartile storm in winter with a secondary return period of 0.4 year.

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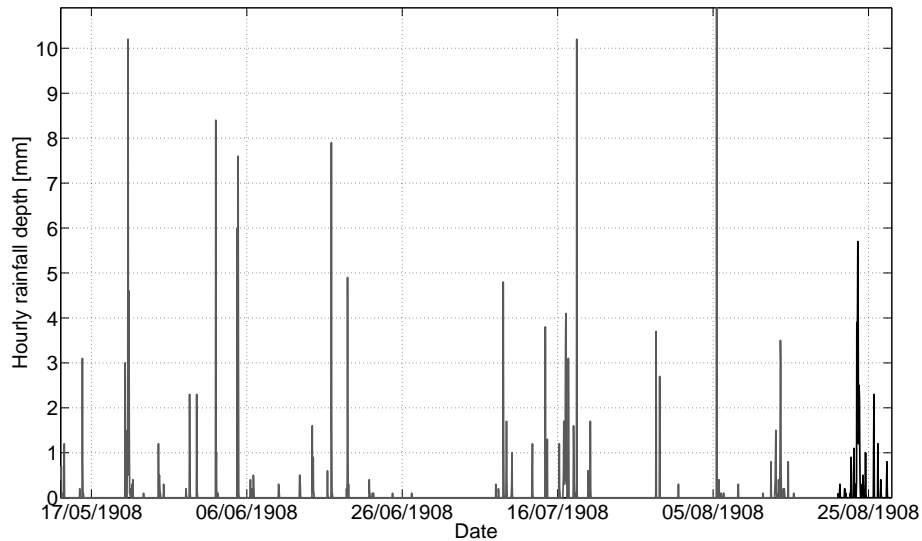


Fig. 9. The rainfall time series used in the rainfall-runoff modelling: the grey storms determine the antecedent soil moisture conditions and the black storm is the historical storm which is replaced by 10 000 randomly generated design storms.

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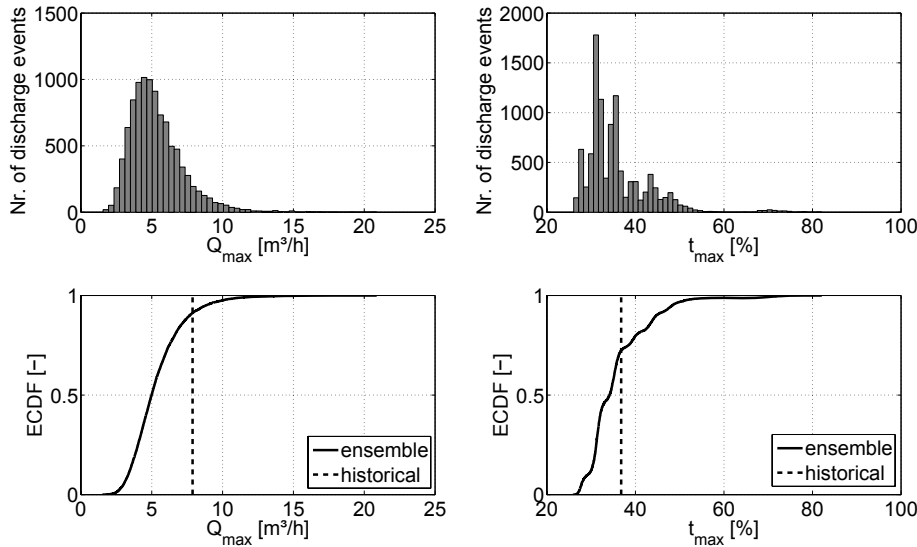


Fig. 10. The ensemble of design storms is able to give an idea of the distribution of the maximum peak discharge and its relative time of occurrence. These properties are also indicated for the historical 2nd-quartile summer historical storm on which the ensemble is based.

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