Complete Multivariate Flood Frequency Analysis, applied to Northern Algeria

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Abstract

Extreme hydrologic events are commonly described by several dependent characteristics, such as duration, volume and peak flow for floods. Traditionally in Algeria and North Africa, flood frequency analysis (FFA) is conducted as a univariate approach focusing separately on each single of flood characteristics. On the other hand, elsewhere, multivariate FFA studies have been conducted focusing on some FFA steps (especially modelling). The current study aims to consider complete multivariate FFA at-site case studies in Northern Algeria using 11 hydrometric stations. It is also among the first studies dealing with multivariate FFA in a complete way by considering all the required steps of the analysis (multivariate outliers detection, multivariate assumptions testing and copula fitting) and on datasets from Algeria. Multivariate stationarity, homogeneity and independence assumptions have been well verified before modelling. The Weibull distribution is mostly selected as margin distribution for the duration, volume and peak flow series. Frank, Clayton and Gumbel copulas are commonly selected to describe the dependence structure on the three flood pairs of variables. These findings should be interesting in water management and flood risk assessment in these regions. Combining these flood characteristics enables the design of more efficient hydraulic structures.

Keywords: Copula; daily flow; flood characteristics; multivariate assumptions; multivariate frequency analysis; Northern Algeria

1. Introduction

Hydrological frequency analysis (HFA) aims to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow et al. 1988 in Rao & Hamed 2000). HFA is mainly composed of the following steps: (a) exploratory analysis and outlier detection; (b) checking the basic assumptions of stationarity, homogeneity and independence; (c) modelling and parameter estimation; (d) risk evaluation and analysis (e.g. Chebana 2012).

Flood events can be described as a multivariate stochastic phenomenon by three main variables, that is it duration (D), volume (V) and peak flow (Qp). Hence, the associated risk analysis should be treated by an effective multivariate probabilistic approach (Reddy & Ganguli 2012). In this context, univariate HFA (based on a single variable) has a number of limitations and drawbacks which leads to considering the multivariate HFA. The latter is the object of a growing number of studies (e.g. Zhang 2005; Grimaldi & Serinaldi 2006b; Kao & Govindaraju 2007; Chebana & Ouarda 2009; Chowdhary 2009; Chebana & Ouarda 2011a, Serinaldi & Kilsby 2013; Requena et al. 2013; Genest & Chebana 2017). The above HFA steps are commonly employed to study flood risk in a univariate setting (e.g. Cunnane 1987 and Rao & Hamed 2000) which is not the case in the multivariate one (see e.g. Chebana et al. 2013).

The copula approach overcomes the restriction of univariate HFA by allowing a combination of different marginal types. It also provides a wider choice of admissible dependence structure as compared to the conventional approach (Chowdhary 2009). The use of copulas in multivariate HFA becomes the appropriate tool to study the dependence structure between the different variables.

67 Hence, several studies were considered copulas in multivariate HFA, e.g. De Michele & Salvadori (2003) identified the relation between intensity and duration of storm rainfall in Italy by using Frank copula. Renard & Lang (2006) suggested applications of Gaussian copula on flood mitigation in France. Grimaldi & Serinaldi (2006a) have proved the adequacy of two copulas (Frank and Gumbel) on the flood characteristics analysed for Kanawha River in West Virginia (USA). Chebana & Ouarda (2007, 2009) presented regional multivariate flood analysis using copula and multivariate L-moments. A Gumbel copula was used by Leonard et al. (2008) to couple the seasonal rainfall maxima marginal distributions on the Murray–Darling Basin, Australia. El Adlouni & Ouarda (2008) proposed the application of copula to analyse the dependence of the water level of Saint-Louis Lake on the maxima flow on the Chateauguay River in Quebec (Canada). Leite Rosa (2011) presented that Frank and Clayton copula fit good in studying a relationship between maximal flow and volume in Portugal. To establish the relation between the different flood characteristics Salarpour et al. (2013) applied the t-copula on the Johor River in Malaysia. A Gumbel copula was selected as the most appropriate model for trivariate frequency analyses of peak discharges, hydrograph volumes and suspended sediment concentrations in Bezak et al. (2014). Drought frequency analysis in Medjerda River basin (Tunisia) was carried using copula in Hamdi et al. (2016) which can be considered as the first multivariate study in North Africa.

85 In Algeria, to our knowledge, there are no published works dealing with multivariate HFA, especially for floods. However, flood frequency analysis (FFA) has always been carried on different approaches involving univariate context, either on flood flows (e.g. Ketrouci & Meddi 2012; Rezak 2014), on maximum daily flow in Boutoutaou et al. 2011, on maximum daily rainfall (e.g. Benhattab et al. 2014; Meddi & Belhadj Bouchaib 2010); on maximum annual by Benameur et al. 2017 under arid climate of Biskra in southern Algeria; and on Intensity-

Duration-Frequency curves (IDF) in order to describe the rainfall threshold generating flood (e.g. Yamani et al. 2016).

Owing to numerous tragic flood events in Algeria (Table 1) a number of 575 projects against flood with a budget of 2 billion Dollars have been launched since 1999, covering 33 Northern provinces over 42. Unfortunately, the desired object is not reached as the floods continue to record serious problems and considerable disasters. Each year, an average of seven to ten large-scale floods is affecting mainly the big cities. A relevant issue has arisen, therefore, looking for new techniques and procedures with better performances to mitigate such hazard event seems a promising solution. In this vision, the present work aims in studying the floods in Northern Algeria within the multivariate framework to provide a blanket solution for flood risk assessment. This study focuses on the regions most affected by repeated floods (as summarized in Table 1). These basins require adequate facilities planning to mitigate flood risk. Multivariate FFA constitutes a powerful tool allowing the dimensioning of suitable installations based on a more accurate flood risk assessment (e.g. Callau Poduje et al. 2014; Balistrocchi et al. 2017; Jiang et al. 2019; Zhou et al. 2019; Liu et al. 2019).

Hence, the objective of this study is to consider the multivariate FFA for Northern Algerian basins based on the most recent techniques with a complete analysis. This work is the first contribution on analysing floods with a multivariate approach considered in Algeria. It is applied to 11 different selected hydrometric stations in Northern Algeria. These data are the subject of the first application on multivariate FFA. On the other hand, the current work is considered as a complete HFA study including, detection of multivariate outliers, multivariate hypothesis testing which are rarely reported combined in the hydrological literature, modelling and risk evaluation. Indeed, Chebana et al. (2013) indicated that ignoring the testing step in multivariate HFA may lead to inaccurate or wrong results and hence to inappropriate decisions regarding, for instance, the design of hydraulic infrastructures.

2. Area and data

The study area covers 11 basins in Northern Algeria investigated to analyse flood (Figure 1). This region extends from the Tunisian border on the East to the Moroccan border on the West with an area of 11400 km^2. It is located between 8° East and 2° West longitudes and 37° and 33° North latitudes. It has an average annual temperature of 17°c, and the average annual rainfall is about 900 mm on the East and 350 mm on the West. The basins selected are the most affected by repeated floods since the last fifty years. Important damages are observed mainly caused by watercourses (wadi) flooding. The average annual hydrological yield can reach 3250 Hm^3 on the extreme East to 5 Hm^3 on the extreme West.

The study area covers 11 basins in Northern Algeria investigated to analyse flood (Figure1). The characteristics of the selected stations are presented in Table 1. Daily average flow is the raw data applying in this study. In some areas, data access is very restricted and hence limits the availability to the daily flow data. The available database from the National Agency of Hydraulic Resources (ANRH) had 30 hydrometric stations. However, after preliminary analysis of this database, we found that the majority of these stations either have short record periods (less than 15 years), or their hydrological regime is disrupted (e.g. by dams), or their series present many gaps. The presence of such anomalies forced us to select only 11 hydrometric stations to conduct the multivariate FFA. To overcome some these limitations, reconstruction of the historical data can be considered for future studies, which may allow extending the FFA to other stations (Grimaldi et al. 2016). In addition, filling the data gaps in a multivariate context using copula is also a promising option (Aissia et al. 2017).

Indeed, the hydrological regime of the studied basins shows that these wadis flow only during the wet season (October to May); while the dry season is marked by the lowest or even zero flows. The dates of the floods show that more than 50% of the analysed floods occur during the winter season (December, January and February), the spring (40 to 20%) then the fall and rarely in the summer (0 to 19%). These observations are valid at hydrometric stations in the east and centre of the country. However, the stations in the far west (Ghazaouet, Sidi Ali Ben Youb and Taria) indicate different behaviour, where autumn and spring dominate in the flood dates. The summer season registers 11 to 26% of the total floods in this region. The transition between the Mediterranean and semi-arid climate create a mixed hydrological regime on the extreme north-western regions (Ghazaouet station). Soultes wadi (Timgad station) is characterised by a complex hydrological regime under a semi-arid climate. A simple hydrological regime dominates the other studied basins (Meddi et al. 2017).

The annual average yields of the studied wadis presented in Table 1 are very low ranging from 2.9 to 304.1 10^6 m^3/year. This is usually in the Algerian context where the flows record the value of zero m^3/s during the dry season (June to September). In Algeria, the hydrological regime of the stream is characterized by temporary flows following the rainfall contributions with the appearance of the systematic seasonal fluctuation of flows. Indeed, the stream flow is very irregular and low flow is insignificant in the dry period, as it is discussed in different previous papers (e.g. Bouanani, 2004; ABH-OCC, 2006; Touazi et al. 2011; Hallouz et al. 2013; Meddi et al. 2017).

Each series of daily flow makes it possible to extract three series of variables (D, V, Qp) characterizing each flood as described below. The missing values in the extracted variables are due to the presence of one or more missing values in the crude database. The Lakhdaria station shows an example with four missing values for each extracted variable. The obtained values are verified with the associated hydrograph while the extracted data series are presented in Appendix A.

3. Methodology

The considered methodology covers all appropriate aspects of multivariate HFA, including data extraction, preliminary analysis, checking assumptions, modelling as well as risk assessment.

Indeed, the selection of flood characteristics is the most important step in this work since all the subsequent results depend on the availability and quality of the input data. It would be more reasonable to separate the fast response from the slow response to estimate adequately the average daily flow (q). However, the dataset obtained from the ANRH presents the average daily flow (q) in m^3/s. This format does not allow separating the fast response from the slow response. The method applied to estimate the flood features is based on a daily average value of flow (q) to construct the yearly hydrograph which corresponds to the hydrological year starting on September 1st of the year (i) and finishing on August 31st of the year (i+1). Then, the associated flood characteristics are extracted. The peak flow (Qp) corresponds to the highest q over the year. The base flow index method has been employed to separate base flow and flood flow (e.g. Yang et al. 2019). In this method, the starting date of the flood coincides with the rise on the annual hydrograph. The ending date refers to the recession curve and the back to the low flow regime. These dates are determined by adjusting the slopes with a linear approximation of the annual hydrograph (e.g. Ben Aissia et al. 2011). Flood duration is the number of days between the start date and the end date of the flood. The volume is calculated by summing the daily flow values recorded during the specified time (here flood duration). The extracted multivariate series (Qp, D, V) is verified year by year for each station.

This data extraction is done similarly to previous studies applied in North America (Canada) by Ben Aissia (2009); Jeong et al. (2013) in Northeastern Canada; Karmakar & Simonovic (2007) in USA; Bačová Mitková & Halmová (2014) in Slovakia; Singh et al. (2015) in India; Hamdi et al. (2016) in Tunisia on droughts.

As a first phase, univariate HFA is carried out on the extracted series for each variable. A descriptive statistical analysis is performed on each of the three flood variables (D, V and Qp); by determining the principal statistical features, such as the mean, the standard deviation, the coefficient of variation (Cv), of skewness (Cs) and kurtosis (Ck). Then, the Pearson correlation coefficient is calculated to identify the correlation between flood variables. The t-test is considered to check the significance of the correlation.

Detection of outliers from the analysed variables is checked. Hunt et al. (1981) defined an *outlier* as "an observation that does not conform to the pattern established by other observations". Rosner test is employed to detect univariate outliers from the analysed series. Rosner's (1983) method assumes that the main body of data is from a normal distribution. Rosner's approach is designed to avoid masking of one outlier by another (in Gilbert 1987).

Testing the basic assumptions on hydrologic data must be verified before starting any HFA. In the univariate framework, Mann-Kendall (Mann 1945; Kendall 1975), Wald-Wolfowitz (1943) and Wilcoxon are respectively selected to test stationarity, independence and homogeneity of hydrological series. These tests are nonparametric and widely applied in univariate HFA (e.g., Bobée & Ashkar 1991; Yue et al. 2002; Kundzewicz et al. 2005 and Khaliq et al. 2009).

The most important step in HFA is a selection of the appropriate distribution model. Identifying the fitted probability distribution allows predicting the probability of exceedance for a specified magnitude (quantile) or the magnitude associated with a specific exceedance probability. Hydrologic literature suggests several methods to estimate the parameters associated with these distributions, i.e., the maximum likelihood method (e.g., NERC 1975; Clarke 1994); method of moments (e.g., Chebana et al. 2010) and L-moment method (e.g., Hosking 1990). The choice of a subset of appropriate distribution is performed by the goodness-of-fit test of Pearson (Chi-square, Chi2), see e.g. Benkhaled et al. 2014 and Benameur et al. 2017. The selection of the best fit distribution for each variable is based on the criteria mainly Akaike and Bayesian information criterion (AIC, BIC) proposed, respectively by Akaike (1974) and Schwartz (1978). These criteria are considered on the above subset of the accepted distribution. The smallest criterion AIC or BIC values identify the best fit distribution (Rao & Hamed 2000).

In the final step, a multivariate HFA is conducted to identify the relationship and dependence between the different characteristics of the flood through the pairs (D, V), (D, Qp) and (Qp, V). Firstly, multivariate outlier detection is carried out using depth-based tests (e.g. Chebana & Ouarda 2011b; Chebana et al. 2017). Multivariate outliers can have negative impacts on the selection of the appropriate distribution as well as on the estimation of the associated parameters (Chebana 2012). Mainly three depth functions are considered to detect multivariate outliers: Mahalanobis, Spatial and Tukey. Then, checking the assumptions in multivariate HFA is an important step in the analysis. Multivariate versions of Mann–Kendall and Spearman tests are applied to check the multivariate trend on the flood pairs (Chebana et al. 2013). Covariance Inversion Test statistic (CIT), Covariance Sum Test statistic (CST), Covariance Eigenvalue Test statistic (CET) for both Mann-Kendall and Spearman tests are analysed at 5% of the significance level. Cramer test, M-test, Wilcox test and Zhang test are selected to check the homogeneity for multivariate series and multivariate copula-based test for serial independence at a significance level of 5%.

In terms of modelling, the dependence structure between two or more random variables is described by using a copula. It is used to join two different marginal distributions in common multivariate distribution. The notion of copula was introduced in Sklar (1959) to decompose a d-dimensional distribution function H into marginal distribution functions $F_1,\ldots, F_d$ and a copula C describing the dependence part of the distribution. A copula is a multivariate cumulative distribution function with univariate uniform margins. Given a random vector $X= (X_1,\ldots, X_d)$ with joint distribution function H and marginal cumulative distribution functions $F_1,\ldots, F_d$. Sklar showed that there always exists a copula C such that, for all $x_1,\ldots,x_d \in R$

$$\Pr (X_1 \leq x_1,\ldots, X_d \leq x_d) = H (x_1,\ldots, x_d) = C \{F_1(x_1),\ldots,F_d(x_d)\} \quad (1)$$

If $F_1,\ldots, F_d$ are continuous, then C is unique.

In this work, five copulas commonly used in hydrology are considered for the multivariate flood analysis namely: Ali-Mikhail-Haq, Clayton, Frank, Gumbel, and Joe (Zhang & Singh 2006; Genest & Chebana 2017). These copulas belong to the Archimedean family. In this work, the copula fitting is based on pseudo-observations in order to avoid parametrically modelling the margins, which is conducted in two steps. Adequate marginal distribution is chosen firstly for each of the studied variables. In the second step, the copula parameter is estimated from the selected copula. This parameter is estimated using the maximum pseudo-likelihood method as the most appropriate method (Kim et al. 2007 and Kojadinovic & Yan 2010). Goodness-of-fit test for copula (Sn and Tn tests) are applied to select potential copula, then among the latter, Akaike information criterion (AIC) is applied to select the most appropriate copula (see Genest & Chebana 2017).

Once the joint distribution is found (including the margins, copula and their parameters), it can be used to calculate multivariate return periods and multivariate quantiles. In multivariate FFA, the return period estimation has an important impact on the designing of the hydraulic structure. Therefore, a given flood event return period may have different occurrence combinations of flood variables (Qp, V, D) and vice versa (Chebana & Ouarda 2011a). Such conditions make the choice of the selected return period an ambiguous and difficult step to establish the joint return period (e.g. Corbella & Stretch 2012). This latter represents, for instance, the event in which x or y or both are exceeded (X > x or Y > y) (e.g. Vittal et al. 2015). Multivariate return period issues have been defined by more authors (see. e.g. Salvadori et al. 2011; Chebana & Ouarda 2011a; Salvadori et al.2013; Requena et al. 2013; Gräler et al. 2013).

Multivariate quantile is presented as a quantile curve describing a specific event for a giving return period. In multivariate HFA, four events are characterized by four quantile curves among many other combinations: simultaneous exceedance $\{X \geq x,\ Y \geq y\}$, exceedance-non-exceedance $\{X \geq x,\ Y \leq y\}$, non-exceedance-exceedance $\{X \leq x,\ Y \geq y\}$ and simultaneous non-exceedance $\{X$

$\le x,\ Y \le y\}$ where the variables X and Y represent the characteristics of a hydrological phenomenon. Therefore, the simultaneous exceedance $\{X \ge x,\ Y \ge y\}$ and simultaneous non-exceedance $\{X \le x,\ Y \le y\}$ would be of interest in studying the hydrological phenomenon. For droughts investigating and on the quantiles evaluation, the event $\{X \le x,\ Y \le y\}$ is considered. However, the event $\{X \ge x,\ Y \ge y\}$ is most important in flood consider and for evaluating a return period (Chebana & Ouarda 2011a).

4. Results

In this section, we present the obtained results by applying the methodology in section 3 on data of section 2.

4.1. Univariate frequency analysis

Descriptive analysis is performed on the verified series and the results are shown in Table 2. It is observed that each station expresses a specific character in describing flood event in each region. V and Qp values are widely different from station to another. However, the mean value of V and Qp are highest in the East region presented by the stations Ain El Assel and Khemakhem, compared to the Central region (El Affroun and Baraki stations) and the West region (Taria and Sidi Ali Ben Youb) with the smallest values. The observed decrease in V and Qp values in East-West orientation can be explained by the natural hydrological regime in Northern Algeria, where the rainfall blade is most important in the East region than the West. Lakhdaria station marks the exception having the maximum V value (340.9 10^6 m^3) and maximum Qp value (1489.5 m^3/s) even though it is located in Central region; because of its large drained area (3620 km^2) and very rough terrain. These features lead to explain that flood at Lakhdaria station is important in term of V and Qp values. While, flood duration is characterized by slight variation, where its maximum values range between 11 and 22 days over the study area. The variability of flood characteristics between the different stations can be explained by the watershed structure, the relief nature, drainage density, soil moisture and the characteristics of the watercourse, or related to the type of flood itself. It is noted that V of the flood follows the same behaviour as D and Qp at the studied stations. This can provide information on the existence of a possible connection between these three variables that may be identified in the multivariate analysis. According to Meddi et al. (2017) in a univariate regional study, Ghazaouet station fits in region II which is characterized by rugged terrain that favours the formation of rapid and catastrophic floods. Timgad station belongs to the third region where the flash floods are dominated importantly on autumn season. The other stations appear in the region I characterized by rugged terrain that is very favourable to flow and the rapid advance of a flood.

The Rosner test identifies the detected values as no outliers for all the stations and all variables (Appendix A). Furthermore, correlation analysis (Table 3) between the three flood characteristics shows a significant correlation between the majorities of the analysed pairs. The T-test indicates a weak correlation between D and Qp. Pearson coefficient expresses a strong correlation (> 0.78) between Qp and V at all the studied stations. This correlation means that flood Qp is positively related to flood V.

The results of checking the basic assumptions using the appropriate tests on all the margins and all stations are summarized in Table 4. We observe that all assumptions can be considered as satisfied for all variables and all stations at the significance level 5%. Except for stationarity (Azzefoun), homogeneity (Azzefoun, Khemakhem and Sidi Ali Ben Youb) and independence at Taria can be accepted at level 1%. This decision is reasonable (see e.g. Benameur et al. 2017), especially when the length dataset is relatively short (25 and 26 years in these cases). According to the Chi-square test of goodness-of-fit and the lowest AIC value, the selected marginal distributions are shown in Table 5. These later allowed the determination of return periods for flood characteristics (Figure 2). Most of the quantiles estimated at 50 or 100 years of return period exceed the maximum values of V and Qp on the analysed series. For instance, the flood of 50 years at Baraki station marks a larger V of 143.7 $10^6 m^3$ than already observed. While the flood of 100 years notes Qp of 930.8 m^3/s higher than the maximum value (876.4 m^3/s). At Ain El Assel, the quantiles calculated of V and Qp for a 100 years return period are smaller than observed in the analysed data. A return period of 100 years of a flood on wadi Mekkera records V of 21.2 $10^6 m^3$ and Qp of 177.6 m^3/s exceeding the maximum observed values. At Timgad station, wadi Soultes revealed that a 50 years return period is characterized by Qp (91.8 m^3/s) and V (10.1 $10^6 m^3$) which are outside the range of observation. Wadi Isser at Lakhdaria station records V exceeding the observed values for a 100 years return period. However, the bicentennial flood notes Qp more than 1489.4 m^3/s.

4.2. Multivariate frequency analysis

Regarding the outliers detected by the depth functions, are mostly retained for all variables. In another case, some values are considered as outliers even are not identified by the depth function, because these values are accepted according to the natural flow regime in these regions and the stream flow characteristics: For instance, the detected outliers are not retained in their totality because their consideration may affect the chronology series length, example with (V, Qp) series for El Affroun station (Figure 2, Appendix C) where five years are not considered (1972, 1974, 1979, 1980, 1983). Sometimes, the identified outliers are replaced by other ones which allowed the best verifying for the assumption tests, example with (D, V) series for Azzefoun station where the values corresponding to the years of 2000, 2003 and 2010 are replaced by those of 1988 and 2006; or because it seems due to an error in curded data. The other stations give similar results (see Figures 1 to 10 in Appendix C). In other cases, the defined outliers are not retained in order to keep a long chronological series (Timgad, Ghazaouet, and Baraki).

Further, the multivariate trend tests of the studied pairs show that all tests accept the no trend assumption for all the stations at level 5%. Except (D, V) and (D, Qp) series for Azzefoun station where CET and CIT (Mann-Kendall) and CET (Spearman) for (D, Qp) and (Qp, V), and for

Taria station where CIT (Mann-Kendall) accept at significance level of 1% (Table 6). For the multivariate serial independence test, the obtained results (Table 7) indicate that all pairs for all station are independent. Also, the multivariate homogeneity tests express that all studied series for all the stations are homogeneous (Table 7). Except, El Affroun (D, V) and Sidi Ali Ben Youb (D, Qp) where M-test is accepted at the significance level of 1%, and C-test at Sidi Ali Ben Youb for the pair (D, V). These satisfied finding made it possible to run the final step of the multivariate analysis: copula fitting.

Copula Fitting and Parameter Estimation

The selected as best fit copulas (corresponding to the p-value of the Sn test and Tn test and the smallest AIC value) for flood characteristics pairs are indicated in Table 8. Frank is the predominant copula (11 over 33 cases) followed by Clayton (9 over 33) and Gumbel (8 over 33). Each pair of flood characteristics is described by the appropriate copula which leads to estimate the corresponding quantiles. The occurrence of a flood event is obtained from the contour line of pairs according to the selected copula. Figure 4 gives a graphic presentation of quantiles curves corresponding to the event $X \geq x \cap Y \geq y$. Exceeding probability is applied to calculate the corresponding return period (i.e. 2, 5, 10, 20 and 50 years for all the studied station). The different shapes of the quantile curves from pairs and stations are mainly because of the different copulas and strength of the dependence For instance, the curves lines of (D, Qp) at the stations of Timgad and Taria are likely to be linear since the dependence is very low. The curves lines at Ammi Moussa station (Figures 4-a1, 4-a2, 4-a3) of (D, V) and (D, Qp) pairs are condensed for return period superior than 2 years for flood that last between 10 to 16 days, while the corresponded V and Qp have spaced curves which indicates that a single duration flood could have numerous joint V or Qp value. In studying flood structure dependence, it is important to care an interest considering to (D, V) and (D, Qp) pairs where it is most significant to identify a flood which happens with a short D and the highest Qp or highest V because it does not have the same impact, especially on hydraulic structures (e.g. dams, bridges). Therefore, (Qp, V) pair can describe well a flood at stations presented a similar structure.

Quantile curves of the pairs (D, V) and (D, Qp) present the same shape of contour lines at the same station for all the analysed stations. For instance, the curves lines of the flood return period of 5 to 50 years at Khemakhem station show that flood duration ranges between 11 to 18 days. The experimental data are distributed between the contour line of the selected return periods and mostly condensed for the period return inferior to five years. The figures (4-k1, 4-k2) on Wadi El Harrach show that the experimental data present flood with a duration from 10 to 18 days. For the figures (4-g1, 4-g2) for wadi Isser, the maximum V and Qp are recorded for the medium duration (8 to 9 days) for the short return period (2 and 5 years) against the long duration (>17 days) for 50 years return period. These observations justify the interest to give in studying flood at Lakhdaria station based on a combination between D and V because the rough relief favours a large V over a small period of time. The curves lines at El Affroun station (figures 4-c1, 4-c2) indicate that the flood with a duration between 14 to 16 generates a large V and important Qp, which is recorded at the short return period (2 to 5 years).

Dependence structure designed for the given return period (2 to 50 years) by the quantiles curves of the pair (Qp, V) on the analysed flood show similarity in the joint structure. The contour lines have a shape of a right angle since the correlation is greater than 0.9, which present the linear form of the dependence structure of the analysed data. For instance, figure 4-b3 indicates that the analysed data are condensed in the short return period (inferior de 5 years). However, the maximum value of V and Qp have a joint return period of 20 years, which is really important in designing the hydraulic development in this basin. Ain El Assel (figure 4-e3) shows that most flood events have a return period between two to five years. This indicates the interest to give in planning water management at a short return period in this watershed. The figure 4-g3 at Lakhdaria notes that the analysed floods are mostly dominant for the short return period.

The similar joint structure of (Qp, V) is identified on the other stations, which indicate the necessity to focus on the short and medium return period and the behaviour of this couple, in identifying the values of V and Qp in water structure designing and a flood mitigation programs. According to the analysed pairs, these stations show a slight difference in behaviour from the Eastern to the Western regions in responding to flood event. These spatial trends may be explained by the basin structure and nature, or the length of the corresponding wadi, or in the human activities in using the soil surface.

5. Discussion

The main purpose of this study is to give an appropriate method to analyse flood in the regions affected by repeated flood in northern Algeria. For that, complete multivariate frequency analysis on the flood characteristics (all steps not only modelling) is applied. Eleven basins are selected according to the availability of data (time series length and continued observation). It is noticed that these watersheds present different physiographic and climate characteristics from the East (Eastern Constantine Coastal basin) to the West (Oran Coastal basin); which give an appropriate description of the hydrology variability in northern Algeria. On the other hand, in Algeria FFA has been always carried as univariate by using a single variable (usually Qp); while in this study, three variables are extracted (Qp, V and D). We use these 11 stations because they present continuous series without gaps compared to other stations; which is relatively the longest among those made available to us by the services of the ANRH. For future work, thinking on extrapolating this method to the ungauged sites should be considered where no or less hydrological information is available. Therefore, this finding will be used on the hydraulic structures design and the protection of towns and villages as well as the agricultural lands against floods. Hence, this first step allows us to conclude on the reliability of such an approach in our regions.

The daily flow series allows the extraction of three main variables to characterize the flood event risk. This latter is described by the joint dependence structure defined by the associated pairs of flood variables. The dependence structure modelling is performed by using a copula approach which provides important information about flood risk assessment. In Algeria, flood risk issues have been treated in the univariate approach by identifying the best (univariate) distribution which allows estimating quantile for an associated return period. In the presented study, multivariate FFA is conducted in Northern Algeria where 11 watersheds are analysed. A complete multivariate FFA is carried on the extracted variables (D, V, Qp). The correlation of flood variables shows the link that an important flow can generate a large volume and vice versa. In the same sense, Yue et al. (1999); Kim et al. (2003) and Ben Aissia et al. (2009) revealed a strong dependence between Qp and V. Most of the identified change point dates belong on the 1970's decade for three mains flood variables (Table B.2). The same period was detected by Bakreti et al. (2013) and Halouz et al. (2013) in analysing the change in the hydrological regime on Western Algeria. The detected change points are not retained because they are located on the series boundaries which affect strongly the ability of the applied test (see e.g. Xie et al. 2014; Xiong et al. 2015; Nayak et al. 2016). Indeed, as a first step, for univariate quantile estimation, Weibull is mostly selected for the duration series (7 out of 11), also for peak flow series (6 out of 11). For volume series (6 out of 11) and Log-Normal type 2 (4 out of 11) are the selected marginal distributions. This manuscript presents a study of at-site FFA where the selected multivariate models for the studied stations are not transferable to other stations (even though it is the same methodology). Hence, there is no need to validate on other stations. In addition, since the aim of FFA is not the forecasting, it is not appropriate to validate on sub-samples (e.g. Salvadori & De Michele, 2004; Zhang & Singh, 2006; Reddy & Ganguli, 2012; Requena et al. 2013; Callau Poduje et al. 2014). The depth functions are used in identifying multivariate outliers. Multivariate tests are used to check the basic assumptions of trend, homogeneity and serial independence. Then, the modelling step is performed based on copulas to model the dependence structure. Based on selection criteria (AIC and BIC), as well as on goodness-of-tests and graphical tools, mostly three copulas (Frank, Clayton and Gumbel) are retained for the flood variables to describe the joint structure of the analysed pairs. A total of 33 pairs are analysed (three pairs for each of the 11 stations), where Clayton (4 out of 11) and Gumbel (4 out of 11) are selected for (D, V); Frank (5 out of 11) and Clayton (3 out of 11) are retained for (Qp, V) and Gumbel (4 out of 11) and Frank (4 out of 11) describe the couple (D, Qp). It is noted that a given return period for a flood event may have various occurrence of flood variables and vice versa. Such findings are valuable tools for water surface management and engineers for hydraulic structures design (dams, sewage systems, bridges, and watercourses developments). Regarding multivariate HFA studies in Mediterranean region, e.g., Leite Rosa (2011) and Hamdi et al. (2016), we notice the similarity in the behaviour of the hydrological variables to assess the extreme event; where Frank and Clayton were selected to model the dependence of the studied variables.

The results presented in this manuscript of a multivariate analysis of flood variables (D, V, Qp) offer an important opportunity to develop a new strategy of water management (water supply, irrigation), sewage systems, flood control and reservoir operation, where the several combinations of flood features should be involved to enhance the efficiency and sustainability of water structure. A better knowledge of the hydrological behaviour of flood variables combinations (D, Qp), (D, V), (V, Qp) in multivariate approach is a promising step in Algeria, as it is already in other parts of the world. However, the water demand is increasing especially in its northern part where the majority of the population is located. Therefore, managing the flood to reuse the water in irrigation, or recharge the groundwater may help to minimize the damage caused by flood events and contribute to providing an important quantity of water when the water supply-demand is rising (e.g. summer season).

For instance, the return period of 100 years is required in watercourses facilities. Through the combination of two or more hydrological variables, mainly Qp and V, provide more reliability for hydraulic structure designing, water reservoir management, flood risk assessment and support flood mitigation in the studied basins (e.g. Salvadori & De Michele, 2004; Zhang & Singh, 2006; Reddy & Ganguli, 2012; Requena et al. 2013; Callau Poduje et al. 2014; Balistrocchi et al. 2017; Jiang et al. 2019; Zhou et al. 2019; Liu et al. 2019).

This work presents a case of study of at-site FFA and not regional analysis. It is important to mention that a regional FFA is not a simple collection of a number of at-site FFA cases (see e.g. Ouarda 2017 for more details). In addition, to the best of our knowledge, there are very limited studies simultaneously on multivariate and regional FFA (see Requena et al. 2016). To do a regional or spatial study, it goes beyond the scope of the present project since it requires first an entire project dealing only with data preparation and extraction. In addition, in the case of the Algerian context, the situation is more complex since the data when they are available they do not fulfil the FFA assumptions. Consequently, we need to consider advanced approaches to deal with missing multivariate data, non-standard multivariate models (e.g. multivariate no-stationary). These elements may be the subject of more than one additional manuscript, not to mention the fact that some approaches are not even available in the literature.

6. Conclusions and perspectives

The work presented in this paper examines multivariate frequency analysis of flood features in Northern Algeria, in order to add to the current knowledge of hydrological systems and flood management in Algeria. The multivariate HFA framework is conducted on flood event for eleven stations (in seven large watersheds) chosen from the extreme East to the extreme West of the country. This data and this analysis are considered for the first time in Algeria. This can provide an interesting illustration for surface water management and identifying the behaviour of flood risk in the watershed. The methodology considered is complete since it includes all steps of the multivariate HFA. Copula concept is applied to identify the structure dependence of the main flood features (D, V, and Qp). As in other studies, a significant correlation between Qp and V is identified. This result shows the necessity to establish the dependence structure between these variables and to conduct multivariate FFA based on copulas. Copulas selection, among three variable pairs and five stations, shows that the Frank copula is most often selected followed by the Clayton and Gumbel copula. The results obtained can be used by water managers to obtain information for given variables of flood in the studied regions. Through these results, it is demonstrated that applying copulas to analyse multivariate correlated flood characteristics can lead to a joint structure which describes the flood event well. The multivariate FFA study, including the dependence structure between the flood characteristics, is considered as efficient tools in managing water supply in the studied watersheds. These findings are an interesting tool to understand the dependence between the multivariate flood variables; to establish more efficient planning strategies against flood risk; providing support for the decision in water management, designing the hydraulic structure, flood control and mitigation and optimize the water reservoir operation according to the local conditions of each basin. Indeed, it provides flexibility for engineers, useful to fill the gaps in the data and the results can be applied for future regional studies. This kind of analysis is often neglected in FFA in Algeria, where usually only one variable is treated (Qp). On the other hand, these results may be involved in the design of hydraulic structures projects such as dams, bridges, and watercourse developments and protection of cities subject to flood problems (e.g. Karmakar & Simonovic 2007; Bačová Mitková & Halmová 2014; Balistrocchi et al. 2017). This study can be used to motivate the authorities to continue recording data in the existing stations so that they can be used in the future to provide better risk assessment. On the other hand, FFA, especially in multivariate approach, requires a specific type and amount of data, and conditions of stationarity, homogeneity and serial dependence compared with those used in another hydrological study e.g. prevision, rainfall-runoff modelization. Behind the specific results obtained for the considered case studies, the paper has presented a full methodological framework for a complete multivariate frequency analysis which includes all steps of the analysis, i.e. extracting flood features from daily stream flow, descriptive analysis, hypotheses testing, model selection and estimation, risk assessment. This framework is transferable to other locations, flood variables or hydrological events (e.g. droughts, precipitations). Provided the availability of appropriate data sets, it is well recommended to extend this analysis to cover the entire country by adding more dataset and involving more variables. Such a national study would require an additional step of classifying stations in homogenous regions in order to provide a model for each group of stations. The national study also requires a huge work regarding data preparation and databases construction. The present study can be seen as a first and necessary step toward a national study.

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746 **Table 1.** Historical review of riverine flood in Algeria

Event date		Locations	Provinces	Wadis	Impacts
Start date	End date				
06/10/1966	06/10/1966	West	Chlef	Cheliff	57 deaths
November 1967	November 1967	Northeast and Aurès	Batna, Timgad, Constantine	El Grine, Berghout, Soultes, Hammam Grouz, Rhummel	20 deaths
September 1969	October 1969	North centre	Algiers, Medea, Blida, Boumerdès	Djer, Mazafran, El Harrach, Sébaou, Isser, Corso	76 deaths
March 1973	March 1973	Northeast and Northwest	Tlemcen, Annaba, Taref	Seybousse, Saf-Saf, Kebir, Ressoul, Ksob, Sikkak, Isser	21 deaths
28/03/1974	31/03/1974	Central and Western	Algiers, Blida, Boumerdès, Tizi Ouzou, Tlemcen	El Harrach, Djer, Mazafran, M'leta, Sébaou, Sikkak, Isser	52 deaths and 4,570 destroyed houses
November 1984	November 1984	Western	Chlef, Relizane, Sidi Bel Abbes, Tlemcen	Cheliff, R'hiou, Mekkera, Tafna	54 deaths
09/01/1985	09/01/1985	North-East	Constantine, Annaba, Sétif, Batna, Khenchela	Rhummel, Seybousse, Ksob, Kissir, Soultes, Yabous, Lahtiba	26 deaths
21/01/1992	29/01/1992	Central and Western	Algiers, Tipaza, Blida, Ain Defla, Chlef	Djer, Mazafran, El Harrach, Hamiz, Tikezal, Cheliff	21 deaths
19/10/1993	20/10/1993	Western	Relizane, Chlef, Tiaret	R'hiou, Cheliff, Menni	22 deaths
21/09/1994	26/09/1994	Eastern and Western	Borj-Bou-Arreridj, Tiaret, Tissemsilt, Bouira, Naama	Ksob, Aïn Zada, Touil, Mina, El Abed	32 deaths
23/04/1996	30/04/1996	Eastern	El Taref	Kebir, Kebir East, Bougous	4 deaths
06/08/2000	06/08/2000	Eastern	Borj-Bou-Arreridj, Oum El Bouaghi	Ksob, Ain Zada, Boulfreis, El Hammam	7 deaths
13/10/2000	13/10/2000	Western	Ain Temouchent	Maleh, El Kihel	9 deaths
22/10/2000	25/10/2000	Western	Sidi Bel Abbes, Relizane, Tlemcen, Naama	Mekkera, Taria, Mina, R'hiou, Tlata, Mouillah, Tafna	28 deaths
10/11/2001	14/11/2001	Central and Western	Algiers, Blida, Boumerdès, Tizi Ouzou, Tipaza, Chlef, Ain Defla, Relizane, Mascara, Oran, Mostaganem, Saida and Tlemcen	Bab el Oued, Korich, Djer, Mazafran, Kniss, Béni Messous, Tléta, El Kerma, Sidi Arrack, El Harrach, Annassers, Ardjem, Djemaïa, Isser, Djemâa, Ménaïel, Boumzar, Barbara, Sébaou, Guettar, El Hammam, Merdja, Boumerdès, Corso, Hamiz, Arbatache, Taksebt, M'leta, Cheliff, Tikezal, Zeddine, El Abtal, Goussine, Kramis, Mina, R'hiou, El Melah, Tlélat, Tafna, Mekkera, Tlata, Taria	921 deaths and 300 million dollars
17/08/2002	28/08/2002	Eastern and Western	Tébessa, Batna, Mila, Guelma, Oum El Bouaghi, Khenchela, Souk Ahras, Sidi Bel Abbes, Annaba	Melegue, Mejerdah, Soultes, Seybousse, Kebir, Rhummel, Mekkera, Taria	29 deaths and 1.5 million dollars of material damages
09/10/2002	12/10/2002	Eastern	Sétif, Batna, Biskra	Djemourah, Biskra, Abiod, Ain Zada	13 deaths

07/12/2002	07/12/2002	Central	Béjaia, Tizi Ouzou	Sébaou, M’leta, Soummam	6 deaths
02/04/2003	05/04/2003	Central and Eastern	Tizi Ouzou, Béjaia, Annaba, Blida, Constantine	Sébaou, M’leta, Soummam, Djer, Mazafran, Rhummel	15 deaths
13/11/2004	14/11/2004	Central	Algiers	Bab el Oued, Korich, Djer, Mazafran, Kniss, Béni Messous, Tléta, El Kerma, Sidi Arrack, El Harrach, Annassers	19 deaths
21/03/2007	23/03/2007	Western	Relizane, Saida, Oran, Sidi Bel Abbès	Mina, R’hiou, Melah, Tlélat, Tafna, Mekkera, Tlata, Taria	
24/11/2007	02/12/2007	Central and Western	Algiers, Tipaza, Boumerdès, Oran, Tizi Ouzou, Blida	Bab el Oued, Korich, Djer, Mazafran, Kniss, Béni Messous, Tléta, El Harrach, Annassers, Djemaïa, Isser, Djemâa, Larbaa, Sébaou, El Hammam, Boumerdès, Corso, Hamiz, Chiffa, Arbatache, Taksebt, M’leta, El Melah, Tlélat	14 deaths
03/02/2012	14/02/2012	Central and Eastern	Skikda, Boumerdès, Tizi Ouzou	Saf-Saf, Ameur, Boumerdès, Corso, Hamiz, Sébaou, M’leta	49 deaths

Table 2. Characteristics of the selected stations

Watershed	Station	Wadi	Surface (km^2)	Length of the main thalweg (km)	Latitude	Longitude	Period	Annual average yield (Hm^3)
Cheliff	Ammi Moussa	R'hiou	1890	114.5	35.86	1.12	1961-2012	84
Algiers Coastal	Azzefoun	M'leta	36	13	36.89	4.35	1988-2012	11.8
Algiers Coastal	El Affroun	Djer	395	50	36.45	2.59	1970-1993	37.1
Algiers Coastal	Baraki	El Harrach	970	59	36.68	3.09	1972-2008	142.2
Eastern Constantine Coastal	Khemakhem	Saf-Saf	322	27	36.55	6.93	1975-2005	30.7
Eastern Constantine Coastal	Ain El Assel	Kebir East	680	41	36.58	8.37	1948-2003	207.8
Western Oran coastal	Ghazaoute	Tlata	100	8	35.1	-1.87	1971-2012	2.9
Highlands	Timgad	Soultes	194	29.8	35.49	6.46	1970-2005	5.3
Isser	Lakhdaria	Isser	3620	114	36.61	3.58	1967-2011	304.1
Macta	S.A. Ben Y	Mekkera	1890	91.1	34.97	-0.74	1950-2009	20.4
Macta	Taria	Taria	1360	98	35.12	0.09	1974-2012	20.5

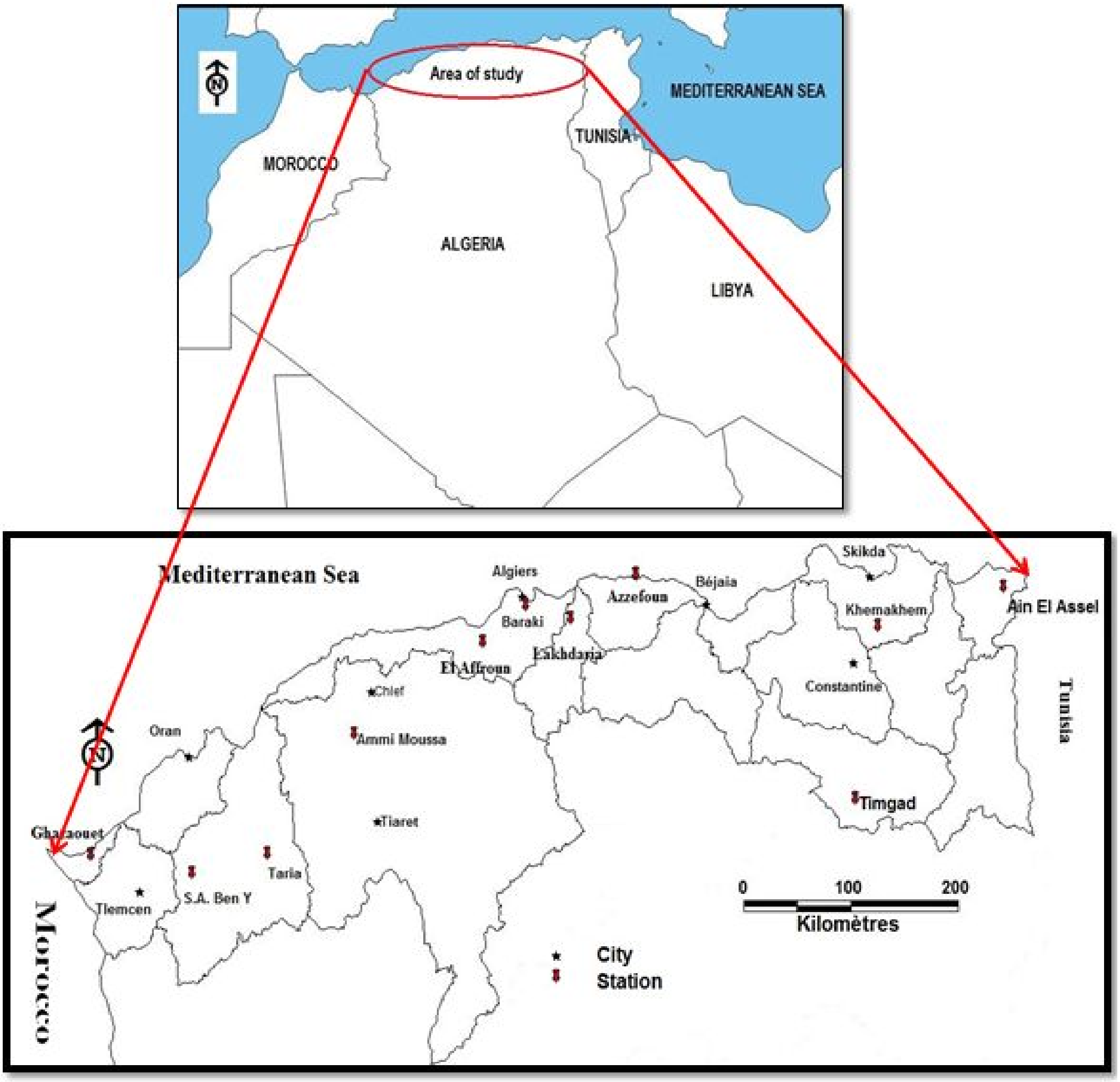

Figure 1. Localization of studied stations

Table 3. Descriptive analysis of univariate variables series

	Stations	Ammi Moussa	Azzefoun	El Affroun	Baraki	Khemakhem	Ain El Assel	Ghazaoute	Timgad	Lakhdaria	S.A. Ben Y	Taria
D	Minimum	3	3	6	7	2	4	2	1	3	1	3
	Maximum	16	11	22	20	17	15	18	12	17	13	19
	Mean	8.7	7.9	14.8	13.3	8.7	8.5	7.9	3.7	8.7	6.5	8.3
	Standard deviation	3.2	1.9	4.01	3.24	4.46	2.48	3.62	2.21	3.6	3.13	3.86
	Median	9	8	15	13	9	8	7	4	8	6	7
	Cv (Variation)	0.4	0.2	0.3	0.2	0.5	0.3	0.5	0.6	0.4	0.5	0.5
	Cs (Skewness)	0.2	-0.9	-0.3	0.1	0.3	0.2	1.1	1.4	0.6	0.4	0.9
	Ck (Kurtosis)	2.3	3.5	2.9	2.5	2	2.5	4.2	6.5	2.5	2.1	3.5
V	Minimum	1.8	0.05	0.2	3.8	0.2	3.1	0.03	0.1	5.1	0.1	0.3
	Maximum	74.3	9.3	57.8	140.4	51.4	143.6	5.5	9.5	340.9	21.2	20.9
	Mean	21.8	3.2	13.9	39.4	9.6	47.4	1.2	1.7	68.1	4.9	4.9
	Standard deviation	17.7	2.7	15.6	36.6	10.5	28.6	1.4	2.3	75.8	5	4.9
	Median	15.9	2.2	6.5	29.2	6.8	43.7	0.6	0.9	43.5	3.1	3.4
	Cv (Variation)	0.8	0.8	1.1	0.9	1.1	0.6	1.1	1.4	1.1	1	1
	Cs (Skewness)	1.4	1	1.4	1.5	2.7	1.3	1.5	2.4	2.2	1.7	1.7
	Ck (Kurtosis)	4.4	2.7	4.2	4.5	10.9	5.3	4.8	7.8	7.4	5.4	5.1
Qp	Minimum	17.3	0.5	0.7	19	1.9	6.4	0.14	0.7	28.7	0.8	2
	Maximum	428.6	71.2	268.1	876.4	132.9	467.9	33.8	77.6	1489.5	177.6	130
	Mean	123.9	21.3	69.7	191.6	42.4	199.7	8.3	15.5	303.5	38.6	34.7
	Standard deviation	86	23	72	223	32.2	98.9	9.3	18.8	302.6	43.5	32.7
	Median	100.2	11.8	42.3	120.1	37.1	200.3	3.8	7.7	213.7	20.7	21.8
	Cv (Variation)	0.7	1.1	1	1.2	0.7	0.5	1.1	1.2	1	1.1	0.9
	Cs (Skewness)	1.3	1.3	1.3	1.7	1.1	0.5	1.3	2.1	2.5	1.7	1.2
	Ck (Kurtosis)	5.2	3.2	3.9	5.2	4.1	3.2	3.6	6.6	8.9	5.3	3.6
	Size	47	25	24	28	26	51	42	36	41	51	37
	Period	1961-2012	1988-2012	1970-1993	1972-2008	1975-2005	1948-2003	1971-2012	1970-2005	1967-2011	1950-2009	1974-2012
	Number of missing years	5	0	0	8	0	6	0	0	4	9	2

Table 4. Correlation matrix of the analysed pairs

	Ammi Moussa	Azzefoun	El Affroun	Baraki	Khemakhem	Ain El Assel	Ghazaoute	Timgad	Lakhdaria	S.A. Ben Y	Tar
(D. V)	**0.45**	**-0.15**	0.28	0.03	**0.62**	**0.37**	**0.55**	**0.23**	**0.42**	0.26	**0.3**
(D. Qp)	**0.25**	**-0.23**	**0.25**	**-0.2**	**0.46**	**0.23**	0.38	**0.17**	**0.25**	**0.15**	**0.1**
(Qp. V)	**0.86**	**0.95**	**0.92**	**0.92**	**0.85**	**0.78**	**0.95**	**0.96**	**0.88**	**0.94**	**0.8**

Bold character: significant correlation

Table 5. Checking of the basic assumptions for the margins

		Stationarity				Independence		Homogeneity	
		Mann-Kendall		Spearman		Wald-Wolfowitz		Wilcoxon	
	Station	K	p-value	S	p-value	U	p-value	W	p-value
D	Ammi Moussa	-1.92	0.054	-1.79	0.08	1.86	0.063	1.43	0.15
	Azzefoun	-1.7	0.09	-0.94	0.36	0.94	0.35	0.8	0.43
	El Affroun	-1.33	0.18	-1.41	0.17	1.57	0.12	1.66	0.1
	Baraki	0.4	0.69	0.81	0.42	0.16	0.87	0.67	0.5
	Khemakhem	-0.89	0.38	-0.72	0.48	0.95	0.34	0.49	0.62
	Ain El Assel	-0.72	0.47	-0.4	0.69	1.86	0.06	0.73	0.46
	Ghazaoute	-1.15	0.25	-0.76	0.45	0.063	0.95	1.03	0.3
	Timgad	-0.8	0.42	0.086	0.93	0.8	0.42	1.25	0.21
	Lakhdaria	0.27	0.79	0.46	0.65	0.89	0.37	0.7	0.49
	S.A. Ben Y	1.64	0.1	1.98	0.05	0.76	0.45	2.56	0.01*
	Taria	-1.82	0.07	-1.7	0.1	0.16	0.88	1.73	0.08
V	Ammi Moussa	-1.55	0.12	-1.43	0.16	1.18	0.24	1.15	0.25
	Azzefoun	2.02	0.04*	2.29	0.03*	0.094	0.92	1.9	0.06
	El Affroun	-1.8	0.07	-1.88	0.08	0.48	0.63	0.7	0.48
	Baraki	-1.84	0.07	-2	0.06	0.51	0.61	0.53	0.6
	Khemakhem	0.26	0.79	0.21	0.84	0.3	0.76	1.41	0.16
	Ain El Assel	-0.49	0.63	-0.47	0.64	0.58	0.56	0.58	0.56
	Ghazaoute	-1.68	0.09	-1.66	0.1	0.57	0.57	1.32	0.19
	Timgad	0.041	0.97	-0.017	0.99	1.95	0.05	0.49	0.62
	Lakhdaria	-1.65	0.1	-1.53	0.13	1.24	0.21	1.4	0.16
	S.A. Ben Y	0.96	0.34	1.16	0.25	1.14	0.25	1.6	0.11
	Taria	-0.052	0.96	0.17	0.87	1.74	0.08	0.81	0.42
Qp	Ammi Moussa	-0.42	0.67	-0.25	0.81	0.42	0.67	0.064	0.95
	Azzefoun	1.9	0.06	2.7	0.01*	0.013	0.99	2.38	0.02*
	El Affroun	-1.58	0.11	-1.78	0.09	0.59	0.55	1.09	0.28
	Baraki	-1.8	0.07	-1.96	0.06	0.025	0.98	0.44	0.66
	Khemakhem	1.41	0.16	1.26	0.22	0.38	0.71	2.19	0.03*
	Ain El Assel	-1.66	0.1	-1.62	0.11	0.76	0.45	1.6	0.11
	Ghazaoute	-1.8	0.07	-1.81	0.08	0.11	0.92	1.37	0.17
	Timgad	0.52	0.6	0.42	0.67	1.71	0.09	0.81	0.42
	Lakhdaria	-1.91	0.06	-1.93	0.06	0.77	0.44	1.12	0.26
	S.A. Ben Y	1.22	0.22	1.31	0.2	1.12	0.26	1.66	0.1
	Taria	1.53	0.13	1.52	0.14	2.19	0.03*	1.88	0.06

*: accepted at level of 1% but rejected at 5%

790 **Table 6.** Selected marginal distribution

Variable	Station	Marginal laws	Estimation method	Parameter 1st	2nd	3
Duration	Ammi Moussa	Weibull	Maximum Likelihood	9.64	3.14	-
	Azzefoun	Weibull	Method of Moments	8.55	4.81	-
	El Affroun	Weibull	Method of Moments	16.33	4.17	-
	Baraki	Weibull	Method of Moments	14.57	4.68	-
	Khemakhem	Weibull	Maximum Likelihood	9.93	2.14	-
	Ain El Assel	Gamma	Maximum Likelihood	1.47	12.72	-
	Ghazaoute	Gumbel	Method of Moments	6.32	2.82	-
	Timgad	Weibull	Method of Moments	4.54	1.87	-
	Lakhdaria	Gumbel	Method of Moments	7.09	2.81	-
	S.A. Ben Y	Weibull	Method of Moments	7.35	2.19	-
	Taria	Gumbel	Method of Moments	6.56	3.01	-
Volume	Ammi Moussa	Log-Normal type 2	Maximum Likelihood	2.77	0.84	-
	Azzefoun	Exponential	Maximum Likelihood	0.85	2.53	-
	El Affroun	Weibull	Maximum Likelihood	15.16	0.99	-
	Baraki	Weibull	Method of Moments	40.5	1.08	-
	Khemakhem	Weibull	Method of Moments	9.22	0.91	-
	Ain El Assel	Weibull	Method of Moments	53.11	1.71	-
	Ghazaoute	Weibull	Maximum Likelihood	1.12	0.88	-
	Timgad	Log-Normal type 2	Maximum Likelihood	-0.15	1.2	-
	Lakhdaria	Log-Normal type 2	Maximum Likelihood	3.78	0.93	-
	S.A. Ben Y	Weibull	Maximum Likelihood	4.96	1.03	-
	Taria	Log-Normal type 2	Maximum Likelihood	1.17	0.97	-
Peak flow	Ammi Moussa	Gamma	Maximum Likelihood	0.017	2.15	-
	Azzefoun	Log-Normal type 2	Maximum Likelihood	2.84	0.87	-
	El Affroun	Weibull	Maximum Likelihood	72.27	0.98	-
	Baraki	Weibull	Maximum Likelihood	186.72	0.95	-
	Khemakhem	Weibull	Method of Moments	46.03	1.33	-
	Ain El Assel	Weibull	Method of Moments	225.49	2.12	-
	Ghazaoute	Weibull	Maximum Likelihood	7.61	0.85	-
	Timgad	Log-Normal type 2	Maximum Likelihood	2.13	1.17	-
	Lakhdaria	GEV	L-Moments	167.29	101.12	-0.39
	S.A. Ben Y	Weibull	Maximum Likelihood	37.86	0.96	-
	Taria	Exponential	Maximum Likelihood	3.86	31.86	-

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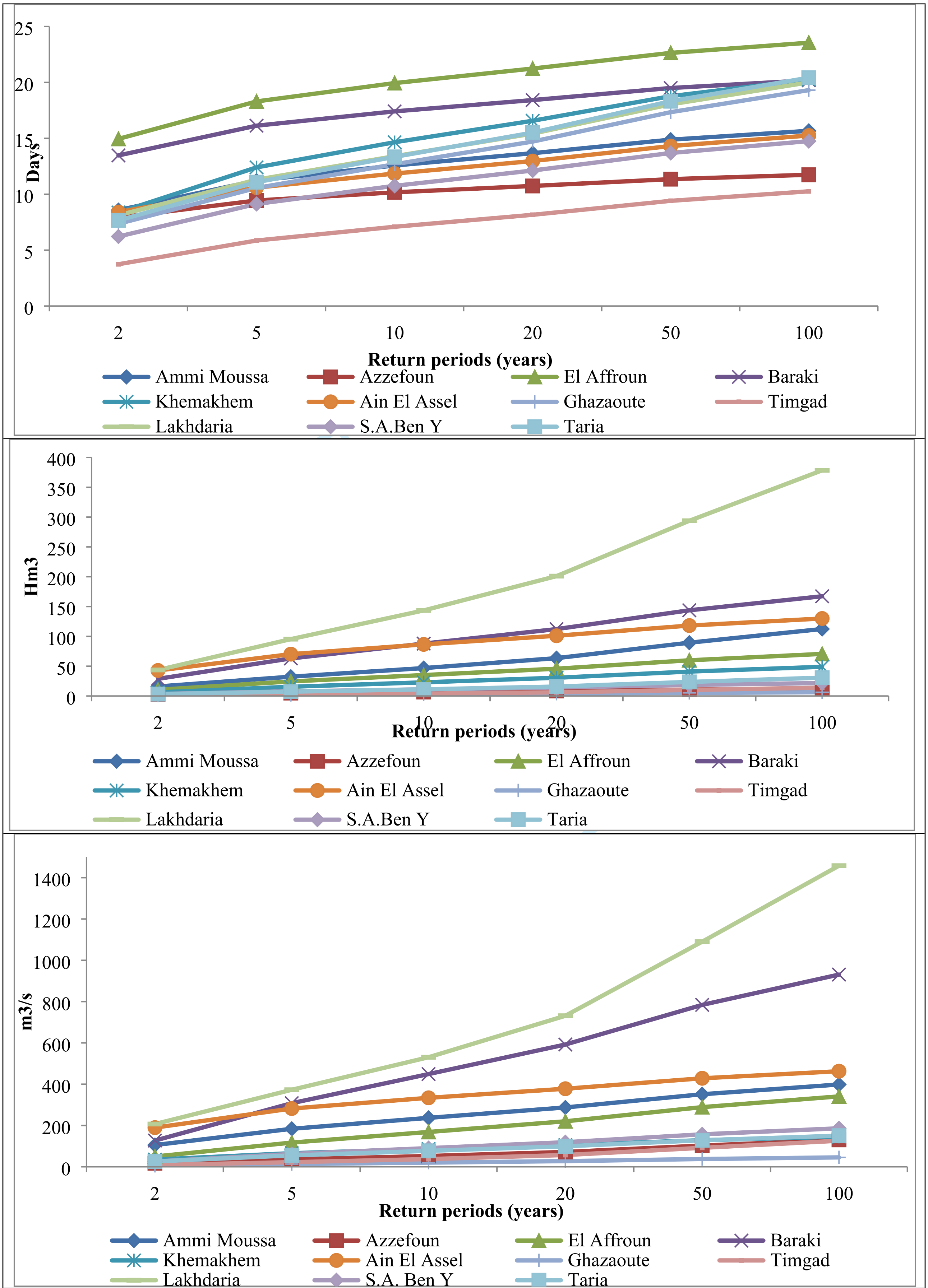


Figure 2. Univariate quantiles and return periods for flood characteristics

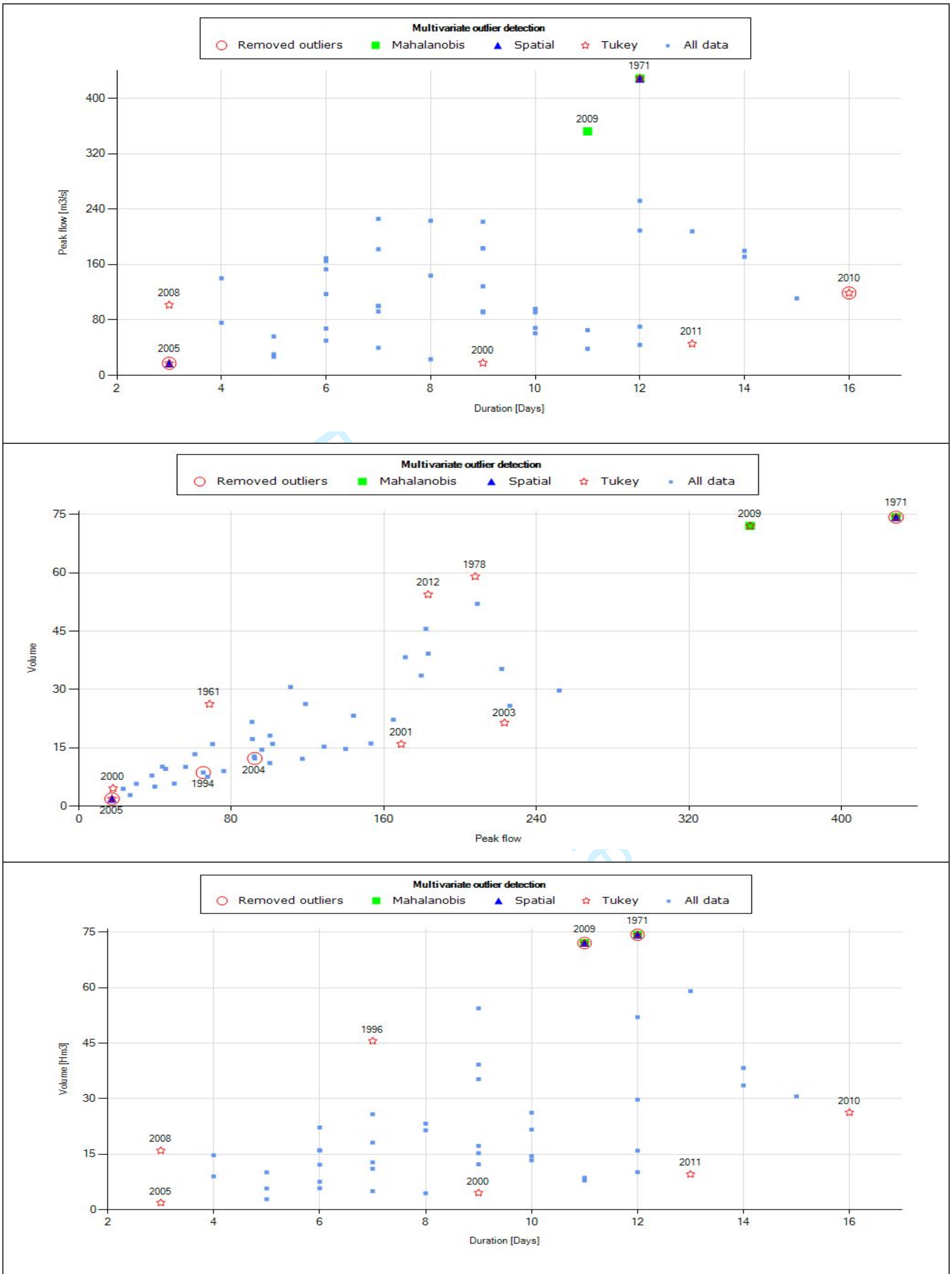


Figure 3. Multivariate outliers detection for the flood characteristics at Ammi Moussa

Table 7. Multivariate trend testing results with Mann–Kendall and Spearman (5% is the considered significance level)

		MK tests						Spearman test					
		CST		CET		CIT		CST		CET		CIT	
Pair	Station	Value	p-value	Value	p-value	Value	p-value	Value	p-value	Value	p-value	Value	p-value
(D, V)	Ammi Moussa	1.18	0.24	56869	0.07	3.77	0.15	0.97	0.33	4929433	0.15	2.73	0.26
	Azzefoun	0.14	0.89	8500	0.01*	7.8	0.02*	0.43	0.67	142885	0.05	5.82	0.05
	El Affroun	1.15	0.25	6074	0.08	3.97	0.14	1.13	0.26	172296.5	0.1	3.75	0.15
	Baraki	0.58	0.56	9277	0.16	3.75	0.15	0.43	0.67	525925	0.12	4.47	0.11
	Khemakhem	0.21	0.83	1850	0.56	2.23	0.33	0.17	0.86	48938.5	0.67	1.46	0.48
	Ain El Assel	0.38	0.7	9077	0.7	0.53	0.77	0.097	0.92	251914.5	1,00	0.16	0.92
	Ghazaoute	1.02	0.31	35572	0.13	3.08	0.21	0.8	0.43	2732876.5	0.22	2.61	0.27
	Timgad	0.12	0.9	2474	0.66	1.02	0.6	0.22	0.83	39218.5	0.9	0.21	0.9
	Lakhdaria	0.49	0.63	22529	0.23	4.61	0.1	0.22	0.83	2517205	0.21	5.89	0.05
	S.A. Ben Y	0.8	0.42	40322	0.23	2.28	0.32	1.12	0.26	12675744.5	0.07	4.78	0.09
	Taria	0.71	0.48	19346	0.19	3.56	0.17	0.5	0.62	1161257	0.3	2.76	0.25
(D, Qp)	Ammi Moussa	0.72	0.47	29045	0.24	2.79	0.25	0.49	0.62	2108665	0.44	1.67	0.43
	Azzefoun	0.33	0.74	9316	0.01*	7.94	0.02*	0.71	0.48	242521	0.02*	8.17	0.02
	El Affroun	1.22	0.22	8692	0.07	4.33	0.11	1.27	0.2	331124	0.06	4.76	0.09
	Baraki	0.61	0.54	8905	0.17	3.31	0.19	0.46	0.65	511394	0.13	3.69	0.16
	Khemakhem	0.29	0.77	3145	0.36	2.52	0.28	0.27	0.79	655001	0.54	1.46	0.48
	Ain El Assel	0.87	0.38	42365	0.22	2.58	0.28	0.55	0.58	4903528.5	0.32	2.35	0.31
	Ghazaoute	1.1	0.27	39125	0.1	3.68	0.16	0.88	0.38	3197912.5	0.18	3.12	0.21
	Timgad	0.66	0.51	7081	0.28	2.61	0.27	0.34	0.73	75245	0.77	0.49	0.78
	Lakhdaria	0.37	0.71	20714	0.19	4.16	0.12	0.13	0.9	2492786.5	0.11	5.64	0.06
	S.A. Ben Y	0.79	0.43	29125	0.3	1.91	0.39	1.09	0.27	8789645	0.09	4.15	0.13
	Taria	0.044	0.96	20225	0.11	4.04	0.13	0.15	0.88	1171452.5	0.16	3.33	0.19
(Qp, V)	Ammi Moussa	0.26	0.8	9197	0.5	4.99	0.08	0.13	0.9	874602	0.54	5.56	0.06
	Azzefoun	1.23	0.22	6760	0.05	4.05	0.13	1.32	0.19	191801	0.04*	4.48	0.11
	El Affroun	0.94	0.35	5570	0.13	3.93	0.14	0.95	0.34	167858.5	0.13	3.52	0.17
	Baraki	1.18	0.24	17300	0.06	3.53	0.17	1.21	0.23	872581	0.06	3.67	0.16
	Khemakhem	0.4	0.69	1828	0.47	2.9	0.23	0.26	0.79	38034	0.59	2.7	0.26
	Ain El Assel	0.61	0.54	33410	0.28	3.35	0.19	0.58	0.56	4695522.5	0.31	3.03	0.22
	Ghazaoute	1.12	0.26	52225	0.08	3.32	0.19	1.07	0.28	5297976.5	0.09	3.22	0.2
	Timgad	0.42	0.68	4505	0.5	3,00	0.22	0.37	0.71	270442	0.55	2.57	0.28
	Lakhdaria	1.03	0.31	35482	0.1	4.35	0.11	0.96	0.34	2988449	0.12	4.53	0.1
	S.A. Ben Y	0.45	0.65	13700	0.48	1.05	0.59	0.55	0.58	2987345	0.39	0.89	0.64
	Taria	0.14	0.89	1933	0.64	7.33	0.03*	0.066	0.95	82100	0.72	6.04	0.05

CST: Covariance Sum Test, CET: Covariance Eigenvalue Test, CIT: Covariance Inversion Test.
*: accepted at level of 1%

Table 8. Tests of serial independence and homogeneity for multivariate series

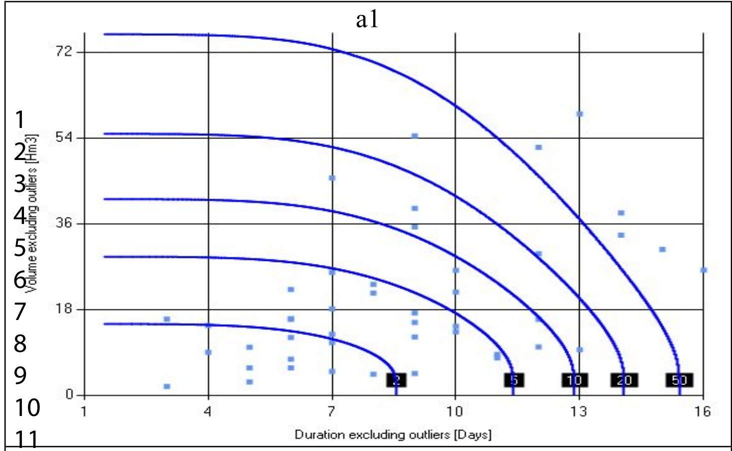
		Multivariate independence test		Homogeneity multivariate tests							
				C-test		M-test		W-test		Z-test	
Pair	Station	Value	p-value	Value	p-value	Value	p-value	Value	p-value	Value	p-value
(D, V)	Ammi Moussa	0.0035	0.08	9.02	0.27	0.58	0.14	0.9	1	0.0011	0.97
	Azzefoun	0.000093	0.79	2.19	0.25	0.26	0.13	0.7	1	0.64	0.43
	El Affroun	0.00052	0.24	16.12	0.13	0.22	0.04*	0.61	1	0.31	0.58
	Baraki	0.0003	0.73	15.6	0.43	0.94	0.77	0.97	1	0.099	0.75
	Khemakhem	0.0018	0.19	8.42	0.16	0.4	0.16	0.75	1	0.66	0.41
	Ain El Assel	0.00092	0.51	18.03	0.3	0.85	0.49	0.93	1	1.02	0.31
	Ghazaoute	0.0012	0.28	3.11	0.17	0.81	0.49	0.86	1	0.98	0.32
	Timgad	0.0024	0.07	0.71	0.83	0.88	0.6	0.92	1	0.014	0.91
	Lakhdaria	0.0012	0.34	68.38	0.1	0.63	0.26	0.79	1	0.36	0.55
	S.A. Ben Y	0.0012	0.33	9.17	0.02*	0.56	0.16	0.77	1	0.74	0.39
	Taria	0.00084	0.35	5.93	0.12	0.43	0.06	0.73	1	0.92	0.34
(D, Qp)	Ammi Moussa	0.0021	0.07	10.76	0.96	0.77	0.35	0.89	1	0.0066	0.93
	Azzefoun	0.00037	0.17	16.89	0.15	0.67	0.51	0.76	1	0.13	0.72
	El Affroun	0.00055	0.31	70.66	0.11	0.31	0.07	0.57	1	0.053	0.82
	Baraki	0.0002	0.56	58.71	0.61	0.97	0.96	0.99	1	0.26	0.61
	Khemakhem	0.00077	0.26	32.32	0.09	0.37	0.11	0.77	1	1.23	0.27
	Ain El Assel	0.0015	0.12	99.41	0.13	0.72	0.15	0.84	1	0.085	0.77
	Ghazaoute	0.00083	0.39	7.57	0.19	0.61	0.14	0.88	1	0.88	0.35
	Timgad	0.0021	0.06	1.67	0.94	0.95	0.92	1,00	1	0.001	0.97
	Lakhdaria	0.0004	0.95	121.94	0.33	0.55	0.2	0.84	1	0.14	0.71
	S.A. Ben Y	0.00082	0.38	52.74	0.06	0.28	0.03*	0.8	1	0.31	0.58
	Taria	0.00035	0.41	29.09	0.13	0.44	0.06	0.68	1	1.56	0.21
(Qp, V)	Ammi Moussa	0.0084	0.06	22.69	0.68	0.61	0.25	0.89	1	0.59	0.44
	Azzefoun	0.0047	0.06	17.06	0.23	0.69	0.59	0.84	1	0.25	0.61
	El Affroun	0.001	0.56	49.15	0.26	0.28	0.33	0.83	1	1.76	0.18
	Baraki	0.0011	0.74	61.66	0.6	0.76	0.54	0.92	1	0.013	0.91
	Khemakhem	0.0011	0.58	29.72	0.1	0.44	0.42	0.77	1	1.83	0.18
	Ain El Assel	0.00098	0.93	97.26	0.14	0.57	0.07	0.81	1	0.41	0.52
	Ghazaoute	0.0022	0.31	6.76	0.2	0.66	0.12	0.83	1	0.0013	0.97
	Timgad	0.005	0.07	4.35	0.62	0.68	0.28	0.78	1	0.32	0.57
	Lakhdaria	0.001	0.95	148.3	0.28	0.84	0.59	0.89	1	0.18	0.67
	S.A. Ben Y	0.0028	0.25	44.46	0.08	0.53	0.11	0.87	1	1.21	0.27
	Taria	0.0029	0.14	6.6	0.8	0.4	0.1	0.68	1	0.024	0.88

W-test: Wilcox test; Z-test: Zhang test; C-test: Cramer test

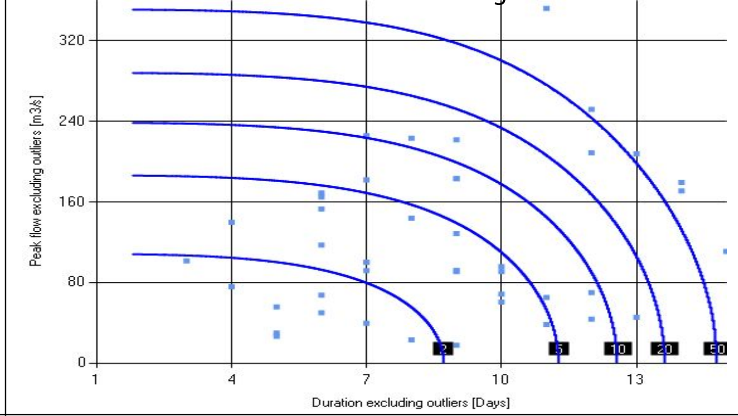
Table 9. Retained copula for flood characteristics

	Ammi Moussa	Azzefoun	El Affroun	Baraki	Khemakhem	Ain El Assel	Ghazaoute	Timgad	Lakhdaria	S.A. Ben Y	Taria
(D, V)	Clayton	Frank	Clayton	Clayton	Gumbel	Frank	Joe	Gumbel	Gumbel	Clayton	Gumbel
Parameter	0.85	-1.36	1.15	0.39	2.02	2.72	1.88	1.2	1.61	1.16	1.25
Sn p-value	0.0005	0.0005	0.09	0.05	0.09	0.0005	0.0035	0.0005	0.0005	0.0015	0.0005
Tn p-value	0.17	0.06	0.005	0.03	57	0.0045	0.21	0.05	0.28	0.08	0.19
AIC	-8.56	1.25	-4.76	0.29	-13.84	-7.14	-11.61	0.19	-11.96	-16.02	-1.39
BIC	-6.75	2.25	-3.67	1.63	-12.58	-5.23	-9.87	1.59	-10.25	-14.11	0.22
(D, Qp)	Frank	Ali-Mikhail-Haq	Clayton	Frank	Joe	Frank	Joe	Clayton	Frank	Clayton	Frank
Parameter	1.24	-0.51	0.52	-1.17	1.61	1.53	1.68	0.32	1.67	0.54	-0.62
Sn p-value	0.0015	0.0005	0.004	0.007	0.03	0.0005	0.0015	0.0005	0.0005	0.0005	0.0005
Tn p-value	0.009	0.26	0.45	0.06	0.58	0.017	0.07	0.05	0.07	0.08	0.1
AIC	0.16	1.73	-0.19	1.08	-2.43	-0.86	-7.36	0.97	-0.57	-2.88	1.64
BIC	1.97	2.77	0.98	2.41	-1.25	1.05	-5.62	2.34	1.06	-1.01	3.16
(Qp, V)	Clayton	Joe	Frank	Frank	Gumbel	Clayton	Gumbel	Gumbel	Frank	Gumbel	Frank
Parameter	3.27	6.52	17.65	14.16	3.24	2.62	6.55	10.67	10.44	4.22	19.33
Sn p-value	0.14	0.7	0.51	0.701	0.38	0.17	0.39	0.29	0.83	0.33	0.11
Tn p-value	0.84	0.17	0.13	0.704	0.83	0.13	0.72	0.36	0.15	0.36	0.73
AIC	-54.73	-36.47	-41.59	-46.35	-31.37	-49.42	-115.73	-128.57	-47.61	-95.73	-71.48
BIC	-52.97	-35.47	-40.5	-45.02	-30.19	-47.51	-113.99	-127.03	-45.94	-93.84	-69.98

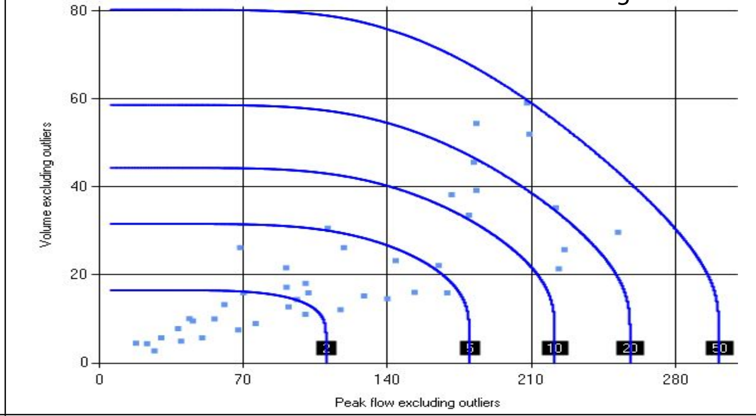
Sn test: based on empirical copula valid for any copula; Tn test: based on K function, valid for Archimedean copulas.



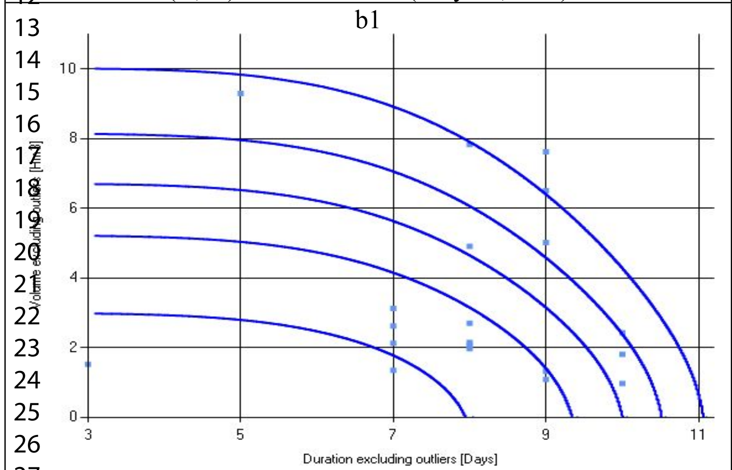
(D, V) Ammi Moussa (Clayton, 0.45)



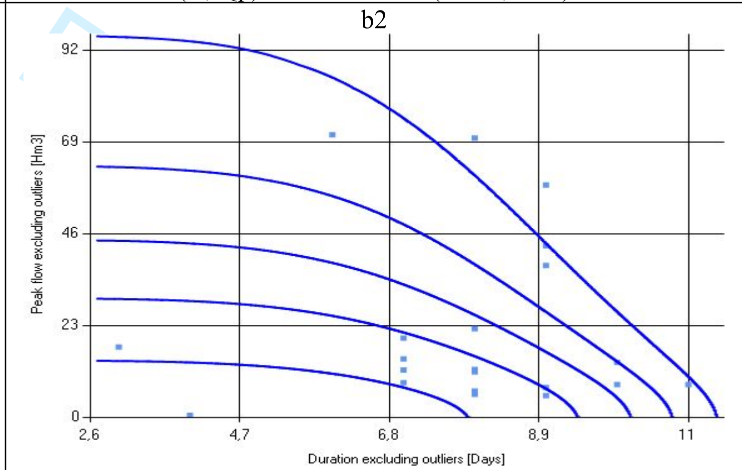
(D, Qp) Ammi Moussa (Frank, 0.25)



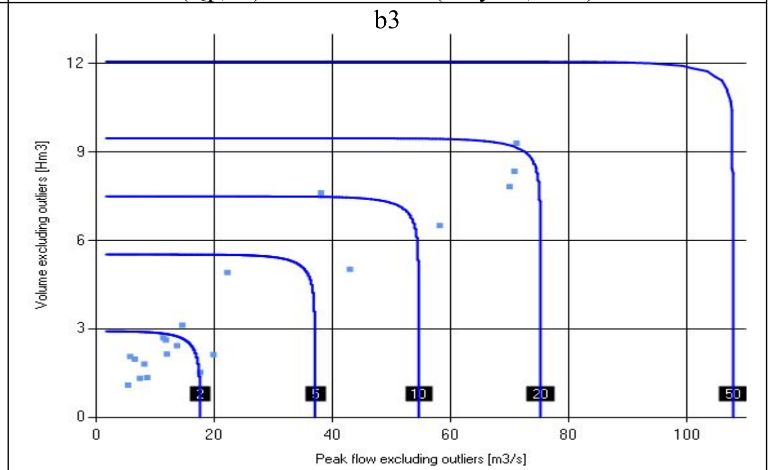
(Qp, V) Ammi Moussa (Clayton, 0.86)



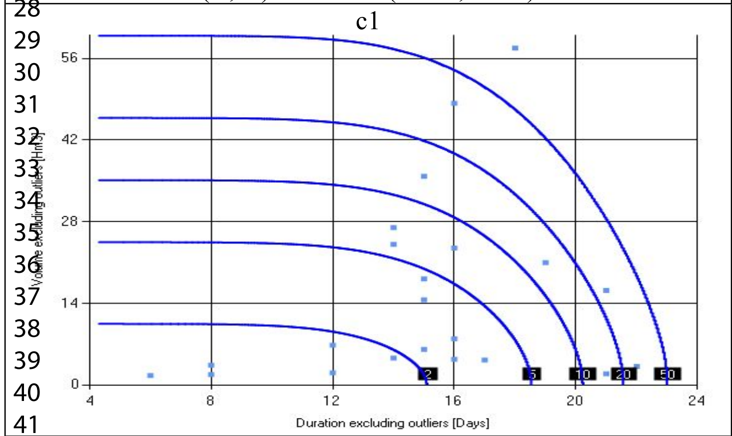
(D, V) Azzefoun (Frank, -0.15)



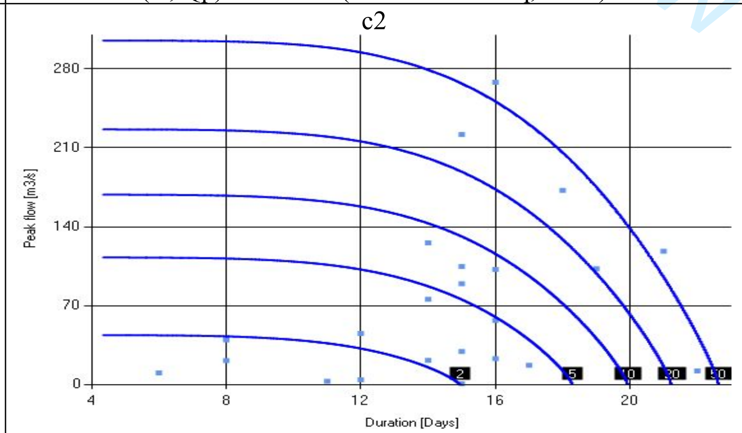
(D, Qp) Azzefoun (Ali-Mikhail-Haq, -0.23)



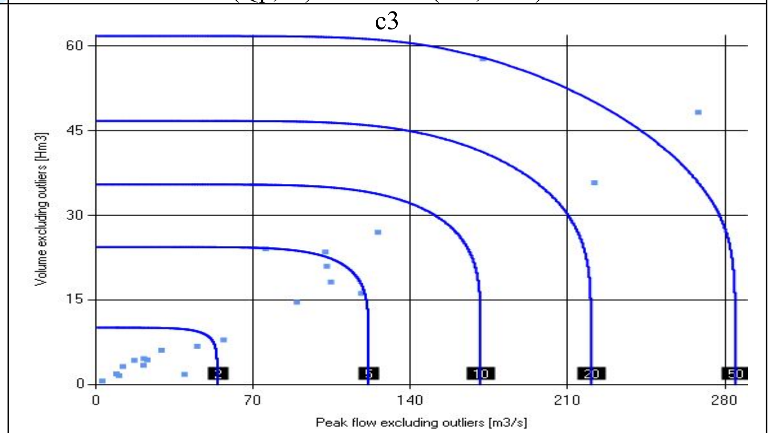
(Qp, V) Azzefoun (Joe, 0.95)



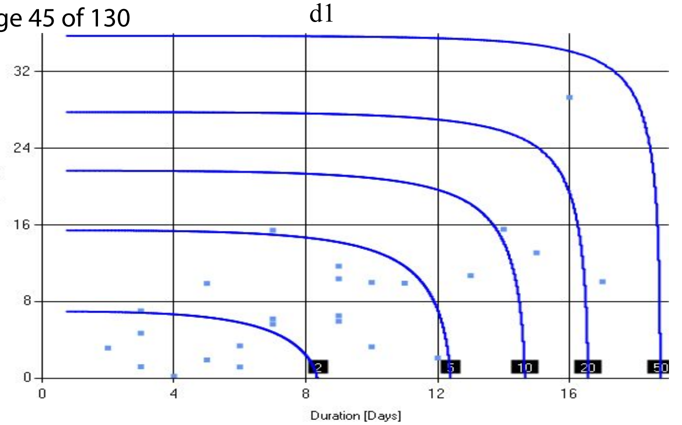
(D, V) El Affroun (Clayton, 0.28)



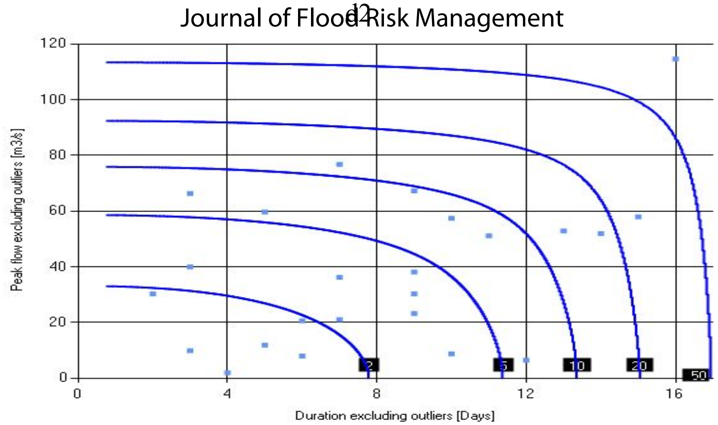
(D, Qp) El Affroun (Clayton, 0.25)



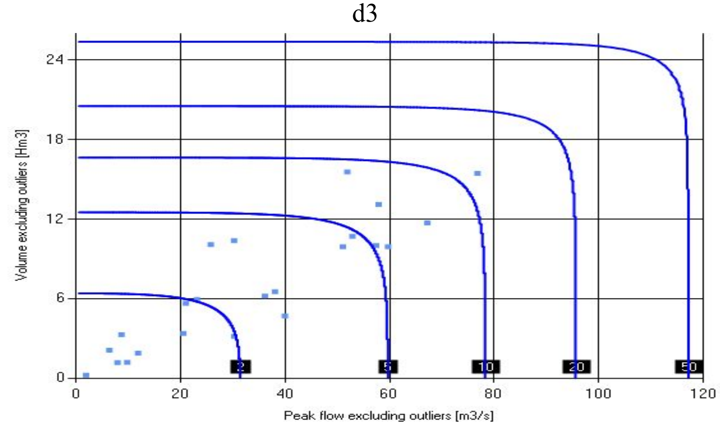
(Qp, V) El Affroun (Frank, 0.92)



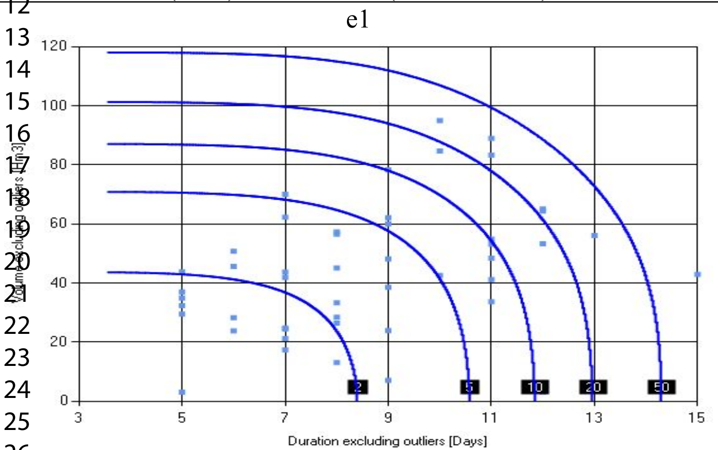
(D, V) Khemakhem (Gumbel, 0.62)



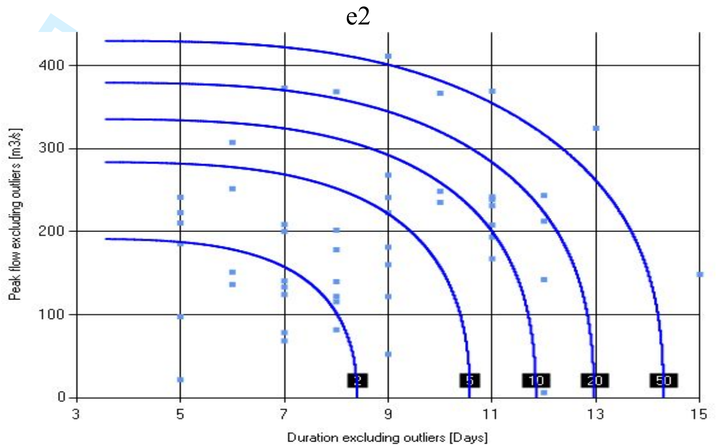
(D, Qp) Khemakhem (Joe, 0.46)



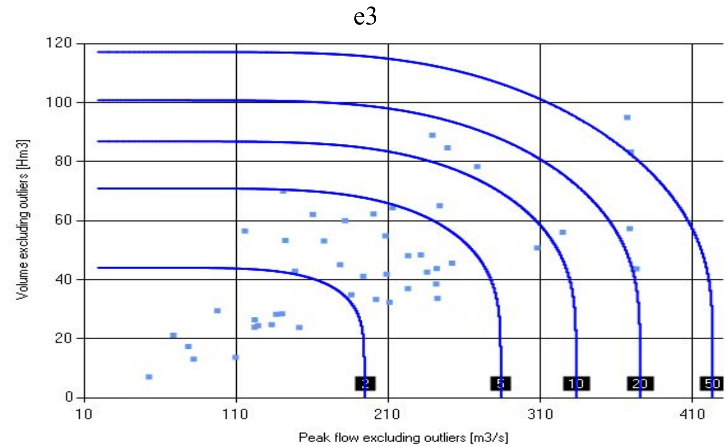
(Qp, V) Khemakhem (Gumbel, 0.85)



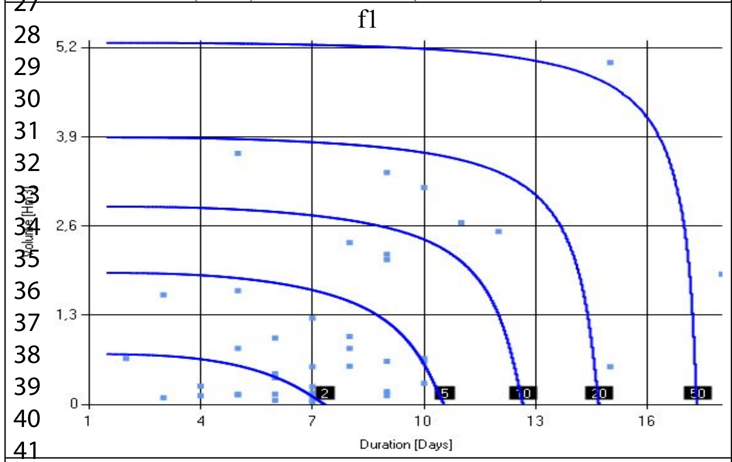
(D, V) Ain El Assel (Frank, 0.37)



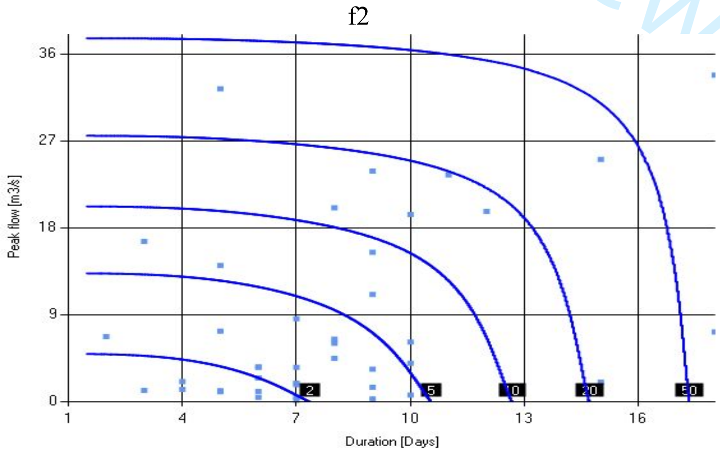
(D, Qp) Ain El Assel (Frank, 0.23)



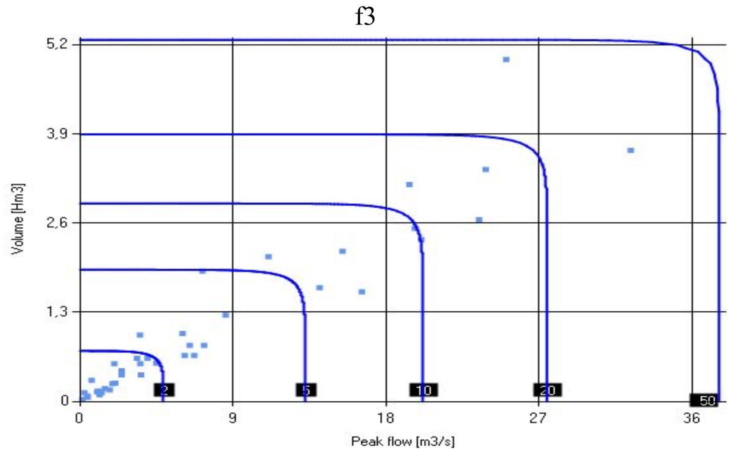
(Qp, V) Ain El Assel (Clayton, 0.78)



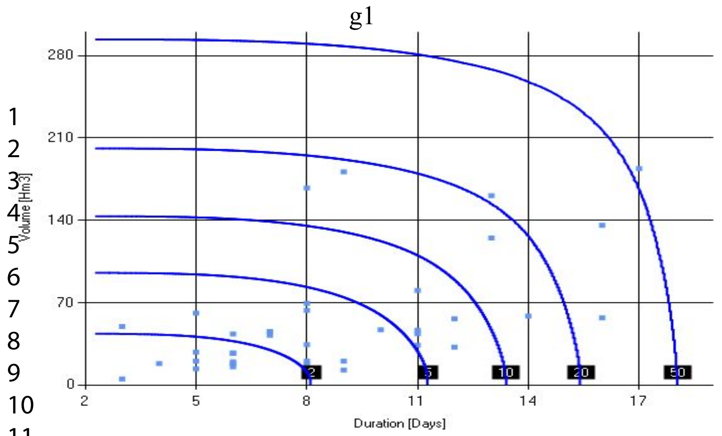
(D, V) Ghazaouet (Joe, 0.55)



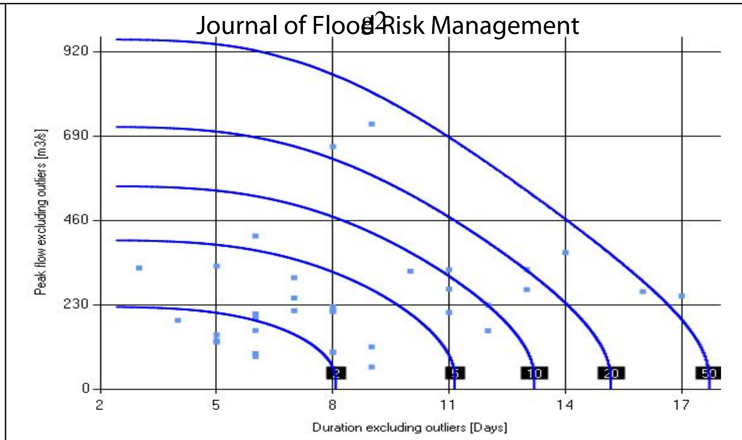
(D, Qp) Ghazaouet (Joe, 0.38)



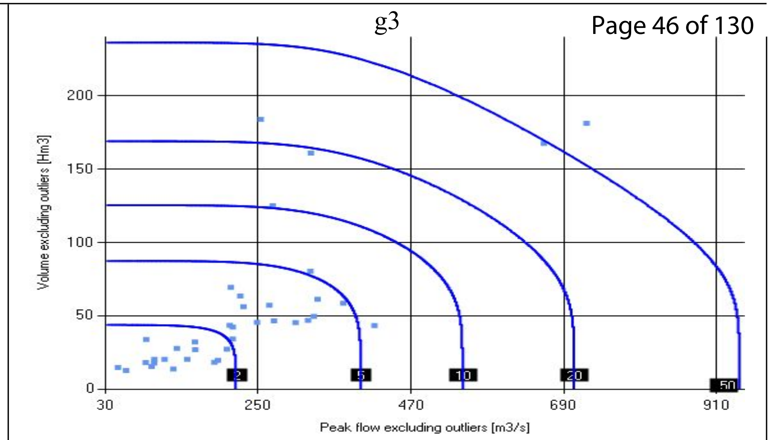
(Qp, V) Ghazaouet (Gumbel, 0.95)



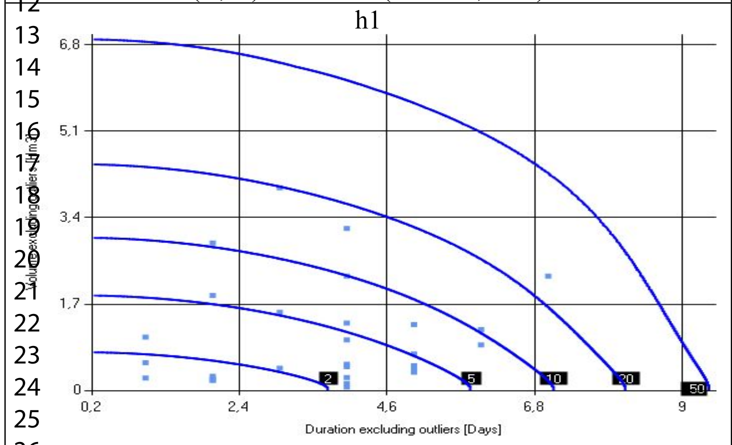
(D, V) Lakhdaria (Gumbel, 0.42)



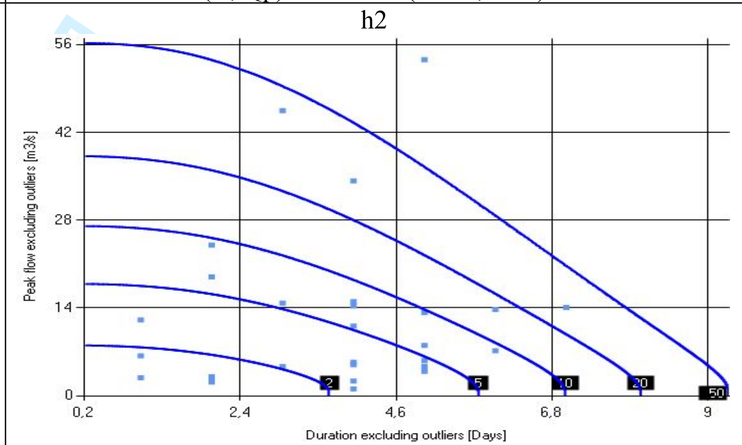
(D, Qp) Lakhdaria (Frank, 0.25)



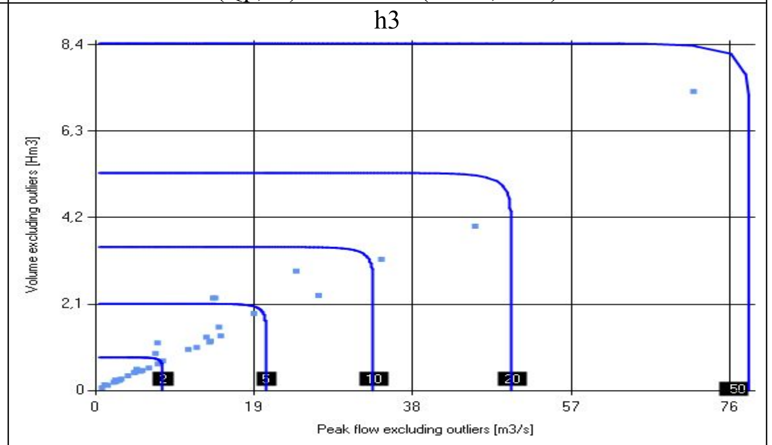
(Qp, V) Lakhdaria (Frank, 0.88)



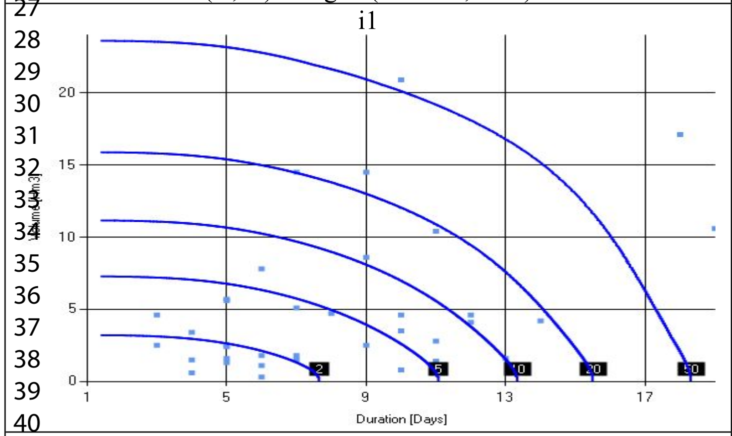
(D, V) Timgad (Gumbel, 0.23)



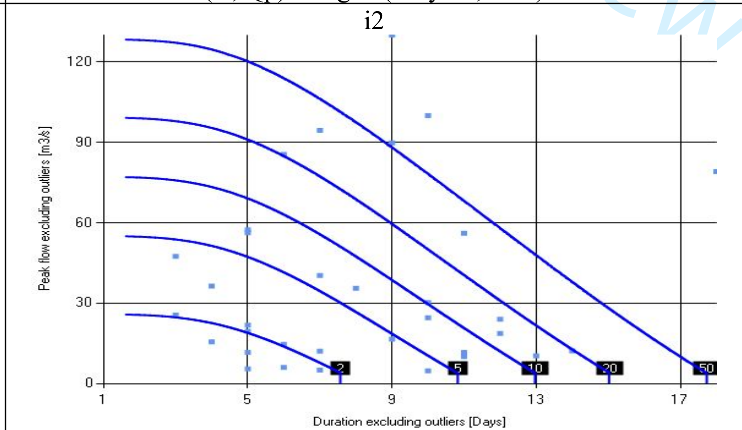
(D, Qp) Timgad (Clayton, 0.17)



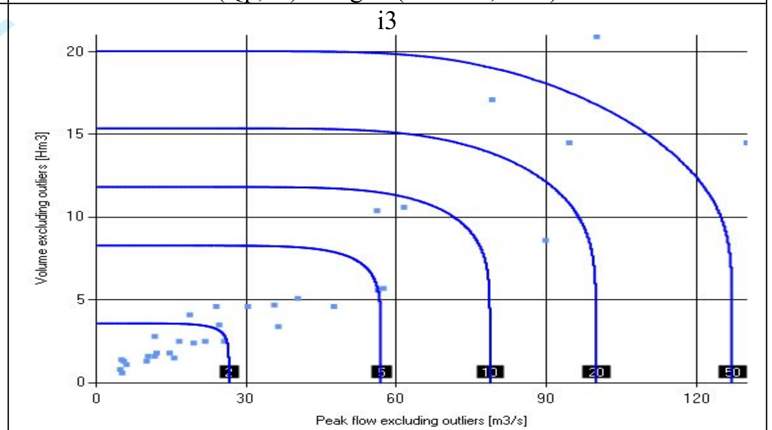
(Qp, V) Timgad (Gumbel, 0.96)



(D, V) Taria (Gumbel, 0.39)



(D, Qp) Taria (Frank, 0.15)



(Qp, V) Taria (Frank, 0.89)

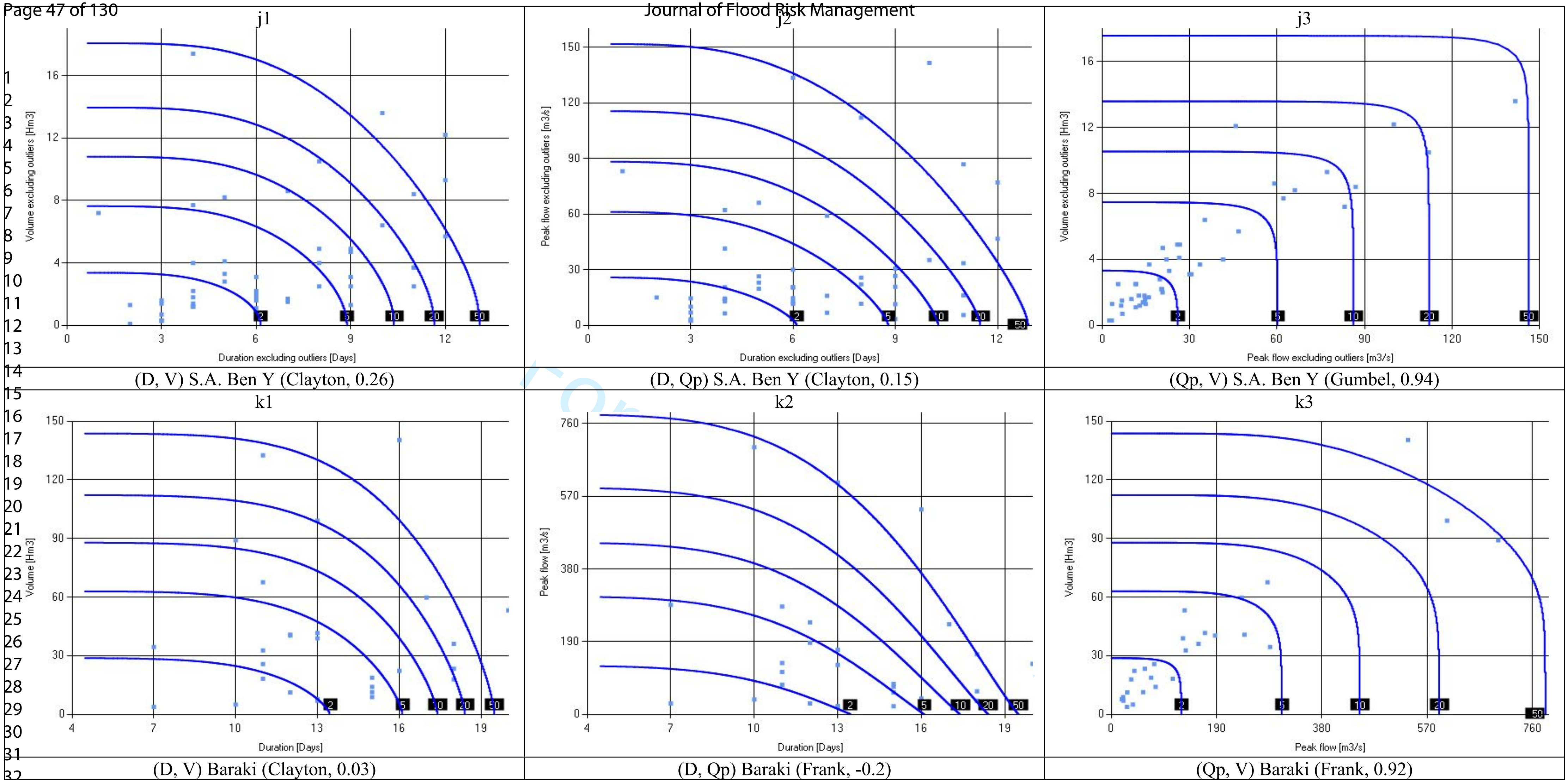


Figure 4. Contour line of pairs according to the selected copula for return period event of X ≥ x ∩ Y ≥ y