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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Frequency analysis of the extreme streamflow by the threshold level method in semi-arid region: Case study of Wadi Mekerra catchment in the North-West of Algeria

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Abstract

Extreme streamflow drought is the direct problem of serious on damaging and on social impacts, so the frequency analysis of hydrological drought is an important work can be done to studying the drought phenomenon in catchments. So the hydrometric data for a river conducts to the establishment of the flow duration curve (*FDC*) as an important index of streamflow drought regime, from this characteristic, a threshold level can be defined for both perennial or intermittent streams. Well, two partial duration series can be derived for each year; the deficit volume and drought duration series. In the catchment of Wadi Mekerra in the North-West of Algeria, the minimum value estimated from the Pareto's annual maximum instantaneous flood population (0.60 $m^3 \cdot s^{-1}$) is considered as the threshold level index where, the largest deficit volume and the largest drought duration occurring in a given year are taken into consideration. Hence, the frequency analysis of the streamflow drought regime of the catchment is analysed with Weibull distribution for both deficit volume and drought duration combined with the probability of occurrence which is determined under some criterion in order to forecasting the streamflow drought in the catchment.

Key words: *Algeria, deficit volume, drought duration, partial duration series PDS, streamflow, Wadi Mekerra*

INTRODUCTION

Drought is a natural disaster. In contrary to disasters as flood and heavy rainfall, a drought develops very slowly [TALLAKSEN, VAN LANEN 2004]. It is the cause of serious and most damaging natural disaster in terms of economic costs like the navigation and hydropower production [CARROLL *et al*. 2009; VAN VLIET *et al*. 2012; WILHITE 2000], social impacts like the increased morality of conflict [GARCIA-HERRERA *et al*. 2010; HSIANG *et al*. 2013]. Drought brings to mind crop failures, parched fields, failing water supplies and reduced electric power production in hydroelectric plants. Their consequences are a terrible reality. The drought can be characterized by the streamflow drought as randomness hydrological phenomena. So, the frequency analysis is an important methodology to analyse and to estimate synthetic streamflow drought for water resource planning, management and design. The hydrologic regime of streamflow droughts is of primary consideration in the design of industrial or municipal water supply systems, navigation development, hydroelectric plants, supplemental irrigation scheme, low flow augmentation systems, recreation facilities and other. Water quality criteria and stream standards are tied to the regime of streamflow droughts that affect also the preservation of fish and fowl habitat. Evaluation of the adequacy of river low flows to supply requirements for disposal of liquid wastes depends also on the characteristics of the process of streamflow droughts.

Streamflow drought is a natural hazard which having a severe consequence in all over the world's regions [VAN LOON 2015]. As natural hydrological phenomena, drought is a sustained period of below-normal water availability [TALLAKSEN, VAN LANEN 2004], so its impact is related to

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its occurring in different stages of the hydrological cycle and usually different types of drought can be distinguished. The deficit in precipitation is the origin of the meteorological drought. It can develop into soil moisture, which may reduce production of agricultural and increase the fires in forests. Also, may develop a deficit in surface water and groundwater, which conduct to reduction in water supply in drinking, irrigation and hydropower production causing death of fish and hampering navigation in certain countries.

The characterization of drought is often referred to some indices, which depend on the hydro-climatology, the characteristics of the soil, the vulnerability of society and the available data too. In case of the streamflow drought or hydrological drought is distinguished into two fundamentals characteristics, streamflow drought duration and drought deficit volume [HISDAL *et al*. 2004; VAN LOON, LAAHA 2015]. The analysis of streamflow duration and its according deficit volume as a time series of different occurrence in each year describes the regime of drought in low flow according to their magnitude that expressed only by the discharge [TALLAKSEN *et al*. 1997].

The stream discharge series are viewed according to time dependent process, well the task is to identify the drought event from the first time to the last of the each year. In this way, a series of drought events can be derived from the discharge series and droughts can be described and quantified by several characteristics, such as drought duration, deficit volume, etc.

The methodology used in this paper, is based on the frequency analysis of the drought duration and deficit volume commonly derived by the threshold level method that is evaluated for its applicability to instantaneous discharges of Wadi Mekerra catchment in the North West of Algeria. The frequency analysis of partial drought duration series of drought deficit series.

STUDY AREA AND DATA

The study has been conducted on the catchment of Wadi Mekerra (Fig. 1) situated in the North-West of Algeria about 400 km from Algiers between 0°30'and 1° of East longitude and 35°15' of North latitude. The catchment covers an area of 3000 km^2 and the length of principal stream of the watercourse is 115 km, from the source in the highlands at Ras-El-Ma to the town of Sidi-Bel-Abbes. The climate is semi-arid and is characterized by irregular rainfall causing significant flooding, with a decennial annual maximum equal to 141 mm.

For the catchment, the data set used in this study is provided by the National Agency of Hydraulics Resources (Fr. Agence Nationale des Ressources Hydrauliques – ANRH) of Algiers, it consists of the discharge time series in both mean daily and instantaneous discharges for the periods 1947/1948 to 1960/1961, 1968/1969 to 1970/1971 and 1974/1975 to 1997/1998 collected at Sidi-Bel-Abbes gauge station. The length of discharge series was 41 years. The total length of mean daily discharge time series is used to determine hydrological drought threshold level index and the length of instantaneous discharge time series is used to calculate the characteristics duration and deficit volume for each year.

Fig. 1. Wadi Mekerra catchment; source: own elaboration

THE FLOW DURATION CURVE

A flow duration curve (*FDC*) represents an interesting relationship between the magnitude of discharge and frequency of daily streamflow in catchment. An *FDC* provides an estimate of the percentage of time a given streamflow was equalled or exceeded over a historical period, also provides a simple, yet comprehensive, graphical view of the overall historical variability associated with streamflow [VOGEL, FENNESSEY 1994]. The *FDC* is constructed by ranking the whole daily streamflow, for each value of the frequency of exceedance computed using empirical frequency plotting position formula (Fig. 2).

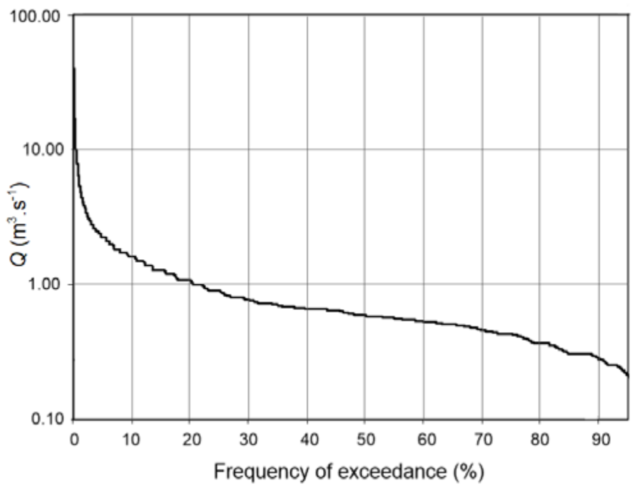

Fig. 2. *FDC* (flow duration curve) of Wadi Mekerra; source: own elaboration

The form of the *FDC* gives information about the possibility to choice of the threshold levels Q_p. Therefore, the drought event is defined as a period of time when the flow does not exceed the assumed threshold level Q_p which is read or referenced from the *FDC*. The value of the percentage *p* is typically between 70% and 95% [HISDAL, TALLAKSEN 2000; SMAKHTIN 2001; STAHL 2001; VAN LOON *et al*. 2011; ZELENHASIC, SALVAI 1987]. The method used for choosing or calculating the threshold level can influence the quantification of drought events [BEYENE *et al*. 2014].

THRESHOLD LEVEL METHOD

Let's Q_p a threshold level, the drought phenomena is characterized when the streamflow discharge drop below the threshold Q_p [YEVJEVICH 1967]. The magnitude of the drought characteristics depends on the level of the threshold. For each drought event the characteristics are the deficit volume V and drought duration d which is the time between down-crossing and up-crossing from the threshold (Fig. 3) from time series of instantaneous streamflow [TALLAKSEN 2000].

The threshold level method [CRAMÉR, LEADBETTER 1967; RICE 1945] is an early application of crossing theory in hydrology includes [FLEIG *et al*. 2006; HISDAL *et al*. 2004; MISHRA, SINGH 2010; 2011; SHEFFIELD *et al*. 2012; YEVJEVICH 1967], where the method is based on the statistical theory of runs for analysing a sequential time series. Statistical properties of the distribution of water deficits, run-length (drought duration, d_i), run-sum (deficit volume, V_i) are recommended as parameters for streamflow drought definition. Simultaneously it is possible to define the minimum flow, $Q_{\min i}$ and time of occurrence, t_i (Fig. 3). The minimum flow can be regarded as a low flow measure, one of several characteristics of a streamflow drought event. The time of drought occurrence has been given different definitions as for instance the starting date of the drought, the mean of the onset and the termination date ($t_i + d_i$). For the interval $[t_i, t_i + d_i]$, the value of deficit volume V_i is calculated by the integral of the cubic spline piecewise polynomial approximation (Fig. 3).

The threshold level Q_p as an index of streamflow drought, is chosen to represent the boundary between normal and usually low streamflow. This choice is based on the characteristics of the streamflow regime as a percentile from the flow duration curve and is frequently applied for both perennial and intermittent streams. For perennial streams, threshold levels are chosen between $Q_{70\%}$ and $Q_{95\%}$, for intermittent streams lower exceedance percentiles have to be chosen, depending on the percentage of zero flow [HISDAL *et al*. 2002; TALLAKSEN *et al*. 1997]. The choice of threshold might be in a number of ways and is amongst other a function of the type of water deficit [DRACUP *et al*. 1980].

In the case of Wadi Mekerra catchment, the threshold level that considered is the minimum value $Q_{\min}$ existing in Pareto's population of the annual maximum instantaneous flood flow *QIX* [YAHIAOUI 2012]. So, the Pareto distribution is used to fitting the instantaneous maximum flood flow series (QIX_1, QIX_2, QIX_3, … QIX_{41}) of Wadi Mekerra catchment [YAHIAOUI 2012]. The Pareto probability density function [NEWMAN 2005] is given by:

$$P(X = QIX) = \frac{\kappa - 1}{Q_{\min}} \left(\frac{QIX}{Q_{\min}} \right)^{-\kappa} \tag{1}$$

Where κ is the only parameter (tail) and $Q_{\min}$ is the minimum value existing in the population. By the use of the maximum likelihood method [ALDRICH 1997; GOLDSTEIN *et al*. 2004], the parameter κ is given by:

$$\kappa = 1 + \frac{41}{\sum_{i=1}^{41} \ln \frac{QIX_i}{Q_{\min}}} \tag{2}$$

Hence, $Q_{\min}$ can be obtained as a function of κ:

$$Q_{\min} = \exp\left(\frac{1}{41} \sum_{i=1}^{41} \ln QIX_i - \frac{1}{\kappa - 1} \right) \tag{3}$$

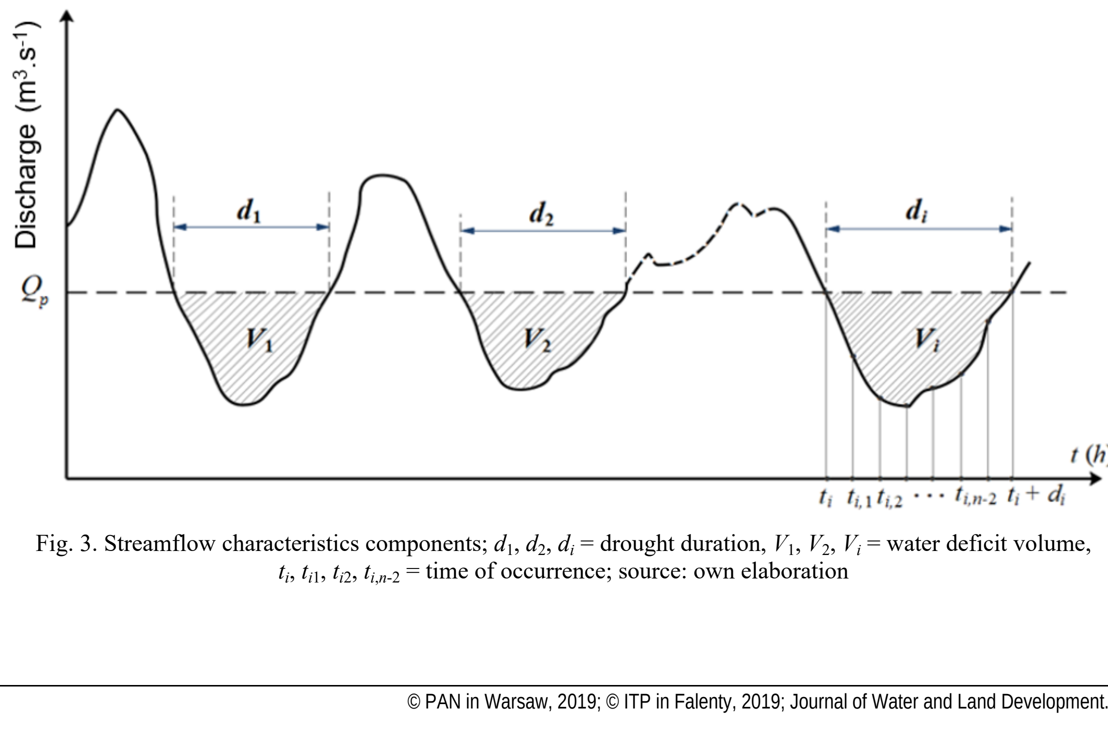

Fig. 3. Streamflow characteristics components; d_1, d_2, d_i = drought duration, V_1, V_2, V_i = water deficit volume, t_i, t_{i1}, t_{i2}, $t_{i,n\text{-}2}$ = time of occurrence; source: own elaboration

To estimate the value of $Q_{\min}$ [YAHIAOUI 2012; YAHIAOUI, TOUAIBIA 2011], lets considering the discrete probability density function of Pareto given by JOHNSON *et al*. [2005]:

$$P(X = k) = \frac{k^{-\kappa}}{\zeta(\kappa)} \tag{4}$$

Where $\zeta(\kappa)$ is the Riemann Zeta function:

$$\zeta(\kappa) = \sum_{m=1}^{\infty} \frac{1}{m^{\kappa}} \tag{5}$$

The estimation of the parameter κ by maximum likelihood method is given by the equation in κ:

$$\frac{\zeta'(\kappa)}{\zeta(\kappa)} = -\frac{1}{41}\sum_{i=1}^{41} \ln QIX_i \tag{6}$$

Where $\zeta'(\kappa)$ is the derivative of the Riemann Zeta function. The value of the ratio $\zeta'(\kappa)/\zeta(\kappa)$ can be generated on most modern mathematical and engineering calculation programs [LOPEZ 2014]. The second member of the Equation (6) is equal to –3.32 so $\kappa = 1.26$ and from the Equation (3), $Q_{\min}$ can be obtained and is equal to 0.60 $m^3 \cdot s^{-1}$, which will be considered as the threshold level. Observing in the flow duration curve, this threshold is corresponding to $Q_{78\%}$ so the stream is in perennial drought.

According to that threshold, the statistical characteristics of the deficit volume and the corresponding streamflow duration series of Wadi Mekerra catchment are given in Table 1.

Table 1. Statistical characteristics of the partial duration series of the volume and drought duration

Characteristic	Deficit volume	Duration
Size	604 elements	604 elements
Mean	4.34 $m^3 \cdot s^{-1} \cdot$day	10 days
Median	1.20 $m^3 \cdot s^{-1} \cdot$day	2 days
Standard deviation	8.37 $m^3 \cdot s^{-1} \cdot$day	20 days
Variance	4.03·104	$2.4 \cdot 10^5$
Variation	1.93	2.04
Skewness	4.4	5.0
Kurtosis	30.14	41.06
Minimum	0.01 $m^3 \cdot s^{-1} \cdot$day	2 hours
Maximum	85.42 $m^3 \cdot s^{-1} \cdot$day	245 days

Source: own study.

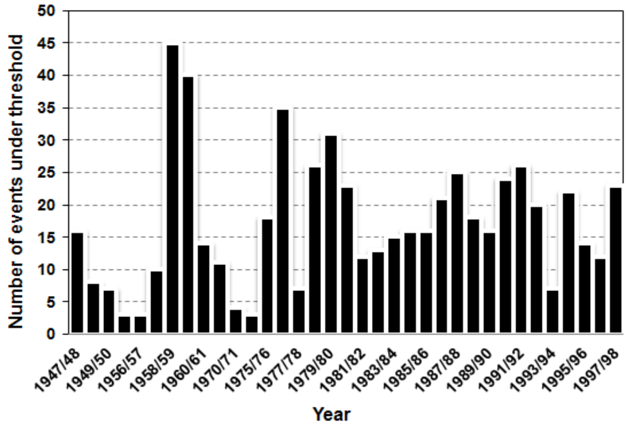

Fig. 4. Number of events under threshold; source own study

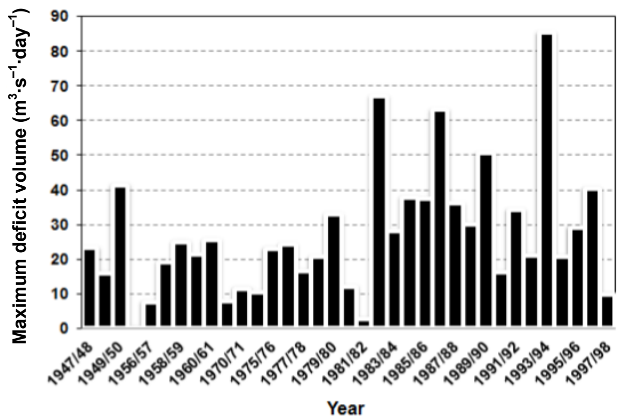

Fig. 5. Annual maximum deficit volume; source: own study

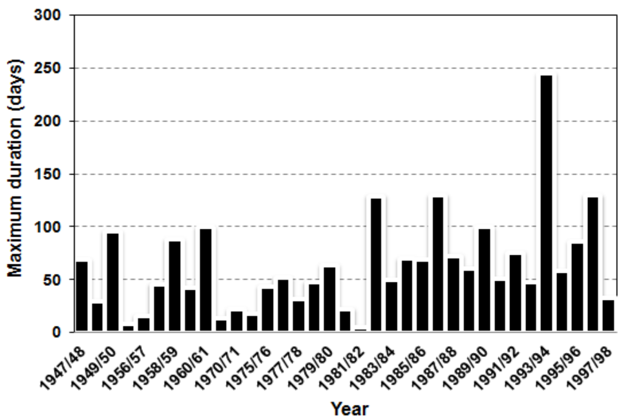

Fig. 6. Annual maximum streamflow duration; source: own study

The number of drought occurring in a period corresponding to maximum deficit volume and maximum drought duration are represented in the Figures 4, 5 and 6.

FREQUENCY ANALYSIS

Frequency analysis of the streamflow aims to fitting to the probability distribution of the drought deficit volume and its corresponding duration that enable one to predict probable possible droughts [HISDAL, TALLAKSEN 2000]. The cumulative distribution function of the largest drought events occurring in a given year, of annual maximum series (AMS) or extracted partial duration series (PDS) like in the case of Wadi Mekerra of drought duration and deficit volume events [ENGELAND *et al*. 2004; ZELENHASIC, SALVAI 1987]. So, the frequency analysis consists of two parts, the first one is to estimate the probability distribution of the number of events occurring during the time interval and the second one is to estimate the distribution probability of the drought deficit characteristics (deficit volume and drought duration) events occurring in the year. The probability distribution function of the largest drought characteristics event in a given time is computed as follow [TODOROVIC, ZELENHASIC 1970; ZELENHASIC, SALVAI 1987]:

$$F(x) \equiv P(X \le x) = \sum_{k=0}^{\infty} [H(x)]^k g(k) \tag{7}$$

Where $H(x)$ is the cumulative distribution function of the drought deficit events; $H(x)$ is the Weibull distribution; $g(k)$ is the probability density function that k events occur in a given year; k, is assumed to be Poisson distributed with probability function:

$$g(k) = \frac{(\lambda)^k}{k!} \exp(-\lambda) \tag{8}$$

The Poisson parameter λ equals to the expected number of occurrences in each year is estimated by the mean of drought deficit events, which equals approximately 17 (Fig. 4). From Equations (7) and (8), $F(x)$ can be expressed by:

$$F(x) = \exp\left[-\lambda(1 - H(x))\right] \tag{9}$$

The important focus of the frequency analysis is to determine the probable evolution of the drought deficit events as in deficit volume and drought duration according to recurrence period.

The Weibull distribution is characterized by two parameters, the shape parameter κ and the scale parameter a. The cumulative distribution function is given by:

$$H(x) = 1 - \exp\left(-\left(\frac{x}{a}\right)^{\kappa}\right) \tag{10}$$

Where a and κ can be estimated by the method of moments by the resolution of the system of equations:

$$\begin{cases} a\Gamma\left(1 + \dfrac{1}{\kappa}\right) = \bar{x}, \\ a^2\Gamma\left(1 + \dfrac{2}{\kappa}\right) - \bar{x}^2 = S^2. \end{cases} \tag{11}$$

Where Γ(.) is the Gamma function [GAUTSCHI 1959].

An approached solution of Equation (11) gives a_v = 2.61, κ_v = 0.56 for deficit volume (Fig. 7) and a_d = 5.55, κ_d = 0.53 for drought duration (Fig. 8).

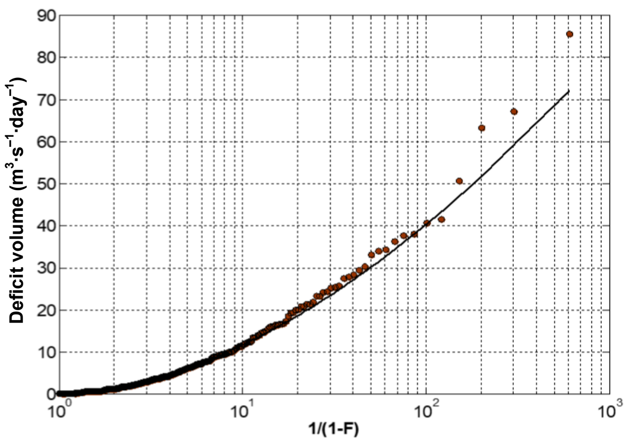

Fig. 7. Fittings of the deficit volume to the Weibull distribution; source: own study

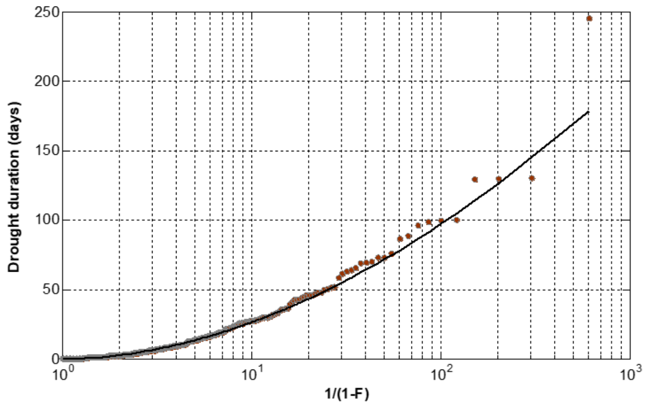

Fig. 8. Fittings of the streamflow duration to the Weibull distribution; source: own study

The goodness of fit test of the Weibull distribution to the both deficit volume and drought duration (Tab. 2), are be done by the probability plot correlation (*PPC*-test) [VOGEL 1986], root mean square deviation (*RMSD*-test) [NERC 1975] and Kolmogorov–Smirnov (KS-test). The values of *PPC* are both near to 1, the values of *RMSD* are less than 1 and the values of observed Kolmogorov–Smirnov are near to 0.10 as theoretical value at 5% of significance. All this tests are accepted.

Table 2. Goodness of fit test of Weibull distribution in both deficit volume and drought duration

Parameter	Drought characteristic		
	PPC	*RMSD*	*KS*
Deficit volume	0.990	0.24	0.06
Drought duration	0.990	0.30	0.10

Explanations: *PPC* = probability plot correlation, *RMSD* = root mean square deviation, *KS* = Kolmogorov–Smirnov statistic.
Source: own study.

RESULTS AND DISCUSSION

According to goodness of fit tests (Tab. 2), the Weibull distribution is adequate for the both deficit volume (Fig. 7) and drought duration (Fig. 8). So the Weibull probability can be used with the probability of occurrences for prediction.

The central part of the frequency analysis is the determination of the distribution function $F(x)$ of the largest annual deficit volume and the largest drought duration in order to predict for different return periods the largest streamflow drought characteristics. Therefore, from the Equation (9), the quantile x_T associated to the return period T can be obtained as:

$$\exp\left[-\lambda(1 - H(x_T))\right] = 1 - \frac{1}{T} \tag{12}$$

But for Weibull distribution, the Equation (12) becomes:

$$\exp\left[-\lambda \exp\left(-\left(\frac{x_T}{a}\right)^{\kappa}\right)\right] = 1 - \frac{1}{T} \tag{13}$$

Hence,

$$x_T = a\left[-\ln\left(\frac{1}{\lambda}\ln\left(\frac{T}{T-1}\right)\right)\right]^{1/\kappa} \tag{14}$$

For known values of λ, a and κ, Equation (14) gives the values of quantiles of the largest deficit volume and the largest drought duration of Wadi Mekerra catchment (Tab. 3).

Table 3. Estimated quantiles of the largest deficit volume and drought duration

Return period (years)	Deficit volume (10^6 m^3)	Duration (days)
2	1.80	50
5	3.09	88
10	4.11	119
20	5.21	153
50	6.80	203
100	8.11	244
500	11.51	354
1 000	13.14	407

Source: own study.

According to the obtaining results (Tab. 3), the streamflow severe droughts as deficit volume and drought duration follow from Equation (7) occur in the whole year. For example, the maximum annual deficit volume $V_{100\text{-years}} = 8.11 \cdot 10^6$ m^3 will be occur in maximum drought duration $d_{100\text{-years}} = 244$ days or larger in the whole year possible in or after 100 years.

Otherwise, the duration of one year ($d = 365$ days), its corresponding return period T obtained from Equation (13) as:

$$T = \frac{1}{1-\exp\left[-\lambda\exp\left(-\left(\frac{d}{a_d}\right)^{\kappa_d}\right)\right]} \tag{15}$$

Numerically, $T \approx 579$ years, according to this value and using the Equation (14), the drought deficit volume is estimated as $V_{579\text{-years}} = 11.85 \cdot 10^6$ m^3, which is a rare value, can be occurred in this period of whole year.

CONCLUSIONS

Streamflow is a natural hazard, which can cover long periods. So, the methodology of the frequency analysis to predict the drought characteristics as the deficit volume and drought duration is based on the threshold level method.

The minimum value in the population of the annual maximum instantaneous flood flow is considered as the threshold of the drought, so the partial duration series of deficit volume and drought duration are derived and frequency analysed by the Weibull distribution probability combined with a distribution of the occurrences.

According to obtaining results, the catchment of Wadi Mekerra as in semi-arid area, can be affected by a predicted severe drought from an occurrence of fifty years with magnitude of a deficit volume of $6.80 \cdot 10^6$ m^3 for probable duration approximately of seven months.

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Analiza częstotliwości ekstremalnych przepływów metodą wartości progowych w regionie o półsuchym klimacie: Przypadek zlewni Wadi Mekerra w północnozachodniej Algierii

STRESZCZENIE

Skrajnie niski przepływ w rzece wywołuje poważne, szkodliwe dla środowiska i społeczeństwa skutki, dlatego analiza suszy jest ważnym zadaniem w celu poznania zjawiska w skali zlewni. Dane hydrometryczne rzeki prowadzą do ustalenia krzywych natężenia przepływu (FDC) jako ważnego wskaźnika reżimu przepływu w warunkach suszy. Korzystając z tych charakterystyk, można zdefiniować wartość progową, zarówno dla cieków stałych, jak i dla okresowych. Dla każdego roku można wyprowadzić dwie cząstkowe serie trwania przepływu: serię deficytu objętości i serię trwania suszy. W zlewni Wadi Mekerra w północnozachodniej Algierii minimalna wartość oszacowana na podstawie rocznej populacji Pareto maksymalnych chwilowych powodzi jest traktowana jako wskaźnik wartości progowej, w związku z czym bierze się pod uwagę największy deficyt objętości i najdłuższe trwanie powodzi w danym roku. Analizę częstotliwości przepływu w warunkach suszy w zlewni przeprowadza się w celu prognozowania przepływu w warunkach suszy w zlewni. Wykorzystuje się do tego rozkład Weibulla, zarówno w odniesieniu do deficytu objętości, jak i czasu trwania suszy w powiązaniu z prawdopodobieństwem wystąpienia, które oznacza się, przyjmując pewne założenia.

Słowa kluczowe: *Algieria, cząstkowe serie trwania PDS, deficyt objętości, przepływ, trwanie suszy, Wadi Mekerra*