JJEES

JJEES (2019) 10 (3): 127-135
ISSN 1995-6681

Jordan Journal of Earth and Environmental Sciences

A Regional Study of Frequency Maximum Daily Flows of the Upper Senegal River Basin (Guinea, Mali, Senegal and Mauritania)

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Received 4 February 2019; Accepted 21 April 2019

Abstract

Frequency analysis of extreme events is among the preferred tools for estimating flood flows and their return periods. In a frequency analysis, the observations must be independent and identically distributed. These assumptions are not often respected, and the parameters of the frequency distributions to be adjusted are time-dependent or co-variable. The objective of this article is to make a statistical analysis of the maximum daily flow of six hydrometric stations located in the upper Senegal River basin. Four frequency distributions were thus retained in this analysis and adjusted in conjunction with the maximum daily flow: the generalized extreme value frequency distribution (GEV), the Pearson type 3 frequency distribution, the Gumbel frequency distribution, and the Log-normal frequency distribution. The comparison between these distributions was ensured through the calculation of adjustment indices, the robustness of simulation method, the visual test, and particularly the chi-square test. The results from the four methods are not significantly different. However, after classifying the frequency distributions, the statistical quality of the adjustment was taken into account. Thus, the Pearson type 3 frequency distribution was chosen to estimate the maximum flow quantiles in the upper Senegal River basin for different return periods.

Keywords: annual maximal flow, statistical adjustment, frequency analysis, estimation, Senegal River basin

1. Introduction

The extreme values are often the maxima of a certain quantity over a given period, characterized either by maximum values (flood) or minimum values (low water). Floods are most often described by three main characteristics: peak, volume, and duration. There has been a renewed interest in research and studies of floods over the last decades. This can be explained by the concerns of the scientific community and decision-makers regarding the increasingly high frequency of the appearance of devastating floods (Meddi and Abbes, 2014). In many studies, this is linked to climate change (Burn, 1998; Vastila et al., 2010; Roy et al., 2001). The effect of climate change on hydrological variables related to extreme events (maximum annual rainfall, maximum annual flow, etc.) can be done by studying the existence of trends in the series observed, or by analyzing the dependence variables studied with other climate variables or indices, called covariates (Katz, 1999).

There are various approaches to studying and predicting floods. Below is the typology proposed by Lang and Lavabre (2007):

- Statistical processing performed on observed flow samples to determine given return period rates.
- Empirical formulations based on observed flow samples to determine volume and duration.
- The use of deterministic transfer and production functions (e.g. the Soil Conservation Service (SCS) method and rational method).

The statistical treatment of hydrometric data is the preferred approach for hydrologists to analyze the risk associated with extreme hydrologic events. Thus, many frequency distributions are often applied in different parts of the world to estimate quantiles of maximum flow rates. Among these frequency distributions are the frequency distribution of Gumbel long used in Algeria, the frequency distribution of the extreme values generalized (GEV) in Great Britain, the Lognormale frequency distribution in China, the frequency distribution Log-Pearson type III (LPIII) in the United States, the Lognormale frequency distribution in the Chéllif basin in Algeria, and the Gamma frequency distribution in Spain (Meddi and Abbes, 2014).

The Senegal River basin (the valley and the delta in particular) is periodically affected by floods and floodings. These extreme events (devastating floods) punctuate the climatic variability which acts directly on the national economy, because of the low level of control of the waters and the bad conditions of the filling of the reservoirs. The city of Saint Louis (in Senegal), located in the delta, has undergone the effects of large and repeated floods. Significant floods and overflows of the Senegal River are indicated in travelers' accounts, historical documents, and ancient maps well before 1903 (beginning of the first measurements of water depth). The major recorded floods are those of 1827, 1841, 1843, 1853 (Kane, 2002), resulting in extremely large overflows of the river to the point that homes were full of water up to the first floor (Hardy, 1921). In the Senegal River basin, water resources can become a problem because of their

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overabundance as was the case with the devastating floods of 1890, 1906, and 1950 (Roche, 2003); hence, their studies are of great importance.

Flood hazard studies provide decision-makers in the planning field with the necessary elements for decision-making. The methods of regional frequency analysis make it possible to estimate, for a given site, and on the basis of the regional information, the quantiles of period of return. These studies are very often used for the design and sizing of hydraulic structures such as water retaining structures, anti-erosion structures, and sewerage networks (Onibon et al., 2004). They are also used more generally to allow an overall description of the characteristics of the spatial structure of the different hydrological phenomena in a region. They were initially developed for the estimation of flood flows (Cunnane, 1988, Ouarda et al., 2001). For the purposes of hydraulic modeling, these studies include the estimation of extreme flood flows corresponding to the return periods of 25, 50, and 100 years, respectively representing high, medium and low recurrences (Meddi and Abbes, 2014). Estimations of extreme event flows are a topic of growing interest in water sciences.

Prior to the statistical modeling of series, it is taken for granted that the following approaches are detrmined (1) the way of constituting a sample, (2) a frequency distribution, (3) a method of estimating parameters and quantiles and (4) a scheme that allows the joint use of local and regional data (WMO, 1989). For the constitution of the samples, one can retain either the maximum values of each year, or all the data above a previously fixed threshold, and for a given time step (Ferrier, 1992). The methodology based on the choice of maximum values for each year is generally preferred by both researchers and designers (Cunnane, 1987) because it is easier to apply and is often more statistically effective. For these reasons, it was also maintained in this analysis. This article is interested in finding a frequency distribution capable of accounting for the maximum daily discharge regime, and the estimation of parameters and quantiles for the prevention of flood risks. Thus, the main objective is to find a theoretical frequency distribution that can show a good presentation of the distribution function of the studied process. Also, this study shows how to adjust several frequency distributions from the maximum flows in the basin and choose the best one, that is the most suitable to evaluate the quantiles of the flood flows through the visual test (graphical quality of adjustment) and the chi test.

2. Study area

The Senegal River, some 1,700 km long, drains a basin of 300,000 km^2, straddling four countries that are upstream, downstream, namely Guinea, Mali, Senegal, and Mauritania (Figure 1). It ranges from 10° 20 'to 17° N and from 7° to 12° 20' W and is made up of several tributaries; the main ones being Bafing, Bakoye and Falémé which take their sources in Guinea and form the top basin (OMVS / GEF / BFS Project, 2008) (Figure 1). The Senegal River thus formed by the junction between Bafing and Bakoye, receives the Kolimbiné then Karokoro on the right and Falémé on the left, 50 km upstream of Bakel. In the southern part of the basin, the density of the surface hydrographic network testifies to the impermeable nature of the terrain (Michel, 1973; Rochette, 1974).

Like the entire intertropical band, the Senegal River basin has experienced a climate upheaval since the 1970s (Faye, 2013). The various studies on this basin have already shown the effects of climate change with changes in its hydrological regime from 1970 (Hubert et al., 1989; Dione 1996; Nicholson et al., 2000; Ardoin-Bardin, 2004; Sow, 2007; Faye, 2013 ; 2015; Faye et al., 2015a; Faye et al., 2015b; Faye, 2017). To remedy the effects of climate change and cope with the changes in its hydrological regime, a set of developments (Diama and Manantali) was started, completely transforming the hydrological dynamics of the Senegal River basin.

The basin is generally divided into three entities: the upper basin, the valley, and the delta which are strongly differentiated by their topographical and climatological conditions. The upper basin, the current study area, extends from the sources of the Senegal River (Fouta Djalon) to the confluence between the Senegal River and Falémé (downstream of Kayes and upstream of Bakel). It is roughly made up of the Guinean and Malian parts of the river basin, and provides almost all of the water supply (more than 80 % of the inflow) from the river to Bakel because it is relatively wet (OMVS / FEM / BFS project, 2008). Rain falls between April and October in the mountainous part of the extreme south of the basin, especially in the Guinean part of the basin, and causes the annual flood of the river which takes place between July and October.

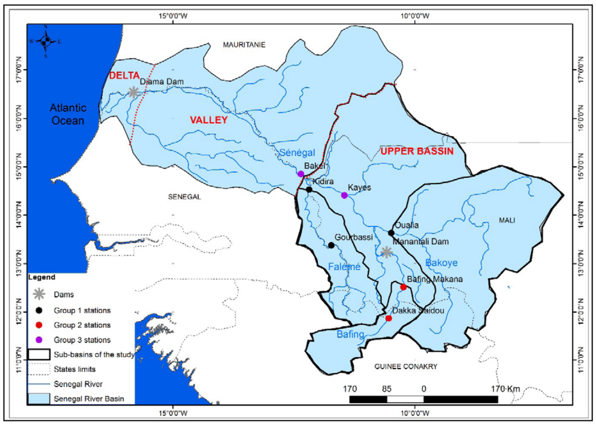

Figure 1. Location of the Senegal River basin and its Upper basin

3. Data and Methods

3.1. Data

The database of stations in the upper Senegal River basin to be maintained for this study should contain a series of daily flows which meet two important criteria: the length of the chronicles on the one hand (cover the largest period of time possible), and the quality of data on the other hand (the least possible missing data). This has been the case at the six stations selected for this study. The hydrometric data in this study were provided by the Senegal River Development Organization (OMVS). These data concern the daily flows (from 1950 to 2014) from which the annual daily maximum flows are calculated. Figure 2 shows the evolution of the maximum instantaneous flow rates observed for the selected stations.

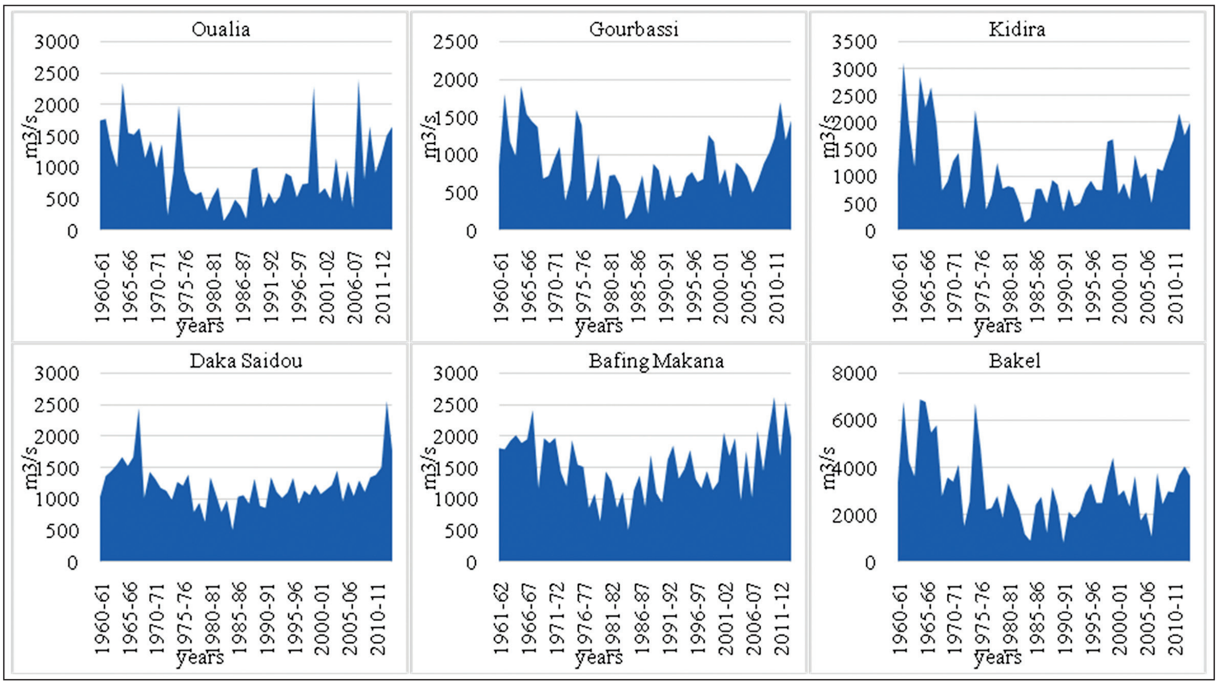

Figure 2. Evolution of annual maximum daily discharges of stations selected in the upper Senegal River basin

3.2. Methods

3.2.1. Statistical Homogeneity Test by Principal Component Analysis

Principal component analysis (PCA) is a statistical technique used (Faye, 2014; Baba-Hamed and Bouanan, 2016) to reduce the number of variables to those that are most significant among a set of variables. It is used to find a link between variables and individuals in order to group them into homogeneous regions. One of the objectives of the PCA is to obtain useful information from a data matrix, and to provide a graphical representation of the data to facilitate analysis. The mathematical procedure of principal component analysis is in fact a multivariate statistical method that serves as a data processing. In this study, all the modules for stations of the upper Senegal River basin were submitted to the principal component analysis in order to determine the affinities between these sub-basins.

3.2.2. Statistical Frequency Distributions for Frequency Analysis of Extreme Flows

Frequency analysis of extreme flows is a statistical analysis that consists of predicting the probability of occurrence of an event of a given importance based on the knowledge of past events, that is flow measurements recorded during a chronicle of several years. In this sample, it is, then, a question of selecting the relevant events which will serve to establish a statistical frequency distribution to represent the studied phenomenon at best. There are different ways to calculate the variables of a theoretical frequency distribution to fit on a sample (Ruf, 2004). The methods used here are those of the moments and that of the maximum likelihood. In this study, the following frequency distributions are used (Table 1):

- Generalized Extreme Value (GEV) frequency distribution: The GEV distribution is recommended for flood studies because it gives good adjustments to the series.
- Gumbel's frequency distribution (doubly exponential frequency distribution): It is adapted to the study of the maximum value of a variable having many achievements over a period (for example by studying floods above a threshold).
- Pearson type 3 frequency distribution: It adjusts easily, but sometimes gives too low probability to a high flood; it works here for the study of variables with positive skewness.
- Log normal frequency distribution: It is recommended by some hydrologists who justify it by the fact that a hydrological event is the result of a large number of factors. The normal log frequency distribution works particularly well when there is a complex varied diet and when there is no regularity of the diets.

Table 1. Probability Density Function of Selected frequency distributions

Frequency distribution	Probability density function	Parameters
GEV	$f(x) = \frac{1}{\alpha}\left[1\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}-1} \exp\left[-\left[1\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}}\right]$	α, u, k
Gumbel	$f(x,\alpha,u) = \frac{1}{\alpha}\exp\left[-\left[-\frac{x-u}{\alpha} - \exp\left(-\frac{x-u}{\alpha}\right)\right]\right]$	α, u
Log normal	$f(x,\alpha,u) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left[\frac{[Lnx-u]^2}{x\sigma^2}\right]$	u, σ
Pearson type 3	$f(X) = \frac{\alpha^\lambda}{\Gamma} e^{-\alpha(x-m)}(X-m)^{\lambda-1}$	α, λ, m

k: shape parameter; α: scale parameter; μ:location parameter; m: the original parameter $m \leq X \leq \infty$; $\lambda > 0$; λ: the shape parameter; X: a random variable

Many techniques exist to compare the four methods of analysis of the frequency distributions of probability and to choose the best one. The chi-square adequacy test has been adopted and remains a good way to judge the quality of an adjustment. Since tests are tools used to facilitate decision-making, they can sometimes help separate two models, but most often, they show comparable results for two well-adjusted frequency distributions (Habibi et al., 2013).

3.2.3. Definition of a Flow Calculation Tool

From the results, an attempt has been made to establish a general flow calculation formula accepted by many authors (Ruf, 2004). For a given frequency, the flood discharge of a watercourse has its logarithm, which increases linearly according to that of the drained surface:

$$Q = A.S^{n} \quad or$$
$$Log\ Q = Log\ A + n\ Log\ S$$

This simple formula chosen therefore only considers the factors A and n which will be representative of the basin as well as its surface S. The factors A and n may still vary according to the geographical position of the basins which will vary, among others, the abundance of precipitation. This formula will be tested on the decennial flows and the centennial flows to define a preliminary tool of the study of the extreme flows.

4. Results and Discussion

4.1. Establishment of Groups of Stations and Homogeneity Tests

For the decomposition of the study area into homogeneous groups of stations, the principal component analysis that was used allowed the upper basin to be subdivided into homogeneous groups of stations. Thus, three main groups stand out and provide a better understanding of the spatiotemporal dynamics of the functioning of the hydrosystem of the upper Senegal River basin (Table 2 and Figure 3).

- Group 1 consists of natural (uncontrolled) reaches of Faleme (at Gourbassi and Kidira) and Bakoye (at Oualia);
- Group 2 is composed of the natural reaches of the Bafing upstream of the Manantali dam (in Dakka Saidou and Bafing Makana);
- Group 3 consists of the semi-artificialized reach after the confluence of Bafing, Bakoye and Falémé (in Kayes and Bakel).

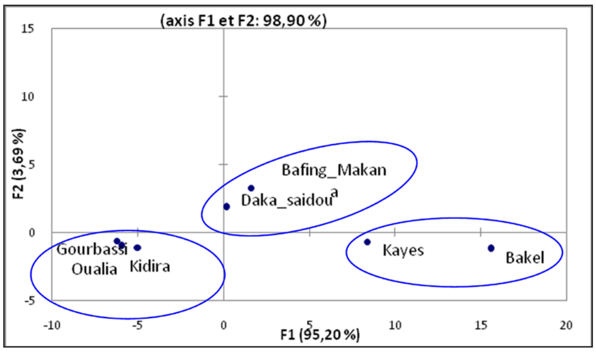

Figure 3. Homogeneity test of different groups compared

Table 2. Results of the homogeneity test of the different basins

regions	basins	Stations	Area km2	Module m^3/s	FMAX m^3/s	Axis 1	Axis 2
Group 1: natural diversions (uncontrolled)	Bakoye	Oualia	84700	118	945	-5.92	-1.01
	Falémé	Gourbassi	17100	108	863	-6.22	-0.64
		Kidira	28900	140	1149	-4.96	-1.09
Group 2: upstream reaches dam	Bafing	Dakka Shelpou	15700	233	1236	0.19	1.83
		Bafing Makana	22000	258	1549	1.61	3.27
Group 3: semi-artificialized bays	Senegal	Kayes	157400	436		8.36	-0.70
		Bakel	218000	597	3173	15.6	-1.21

In this distribution, the basins of the third group (made up of the Senegal River basin) stand out clearly from the basins of the other groups because of their larger surface area (157400 km^2 in Kayes and 218000 km^2 in Bakel) and, therefore, their largest flow past average (436 m^3/s at Kayes and 597 m^3/s at Bakel). In return, the basins of the second group (composed of the sub-basins of the Bafing upstream of Manantali) are distinguished from those of the first group because of a larger flow elapsed (233 m^3/s in Dakka Saidou and 258 m^3/s to Bafing Makana) related to their more southern position. The situation of the basins of the first group, which isolates themselves, is attributed to their lower flow (108 m^3/s Gourbassi and 140 m^3/s and Kidira on the Falémé, 118 m^3/s in Oualia on the Bakoye).

4.2. Application and Choice of the Best Frequency Distribution for Maximum Flows

After the establishment of homogeneous groups, the identification of a regional distribution probability frequency distribution, which is better suited to the annual peak flow series of the stations in each group, was made using the chi-square test (Table 3). This also makes it possible to evaluate the impact of the exclusive use of frequency distributions such as Gumbel and Log Normale in civil engineering and hydraulic engineering studies (Meddi and Abbes, 2014).

Table 3. Values of the p-value on the four models applied with the chi-square test

regions	stations	GEV	Gumbel	Normal Log	Pearson type III
Group 1	Oualia	<0.0001 *	.6338	<0.0001 *	<0.0001 *
	Gourbassi	0.0011 *	.6338	<0.0001 *	0.0002 *
	Kidira	<0.0001 *	.6338	<0.0001 *	<0.0001 *
Group 2	Dakka Saidou	<0.0001 *	.6338	<0.0001 *	<0.0001 *
	Bafing Makana	.9586	.6338	<0.0001 *	<0.0001 *
Group 3	Bakel	<0.0001 *	.6338	<0.0001 *	<0.0001 *

** significant test (risk of error of 0.05)*

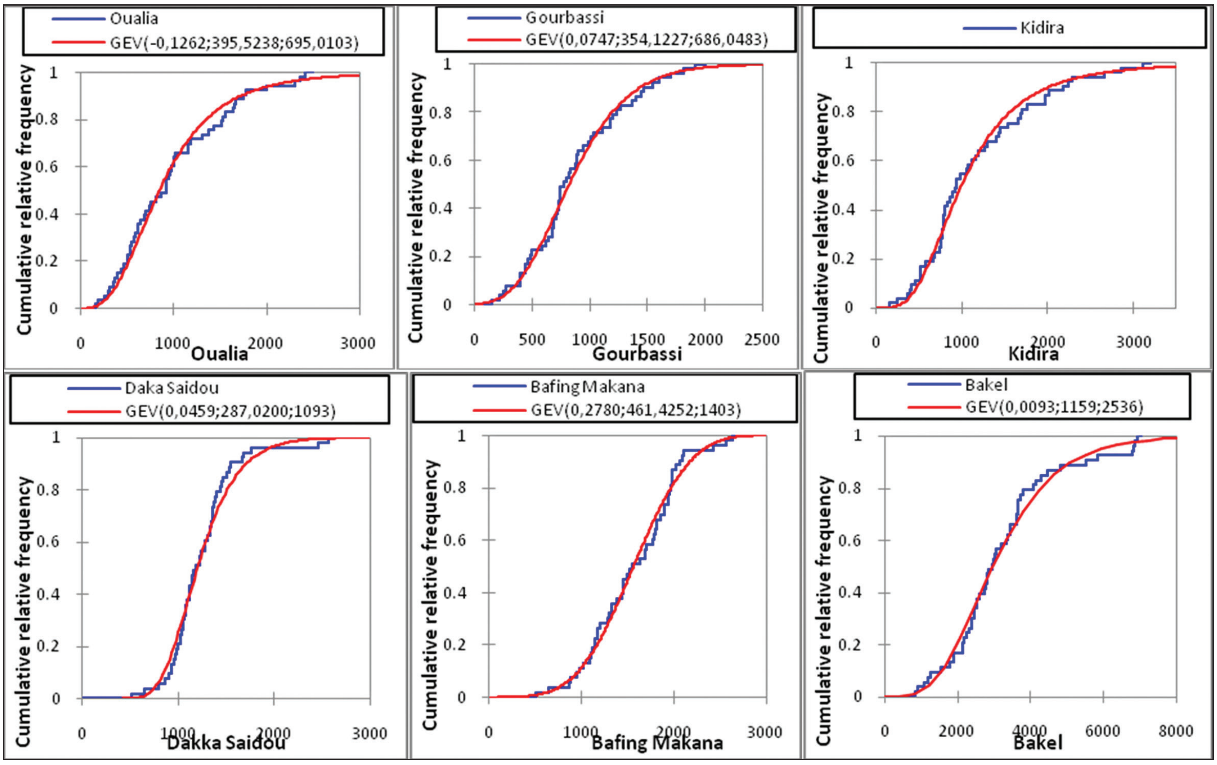

Figure 4. Observed and Simulated Values of the GEV Distribution Function Applied to Annual Daily Maximum Flows in the Upper Senegal River Basin from 1960 to 2014

Of the four distributions considered by visual examination, the frequency distributions of Normal Log, Pearson Type 3, and GEV are well adjusted to the values of the maximum daily flow rates of the six stations and have the advantage of being model simple frequencies, evidenced by the values of p-values which are less than the risk of error of 0.05. These frequency distributions are the distributions of which the adjustment to the regional data of three groups is the most satisfactory. In addition, they are more suitable for estimating quantiles of flood flows in the basin compared to Gumbel's frequency distribution whose p-values are all greater than 0.05 (Table 3). Indeed, the hypothesis of Gumbel's frequency distribution for the six series studied is therefore rejected at the level of significance of 5 %. One of the three frequency distributions that gave the best adjustment of the daily maximum hydrometric series of the stations of the upper watershed of the Senegal River, through the visual test (graphic quality of adjustment) and the chi-square test is the GEV frequency distribution presneted in Figure 4. The results of the frequency distributions of Lognormal, Pearson type 3 and GEV, therefore, allow the estimation of flow quantiles at sites for which no measurement is available (Onibon et al., 2004).

4.3. Estimation of the Parameters of the Distribution Functions

In Tables 4, 5, and 6, the estimated values of the distribution function parameters at the maximum annual flow rates are recorded for each of the three best fit models described above. Of these four frequency distributions usually applied to the study and the frequency analysis of the maximum daily flows, the generalized frequency distribution of the GEV extremes and the Pearson type 3 frequency distribution have three parameters each; those of the extreme values (Gumbel and normal log) have two only. By way of illustration, the maximum likelihood method is used to estimate the parameters of the GEV frequency distribution, while that of the moments is used to estimate the parameters of the normal Log frequency distribution and that of Pearson type 3.

Table 4. Parameter Values estimated by the Maximum Likelihood Method of the GEV frequency distribution

Parameters	Oualia	Gourbassi	Kidira	Daka Saidou	Bafing Makana	Bakel
k	-0,12	0,07	-0,16	0,04	0,27	0,009
beta	395	354	427	287	461	1159
μ	695	686	827	1092	1402	2536

Table 5. Parameter Values estimated by the Moment Method of the Normal Log frequency distribution

Parameters	Oualia	Gourbassi	Kidira	Daka Saidou	Bafing Makana	Bakel
μ	6.69	6.63	6.88	7.08	7.30	7.96
σ	0.64	0.55	0.62	0.27	0.33	0.48

Table 6. Parameter values estimated by the moment method of the Pearson type 3 frequency distribution

Parameters	Oualia	Gourbassi	Kidira	Daka Saidou	Bafing Makana	Bakel
k	2.86	4.23	2.88	12.0	11.2	4.62
beta	340	204	401	102	139	691

Although several authors in the literature have recommended the use of the General Extreme Value (GEV) frequency distribution for the regional frequency analysis of extreme rainfall events (Sveinsson et al., 2002), in this study, the Pearson type 3 has been favored in the search for the best result to model the distribution of the extreme flood flows of the stations of the basin.

4.4. Frequency Analysis of Annual Maximum Daily Flows

As stated in the introduction, the central objective of this study is the development of a regional frequency analysis method for extreme flows. This section is devoted to the presentation of the results of the application of the procedure proposed above for the estimation of the quantiles associated with the annual maximum daily discharges of the stations of each group. After classifying these frequency distributions, based on the criteria of posterior probability, the Pearson type 3 frequency distribution was selected to model annual maximum flow rates. Thus, for each station, the return period quantiles are calculated, using the parameters of the Pearson type 3 frequency distribution (Table 7 and Figure 5).

Table 7. Frequency Flow Values of annual daily peak flows in the upper basin of the Senegal River from 1960 to 2014 following the distribution of Pearson type 3

Stations	Return period (in years)							
	1	2	5	10	20	50	100	200
Oualia	616	1090	1556	1867	2158	2524	2791	3052
Gourbassi	629	977	1309	1525	1725	1973	2153	2326
Kidira	736	1299	1871	2258	2623	3083	3421	3750
Dakka Saidou	998	1334	1641	1835	2011	2198	2380	2549
Bafing Makana	1305	1698	2043	2196	2516	2701	2829	3067
Bakel	2256	3522	4764	5584	6348	7300	7990	8662

The estimation of extreme flows corresponding to quantiles of return periods are commonly used in hydrology (Onibon et al., 2004). The annual discharge series of the basin have been adjusted to different statistical frequency distributions, and the Pearson type 3 frequency distribution presents the best fit for all the stations studied in the basin by the graphical method. However, the estimates often introduce a gap that is characterized by underestimation or overestimation of quantiles. The Pearson type 3 frequency distribution fitted better to a series of asymmetry coefficients and the standard values and the frequency distribution results show a better intensity of the bond. On the other hand, even though Gumbel's frequency distribution is one of the two most used frequency distributions in hydrology (with the normal frequency distribution), it could not model the series of maximum annual flow rates because it was rejected at the first stage of its application. Considered to model the extreme flows, the good estimates of the annual maximum flow rates by the Pearson type 3 frequency distribution can help managers and engineers in the dimensioning of the hydraulic structures as well as the management of the risks. These results are in concordance with those from Riad et al. (2006) in Morocco and López and Francés (2012) in Spain where the Gamma frequency distribution (or Pearson type 3) is better adapted to model annual maximum flow rates. These results also confirm those found by Meddi and Abbes (2014) for some Algerian watersheds.

4.5. Implementation of a Flow Calculation Tool

Based on the results, a general formula for calculating discharge rates on decadal frequency and centennial frequency flows has been tested to obtain a preliminary tool for the study of extreme flows (Ruf, 2004). All the stations studied, which have a hydrological significance because of their extended time of observation and the validity of their calibration curves in the studied domains, have been represented (Figure 6).

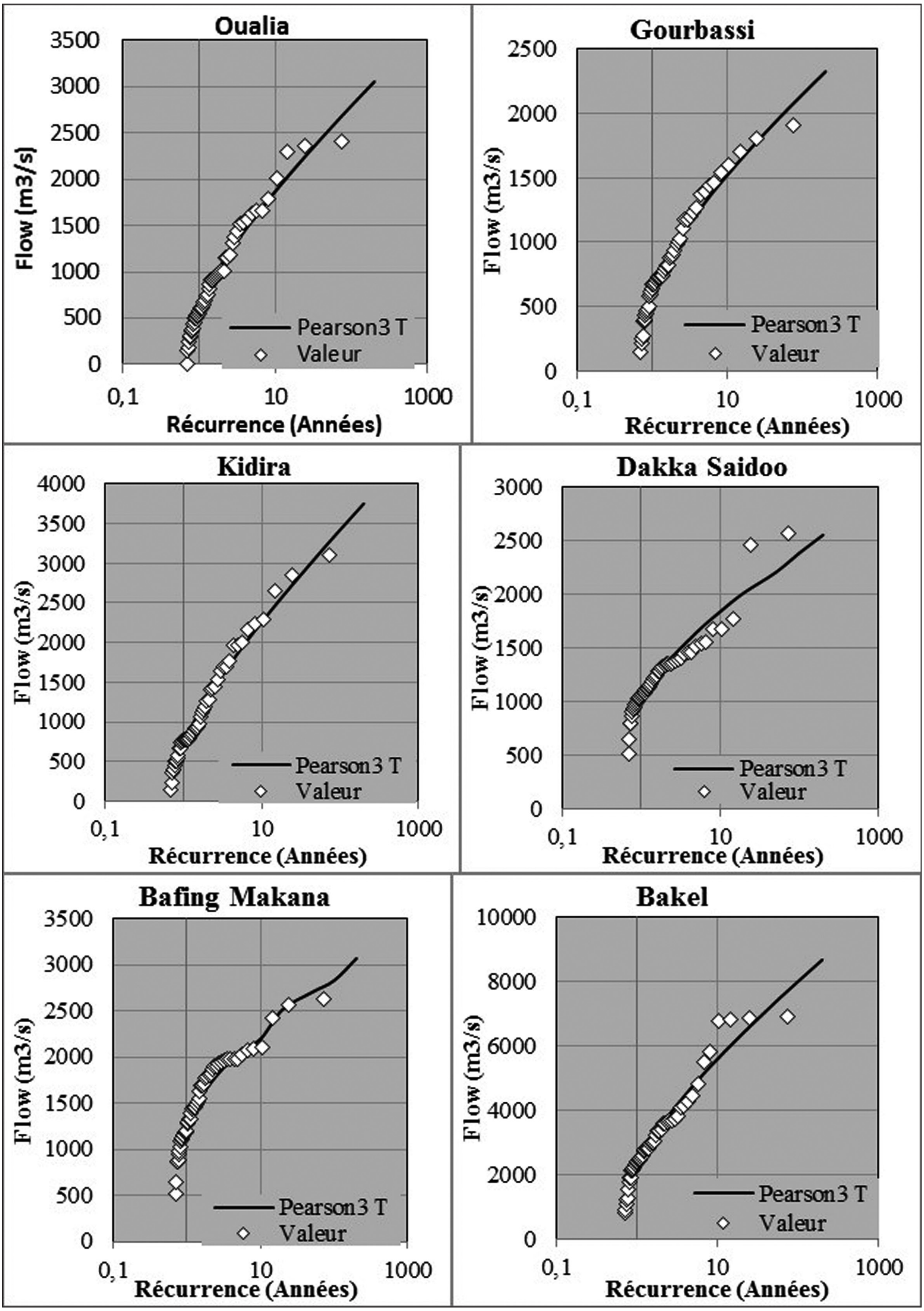

Figure 5. Statistical Adjustments to the Pearson Type 3 Distribution of Annual Maximum Daily Flows in the Upper Senegal River Basin from 1960 to 2014

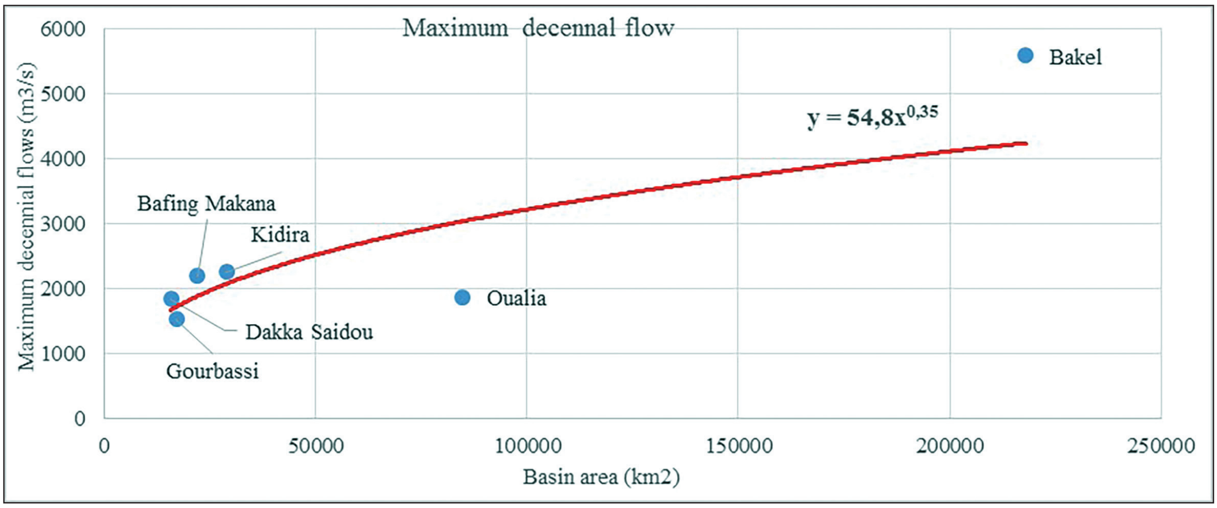

Figure 6. Variation of the maximum decadal flow according to the surface of the basin

Compared to the variation of the maximum decadal discharge according to the surface of the basin, and unlike the other stations of the high basin, the stations of Bakel and Oualia are not disperesed on the trend of the curve. However, these envelope curves could be used as a tool for estimating flows on ungauged basins in Senegal; the general formula is as follows:

$y = 54.8\ x^{0.35}$

These tools are general, and characterize general phenomena. Moreover, they can be used as approximation tools which must be taken with the necessary precautions with regard to their accuracy (Ruf, 2004). They can however be useful during a pre-study for example. Finally, although the estimates are correct despite the remaining errors on the calibration curves (measurement errors), the irregularity of the African tropical regimes does not make us immune to major errors in the major watersheds.

5. Conclusions

The main focus of this work was to find a frequency model capaable of accounting for the regime of extreme flows of the upper watershed of the Senegal River. The basin is subdivided into three homogeneous zones or groups in terms of the average annual flows elapsed. The statistical estimation of extreme flood flows can be done in two ways: the annual maxima method and the values above a threshold method. Based on the length of the series, the first approach was chosen. One of the drawbacks of this procedure is the choice of an insignificant event when no significant flood is recorded during a hydrological year (Meddi and Abbes, 2014). The usual distributions used to adjust the maximum daily flow rates: GEV, the Gumbel, Log normal and Pearson type 3 have given similar results (between GEV, Log normal and Pearson type 3 which are more suitable for the test. on the stations of the three groups), and sometimes different results (using Gumbel compared to the other frequency distributions). From the results of the graphical visual criterion and the chi-square test, it appears that the maximum daily flow rates of the six hydrometric stations preferentially follow the Pearson type 3 frequency distribution, followed closely by the GEV and Normal log. As for Gumbel's frequency distribution, it was not able to model the annual maximum flow series and the high values tended to be overestimated or underestimated. After the classification of the frequency distributions, and based on the criteria of the posterior probability, the selected Pearson type 3 frequency distribution made it possible to model the annual maximum flows and to calculate the quantiles of the period of return. The decennial and centennial frequency rates obtained provided the means, from a power equation, to define the preliminary tool for estimating decennial and centennial flows on Senegal's ungauged basins.

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