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Characterization of river floods on the plain Of Saïdia (North-East of Morocco)

A. Grari[1], M. Chourak[2], F. Boushaba[2], S. Cherif[1]

[1] *Department of Geology, University Mohamed Premier, faculty of sciences, Oujda, Morocco*

[2] *Department of Mechanic and Applied Mathematics, University Mohamed Premier, National School of Applied Sciences, Oujda, Morocco.*

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A Grari
latif_gr2000@yahoo.fr
+212666756615

Abstract
The main purpose of this study is to assess and characterize the flood risk evolution of Oued Moulouya near the city of Saïdia. The objective is to determine the required parameters to assess flood risk, especially since the region had experienced a swift and considerable urban expansion of the city on one hand, and the installation of several protective structures in the vicinity on the other hand. Flood risk prevention of a river requires information on its hydrological regime and the adopted approach for the assessment of the latter is the Flow-Duration-Frequency model (QDF). It was developed from frequency analysis of the average and maximum flows recorded on Safsaf station, in order to extract the monofrequency hydrographs of river floods in Oued Moulouya.

1. Introduction
Recent flood risk assessment methods suggest a comparison between two different kinds of data: hazard and vulnerability. This comparison requires the adoption of a common unit of measurement. In fact, hazard and vulnerability are expressed in terms of water depth, return period and duration [1-5]. In hydrology, hazard and vulnerability are defined in terms of water depth, return period and duration. Synthetic hydrological models known as Flow-Duration-Frequency (QDF) are used for hazard and vulnerability quantification [1]. QDF calculators give a relevant representation of the flow quantiles for return periods ranging from 1 to 1,000 years, allowing us to overcome classic notions such as "reference high water" in river management studies. In addition, they provide a possibility to build Monofrequency Synthetic Hydrographs (MFSH) [6].
The objective of this study is to determine the parameters needed to understand and assess the evolution of flood risk in Saidia, regarding the swift and considerable urban expansion of the city and installation of several flood protective structures. Thus, as a first step a local QDF model for Saïdia was constructed, based on measurements of average flows of Oued Moulouya (Figure 2) recorded in Safsaf station. The elaborated model will be used afterwards for the construction of flood hydrographs for different return periods. The results reveal the importance of this study for the assessment and characterization of river flood risk in the region of Saidia.

2. Materials and methods
2.1. Study area
The coastal plains of Saïdia, which are the subject of this study, are among the 391 sites that are exposed to very high flood risk at the national level. The aforementioned plain belonging to the basin of Triffa is characterized by a very flat topography, where the ground surface is very close to the water table. Furthermore, its position is enclosed between two rivers, Oued Kiss in the east and Oued Moulouya in the west, as well as the plateau of Ouled Mansour in the south (Figure 1) which greatly increases the risk of sudden floods. In addition, the uncontrolled urban and tourist developments are increasingly aggravating these risks [7].

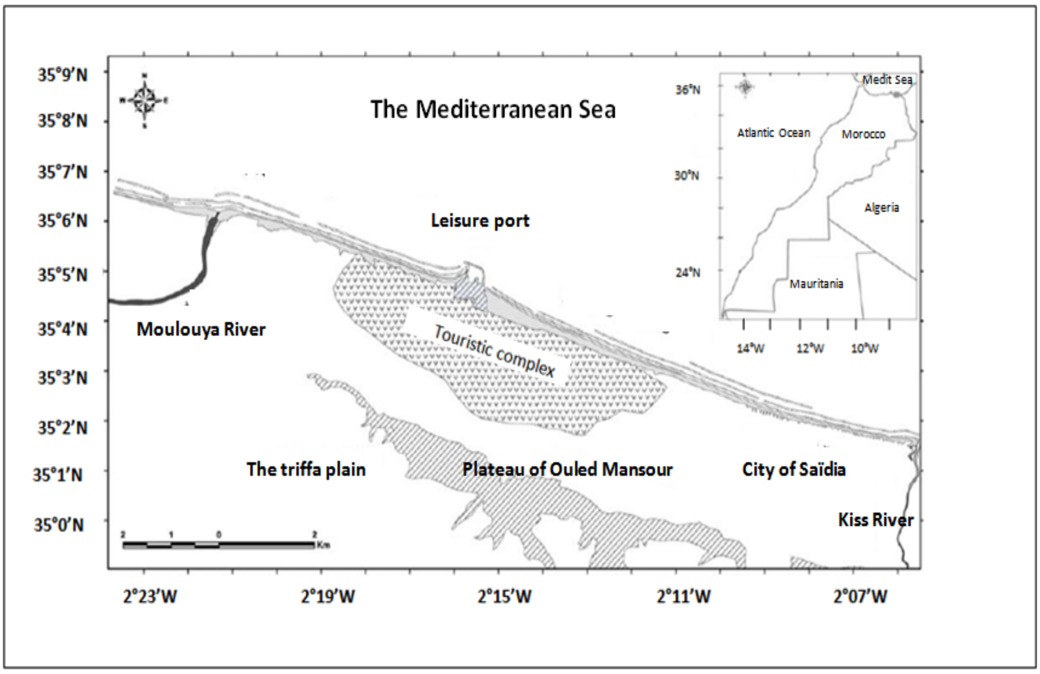

Figure 1: General outlook of Saïdia Bay (North-East of Morocco) [2]

Figure 2 shows series of average monthly flows of the aforementioned stations for the observation period 1969-2001. The resulting QDF model is used to build monofrequency flood hydrographs based on a history of daily fluctuations of water discharges in Moulouya River. Figure 3 shows the seasonal variations in water discharges downstream Moulouya River during the 1978-1979 hydrological years. The highest discharges are between autumn and winter seasons, while during summer, the water flow is the lowest.

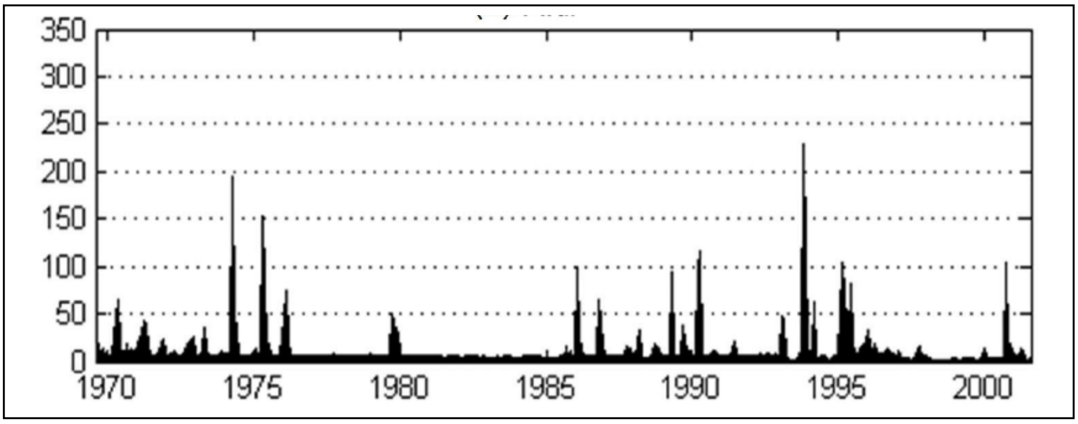

Figure 2: Monthly average flows of Oued Moulouya during the period 1969 to 2001 at the Safsaf station [8]

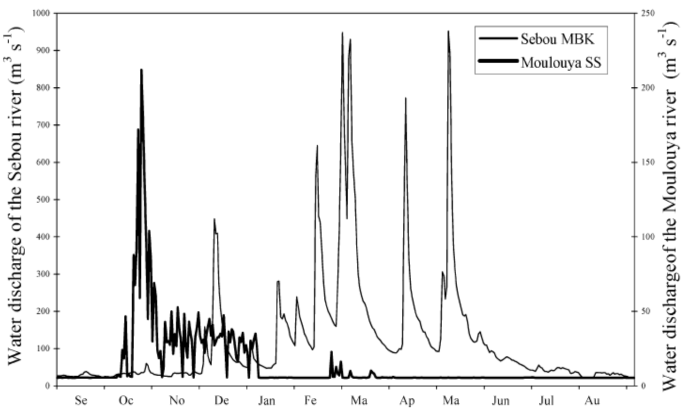

Figure 3: Daily fluctuations of water discharges of the Moulouya River at the Safsaf station during the 1978-1979 hydrological year comparison to the Sebou river [9]

Figure 4 shows the recordings of maximum flows at the Safsaf station between 1969 and 2001 [8]. These observed values will be used to interpret the monofrequency hydrographs that are the subject of this study.

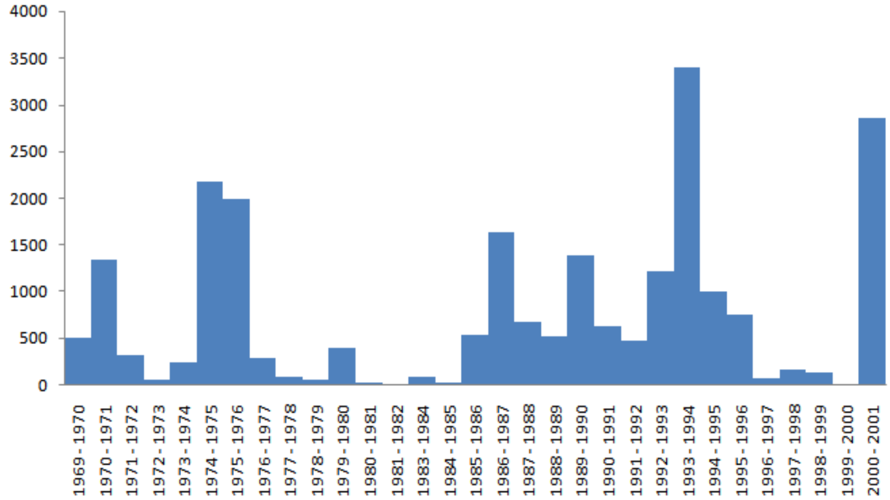

Figure 4: Maxima flows of Oued Moulouya for the period 1969 to 2001observed in the Safsaf station

2.2. Methodology

The average monthly flows in Figure 2 will be exploited to classify the characteristic flows exceeded by J days per year DCJ. For each series of DCJs, the corresponding calibration model is determined. For each return period, the maximum characteristic flow rates and the non-exceedance probability are determined.

The QDF curves will allow the determination of the regression lines to extract the parameters of the proposed mathematical model. The exploitation of the recording of the fluctuations of Oued Moulouya and of the mathematical model will allow us to obtain Monofrequency Synthetic Hydrographs (MFSH).

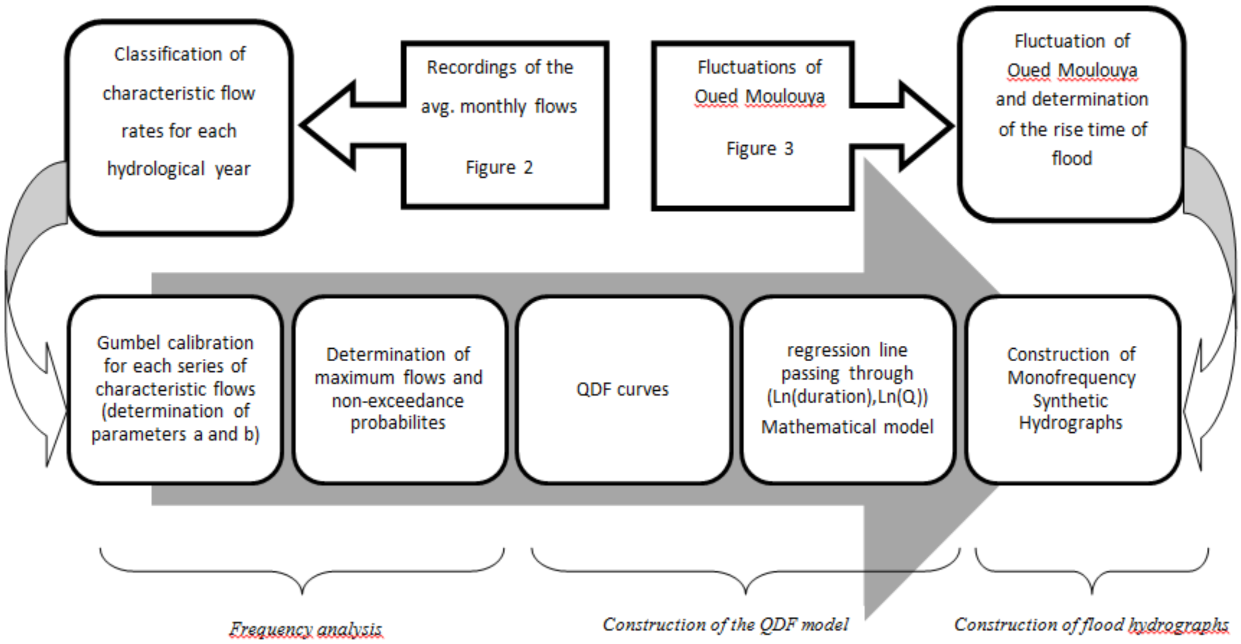

Figure 5: Flowchart of the study method

2.3. *Frequency analysis and statistical calibration of a data series*

According to Meylan and Musy (2008), frequency analysis is a prediction statistical method, consisting of studying past events in order to estimate the probability of their future occurrences. This prediction relies on the definition and implementation of a frequency model, which is an equation describing the statistical behavior of a process. The most common example of a frequency model used in hydrology is the statistical distribution of Gumbel [10] which is expressed as follows:

$$F(x) = \exp\left(-\exp\left(-\frac{x-a}{b}\right)\right)$$

Where F(x) is the cumulative frequency and a et b are the parameters of the Gumbel model.

The annual probability of observing an event greater than or equal to the value x is p(x) = 1- F(x). In hydrology, we often use the notion of the return period of an event of amplitude x, which for a long period occurs once every T (x) year. T (X) is defined by:

$T(x) = \frac{1}{1-F(x)}$ [10]

In our case, the objective is to determine the return period of the maximum flow rates XT for each series of characteristic flow rates DCJ. For the determination of the parameters a and b of the Gumbel model, the method of momentum is used [11].

$$\begin{cases} b = 0.7797\sigma \\ a = \mu - b.05773 \end{cases} \quad \text{with} \quad \mu = \bar{x} \quad \text{and} \quad \sigma = s\sqrt{\frac{n}{n-1}}$$

n is the number of elements in the series. In our case six series have been extracted, DC1j, DC5j, DC20j, DC60j, DC180j, DC355j. Each series consists of 32 values selected from the recordings of average flows of Oued Moulouya during the period 1969 and 2001. μ is the average value, σ^2 is the variance and :

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

2.4. Construction of the QDF model

For the different return periods 2, 5, 10, 20, 50, 100, 200 and 1000 years, the maximum QXT is determined for each characteristic flow rate DC1j, DC5j, DC20j, DC60j, DC180j, DC355j. We can then plot an approximate QDF curve.

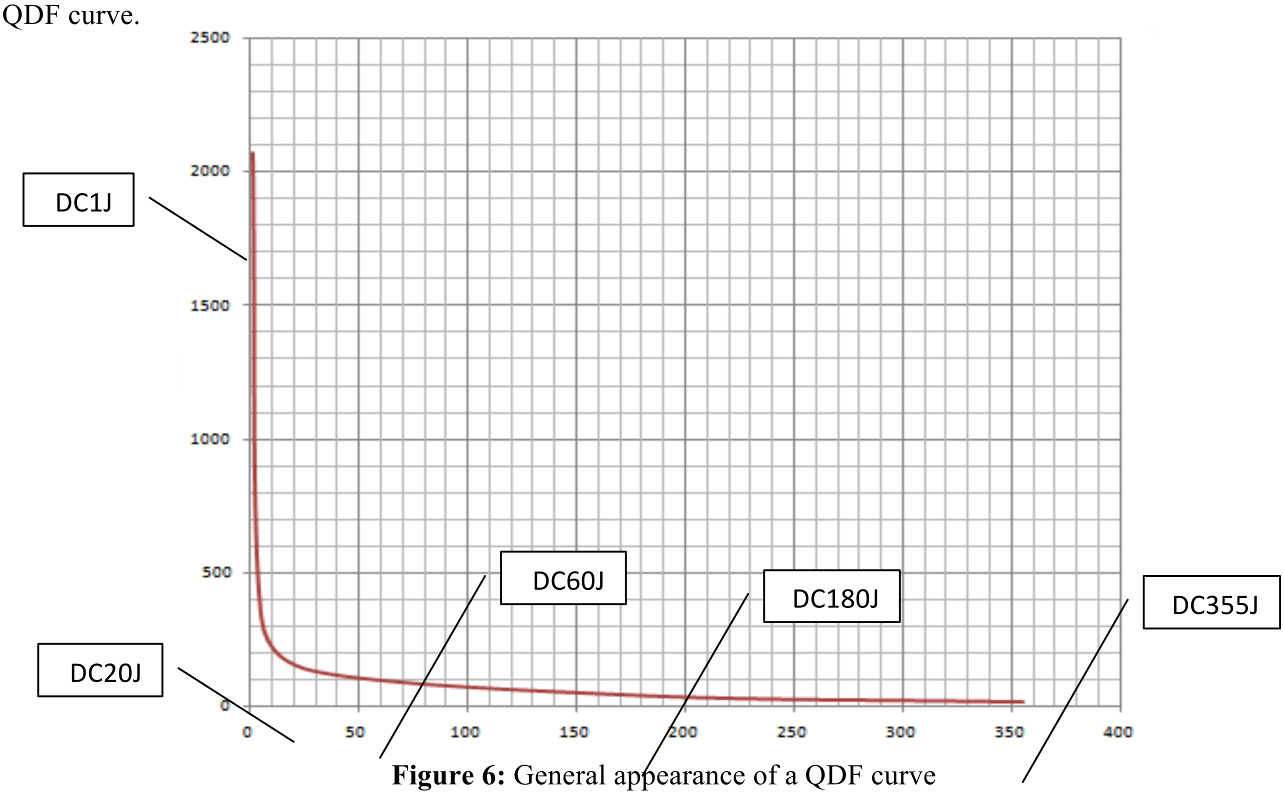

Figure 6: General appearance of a QDF curve

It is noted that each Flow-Duration-Frequency curve has an exponential form (Figure 6) and behaves in the same way as the intensity-duration-frequency curves for rainfall, hence the idea of modeling with Montana formula, which gives very interesting results. The Montana formula is as follows [11]:

$$QXT = \frac{a}{t^b}$$

QXT : Maximum flow in [m^3/s]

a and b : Montana parameters

T : return period [years]

t : duration [hours or days] [years]

The estimation of the Montana parameters a and b is simplified by considering the logarithm of this formula as a linear relation:

$$\ln(\mathrm{QXT(t)}) = \ln(\mathrm{a}) - \mathrm{b}.\ln(\mathrm{t})$$

For a given return period, (ln(t) ; ln(QXT(t)) is represented graphically for each duration t. The regression line passing through (ln(t), ln (QXT(t)) makes it possible to estimate Montana parameters. B is the slope of the regression line and ln(a) is the ordinate at the origin.

2.5. Construction of monofrequency flood hydrographs

By obtaining local QdF curves, it is possible to reconstruct monofrequency hydrographs, which are elaborated by making a first assumption on the rise period of floods. The simplest hypothesis is to assume a linear rise of the hydrograph between the initial basic flow and the flood peak [11]. Once this value is obtained, the corresponding period for each flow rate is reported on the Flow-Duration-Frequency curve at the return period considered from the rise curve of the hydrograph [11]. We thus construct point-to-point the curve of the hydrograph (Figure 7). In this study, the rise period of a flood will be obtained based on the recordings of the 1978-1979 hydrological year of the Moulouya River fluctuations. The rise period of the monofrequency hydrograph is quite close to the characteristic duration of a flood. This duration will be determined by the average rise periods of the fluctuations at their maxima [11].

3. Results and discussion

3.1. Frequency analysis results

The HYFRAN-PLUS software has been designed for frequency analysis in hydrology, particularly for extreme values, as well as for flood analysis [12]. In this study, this platform was adopted for calculation of the statistical characteristics and for the determination of the Gumbell parameters, using the momentum method already explained. With this software, we will also determine the maximum flow rates for the different return periods and their probabilities of non-exceedance. Table 1 below illustrates the statistical characteristics and parameters of Gumbell for each characteristic flow series.

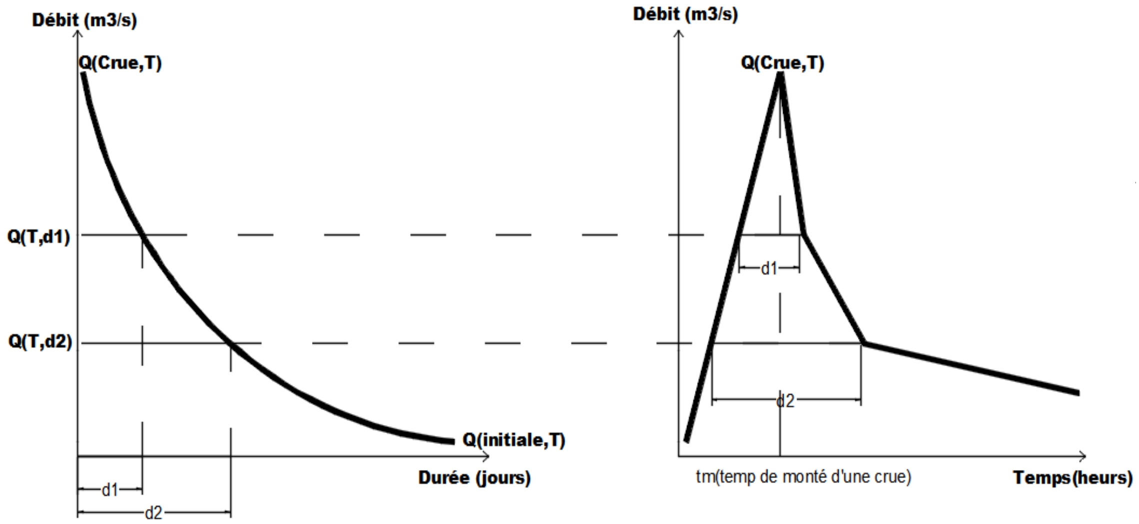

Figure 7: Methodology for elaborating a flood hydrograph based on a QdF [6]

The average and the standard deviation are determined for each DCJ series. These two values will then be used to determine the parameters a and b of the Gumbel formula. Table 1 also illustrates for each series of flow rates, the Gumbel model formulation which will then be used to determine the maximum characteristic rates XTDC1j, XTDC5j, XTDC20j, XTDC60j, XTDC180j, XTDC355j for the return periods 2, 5, 10, 20, 50, 100, 200 and 1000 years. On the basis of the aforementioned relation between the return period and F (X) of Gumbel:

$$\mathrm{T(x)} = \frac{1}{1 - \mathrm{F(x)}}$$

and the one which links the probability of non-exceedance and:

$$F\,(X)\colon p(x) \;=\; 1 - \;F(x).$$

HYFRAN returns the results in the form represented in Figure 8. Table 2 summarizes the maximum flows for each return period.

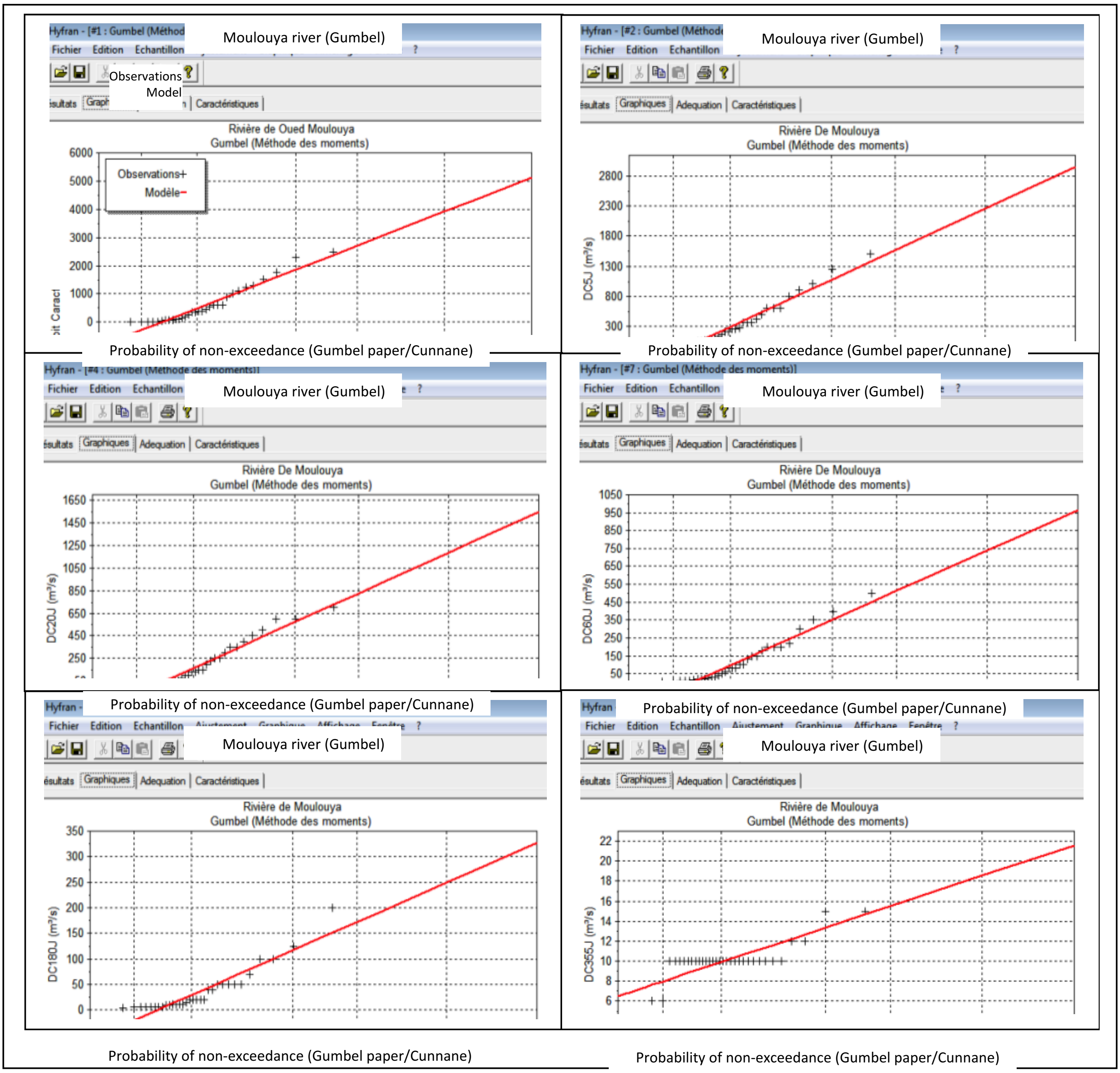

Figure 8: Gumbel calibration for each series of characteristic flows DCJ

Table 1: Parameters of the Gumbel model for each characteristic flow

	μ	σ	a	b	F(x)
DCC1j	593	675	289.441	526.042	$F(x) = \exp\left(-\exp\left(-\frac{x-289.441}{526.042}\right)\right)$
DCC5j	106.785	386	173.571	301.243	$F(x) = \exp\left(-\exp\left(-\frac{x-173.571}{301.243}\right)\right)$
DC20J	197	201	106.785	156.374	$F(x) = \exp\left(-\exp\left(-\frac{x-106.785}{156.374}\right)\right)$
DC60J	118	126	61.2383	98.1746	$F(x) = \exp\left(-\exp\left(-\frac{x-61.2383}{98.1746}\right)\right)$
DC180J	36.1	43.2	16.658	33.6716	$F(x) = \exp\left(-\exp\left(-\frac{x-16.658}{33.6716}\right)\right)$
DC355J	10.2	11.69	1.32018	9.42547	$F(x) = \exp\left(-\exp\left(-\frac{x-1.32018}{9.42547}\right)\right)$

Table 2: Maximal characteristic flows for each return period

Duration in days	Return period in years						
	T=5	T=10	T=20	T=50	T=100	T= 200	T=1000
1	1080	1470	1850	2340	2710	3080	3920
5	625	851	1070	1350	1560	1770	2250
20	341	459	571	717	826	935	1190
60	208	282	353	444	513	581	739
180	67.2	92.4	117	148	172	195	249
355	11.4	12.4	13.3	14.6	15.5	16.4	18.5

3.2. QDF curves model

Table 2 gives an approximation of the Flow-Time-Frequency curves. The graph in Figure 9 groups the QDF curves for the return periods of 2, 5, 10, 20, 50, 100, 200 and 1000 years. Each curve has a decreasing exponential form. For small durations the flows tend to have maximum values, for the long durations the flows are at a minimum.

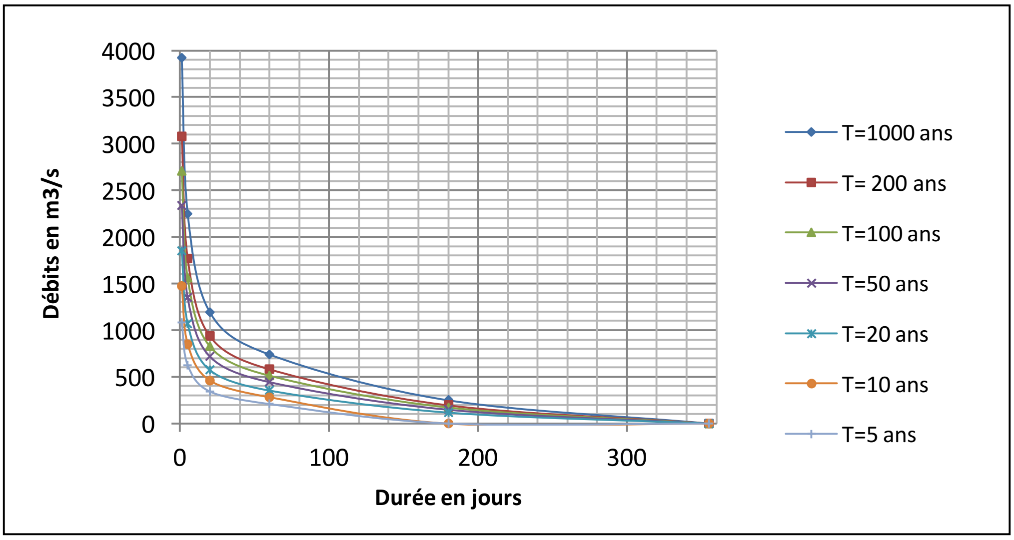

Figure 9: Flow-Duration-Frequency curves for each return period

3.3. QDF Mathematical model

It is noted that each Flow-Duration-Frequency curve has an exponential form in Figure 9, and behaves in the same way as intensity-duration-frequency curves for rainfall, hence the idea of modeling according to Montana formula, $QXT = \frac{a}{t^b}$ where a and b are the Montana parameters.

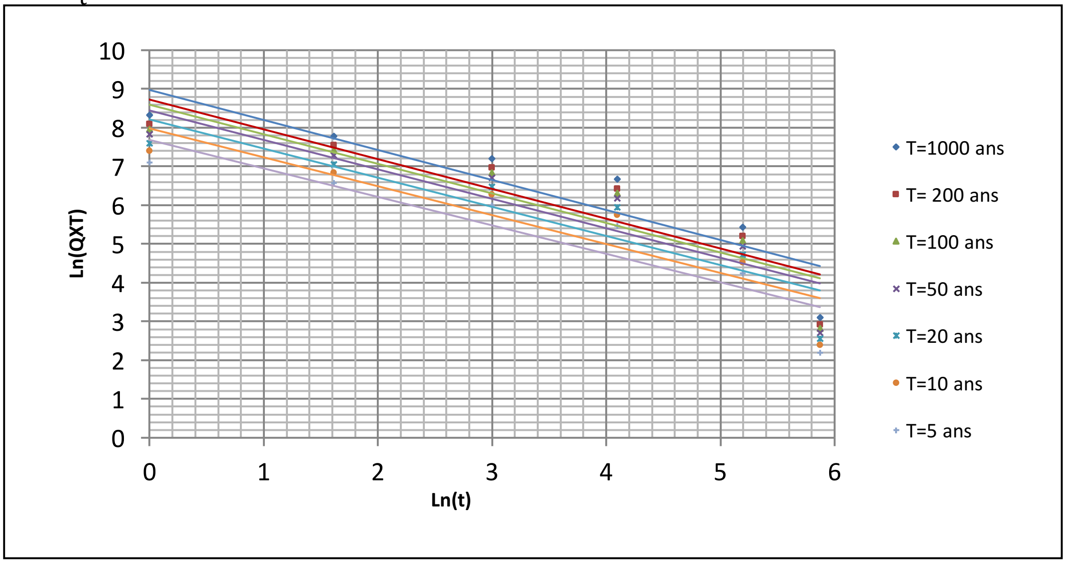

Figure 10 : Regression lines for each return period

For a given return period, (ln(t) ; ln (QXT(t)) are graphically plotted. The regression line passing through (ln(t) ; ln (QXT(t)) makes is possible to estimate Montana parameters. b is the slope of this line, and ln(a) is its ordinate at the origin. Table 3 illustrates the values of a and b and the mathematical formulation of QDF curves for each return period. Figure 11shows a graphical representation of the local mathematical model of the Flow-Duration-Frequency at Safsaf station for: A: Over a period of 1 year, B: Over a period of 100 days.

Table 3: Mathematical formulation of QDF curves for each return period

Return periods	**a**	**B**	**QT(t)**
T=1000 years	3920	0.40633	$QT1000(t) = \frac{3920}{t^{0.40633}}$
T=200 years	3080	0.4053	$QT200(t) = \frac{3080}{t^{0.4053}}$
T=100 years	2710	0.40473	$QT100(t) = \frac{2710}{t^{0.40473}}$
T=50 years	2340	0.4045	$QT50(t) = \frac{2340}{t^{0.4045}}$
T=20 years	1850	0.40301	$QT20(t) = \frac{1850}{t^{0.40301}}$
T=10 years	1470	0.40381	$QT10(t) = \frac{1470}{t^{0.40381}}$
T=5 years	1080	0.4002	$QT5(t) = \frac{1080}{t^{0.4002}}$

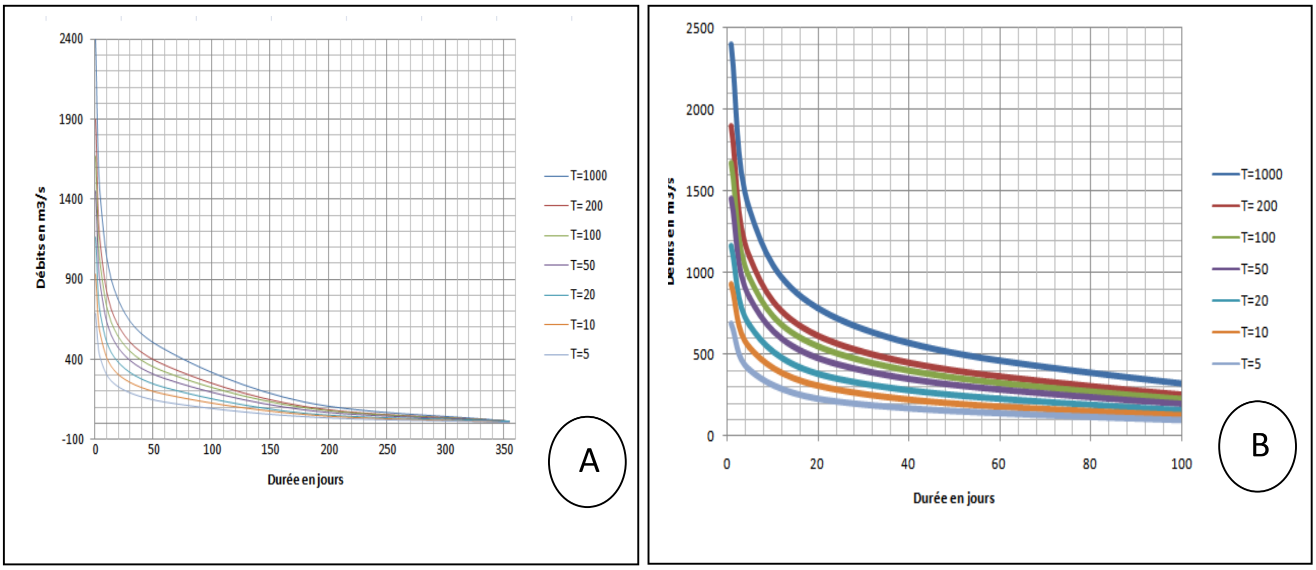

Figure 11: QDF at Safsaf station A: Over a period of 1 year, B: Over a period of 100 days

3.4. Construction of Monofrequency Synthetic Hydrographs

Figure 12 shows the duration of the ascent to reach peak flows of daily fluctuations of water discharge for the Moulouya River recorded at the Safsaf (SS) measurement station for the 1978-1979 hydrological years. The average linear trend between these durations is close to the rise period of a flood [11], the average values are between 22 hours and 35 hours.

The average rise value of a flood will be used to determine the rise curve of the hydrograph for the flood curve. It only requires plotting the durations d1, d2 to dn, taken from the rising curve of the hydrograph, corresponding to each flow rate on the Flow-Duration-Frequency curve, to the considered return period [11]. Thus, the declining curve of the hydrograph is constructed point by point (Figure 7). In our case, the flows corresponding to the decline, read on the QDF curves, correspond to the durations of 5, 10, 15, 20, 25 and 30 days. Table 4 summarizes the results.

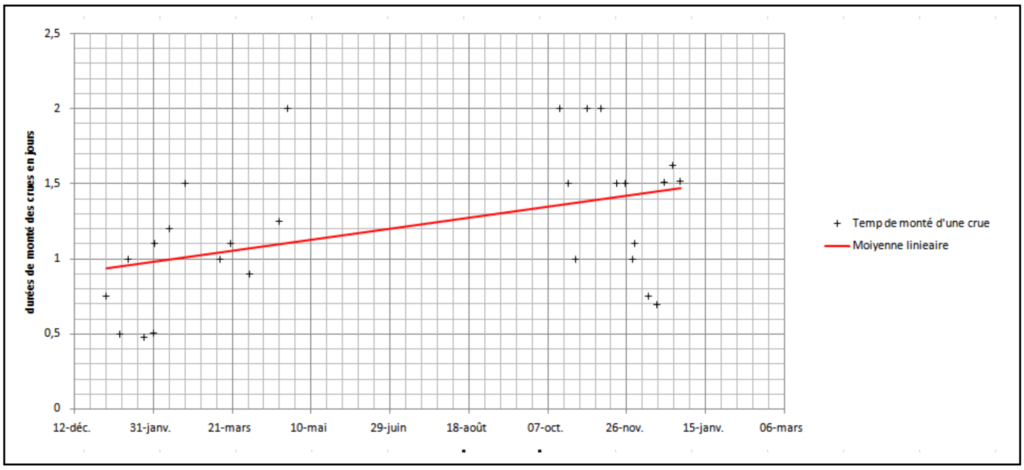

Figure 12 : Determination of the average rise time of a flood in Oued Moulouya

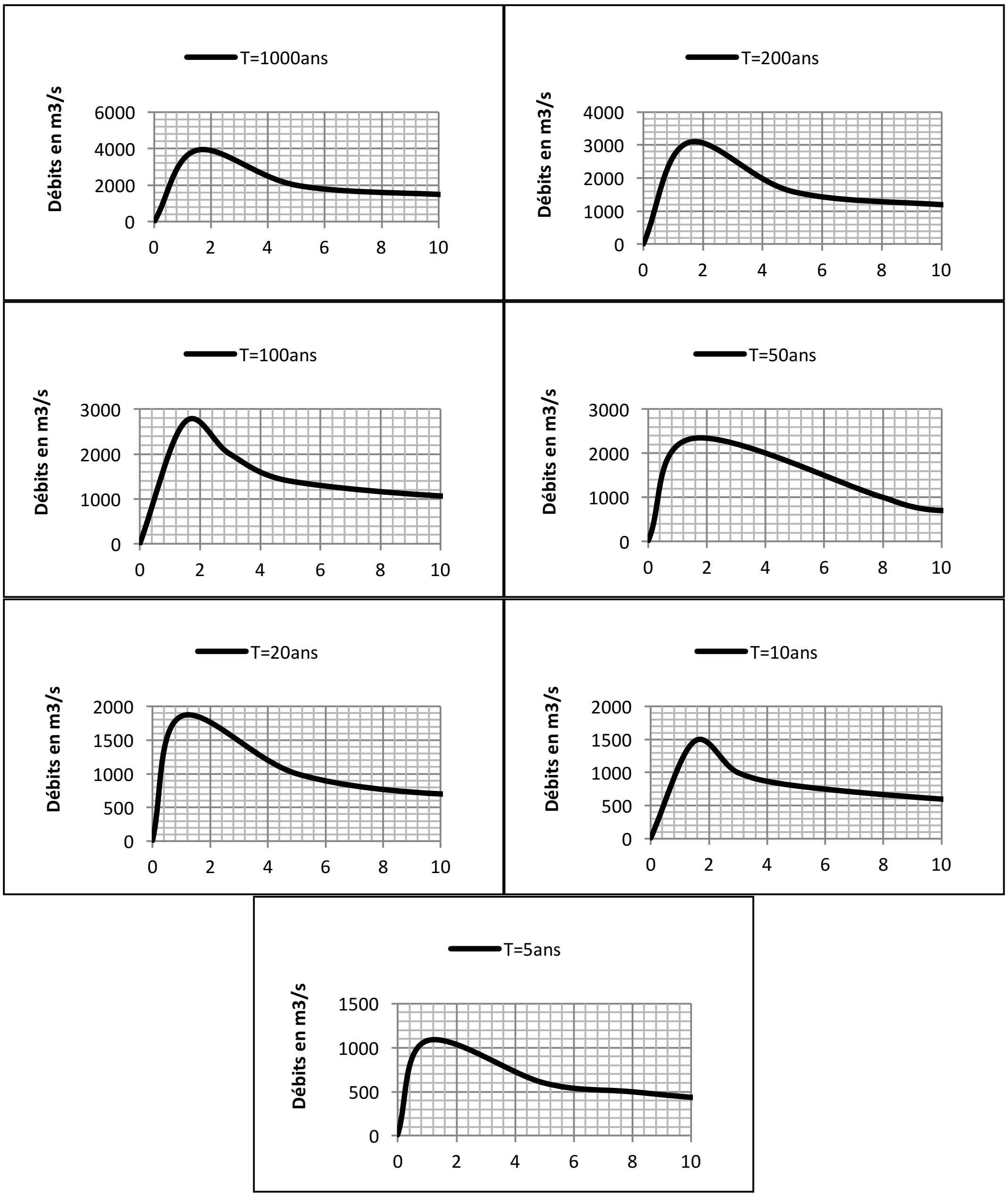

Figure 13: Monofrequency Synthetic Hydrographs for the return periods T = 1000, 200, 100, 50, 20, 10 & 5 years

Table 4: Flow rates in m^3/s read on the QDF for the durations of 5, 10, 15, 20, 25 and 30 days

Return periods	**5 days**	**10 days**	**15 days**	**20 days**	**25 days**	**30 days**
T=1000 years	2000	1500	1300	1200	1100	1000
T=200 years	1600	1200	1000	900	800	760
T=100 years	1400	1100	900	800	750	660
T=50 years	1300	700	800	700	650	600
T=20 years	1000	700	600	550	500	460
T=10 years	800	600	500	450	400	360
T=5 years	600	400	350	320	300	260

Figure 13 shows all of the Monofrequency Synthetic Hydrographs for the return periods T = 1000, 200, 100, 50, 20, 10 and 5 years. There is an observed coherence between the hydrographs and the maximum values measured at the SafSaf station represented in Figure 4 [8]. The floods of 1993 and 2001 can be assimilated with maximum flows of 3000 and 3500 m^3/s respectively, with return periods of 200 years. The floods of 1975 and 1976 can be classified as floods of a return period of 50 years, their maximum flows are 2500 and 2000 m^3/s respectively. The floods of 1971, 1987 and 1990 can be classified as floods of a return period of 10 years. The other floods are considered as floods of a return period of 5 years. It is also noted that for return periods of T = 1000 years, 200 years and 100 years, the flow of Oued Moulouya remains high even after 30 days of decline. For return periods of 50 years, 20 years, 10 years and 5 years, the flow of Oued Moulouya is acceptable in the sense of risk of floods (after 10 days of flood decline).

Conclusions

The present study made possible the construction of the Flow-Duration-Frequency curves at Safsaf station, as well as the determination of Monofrequency Flood Hydrographs for return periods T = 200 years, T = 100 years, T = 50 Years, T = 20 years and T = 10 years. These results will be used to predict flood propagation and to measure degrees of damage caused by floods. The synthetic Flow-Duration-Frequency QDF curves and the monofrequency hydrographs will allow the flood risk assessment on Saïdia plain, based on the hazard and vulnerability. It is also possible to construct and recalibrate the curves of the river Moulouya. These results will facilitate the determination of the hydraulic model of the Moulouya River as well as the calculation of the curve using free surface 2D flow simulation software. This will allow the determination of the flood zones and the submersion height. The Monofrequency Flood Hydrographs contribute to the prediction of sediment transportation and deposition and the calculation of the solid flow due to the relation that connects it with the flood flow and the low flow. In general, it is not possible to construct hydraulic structures for flood protection without the contribution of QDF synthetic curves.

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