The Assessment of Heavy Rains in the Region of Annaba (NE Algeria) to Improve Extreme Flood Forecasting—Use of Depth-Duration-Frequency Curves

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Abstract: The knowledge of space and time distribution of short duration rainfall depths is of primary interest in hydrotechnical studies and in extreme floods modelling. This work is carried out to establish a “DDF (Depth-Duration-Frequency)” relationship for the region of Annaba (Northeast of Algeria) through the examples of Pont Bouchet (El Hadjar), Ain Berda and Chafia-Dam rainfall gauges. The results of the frequency study of stochastically generated annual series (Pearson’s distribution type III model) and the regression analysis (least square method) permitted to develop a master curve that well describes heavy rainfalls distribution in the Annaba region. This 2-parameter model is used to predict, with sufficient accuracy, the amount of rain that could be recorded over a shorter duration from daily rainfall data in basins that lack recording rain gauges.

Key words: Heavy rain, Annaba, DDF, Gamma distribution, Montana’s type, master curve, model validation.

1. Introduction

Short duration extreme rainfalls are the main cause of flash floods and disasters that may occur on small watersheds of the Edough Massif (Annaba region). Due to their torrential character, they also play a significant role in soil erosion and sediment transport that clog the drainage network in Annaba City.

In Algeria, there are few studies on this topic. Officially reported work dates back to more than 30 years [1, 2]. Guilmet’s work was a first approach to study the 3 h to 24 h rainfall storms recorded over a ten year period (1951-1961) in five major cities in Algeria, including Annaba. From a probabilistic viewpoint, the results expressed in terms of absolute frequency, were insufficient to properly describe the IDF (Intensity-Duration-Frequency) concept. Processed data were not suitable to probability distribution fitting. The results of Body’s work derive

from the synthesis of frequency (Galton distribution) and correlation (Montana law) analyzes of maximum daily rainfall data recorded across the country.

Compared to observed data, predicted rainfall values are underestimated for time intervals less than 12 hour duration.

Being a part of a study of the vulnerability to flooding in the city of Annaba, this paper presents the results of an exhaustive analysis of recorded data at three recording rain gauges: Ain Berda, Pont Bouchet (El Hadjar) and Chafia-Dam. These calibration stations have large data sets (20 to 30 years of records) and well represent the study area. Table 1 provides a complete identification of rainfall stations used in this study.

Expressed most often in the form of DDF (Depth-Duration-Frequency) or IDF (Intensity-Duration-Frequency) curves, the results give the expected maximum values of heavy rains for different durations (from 5 minutes to 24 hours) and provide the basic inputs for estimating peak flows in hydrological modeling and storm design projects.

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Table 1 Identification of rainfall stations.

Rain gauge name	Code	Latitude	Longitude	Elevation a.m.s.l. (m)	Period of observations	Processed rain events
Calibration						
Ain Berda	140606	36°39'01"N	07°35'33"E	130.0	1978-2005	322
Pont Bouchet	140631	36°49'15"N	07°44'54"E	3.0	1976-2005	364
Chafia-Dam	031501	36°36'52"N	08°02'12"E	181.0	1986-2005	181
Validation						
Ain Assel	031601	36°46'05"N	08°22'02"E	32.0	1970-2005	388
Zardézas	030903	36°35'56"N	06°53'43"E	189.0	1984-2004	118
Bousnib	030905	36°29'29"N	06°57'56"E	900.0	1977-2003	264
Settara	100711	36°42'03"N	06°53'55"E	280.0	1972-2002	286
Guelma-Lycée	140402	36°37'21"N	07°26'31"E	260.0	1974-2005	273

2. Data Acquisition and Processing

In the study area, the DDF law arises from the rain gauge records at Ain Berda, Pont Bouchet and Chafia-Dam stations, located to the South of the city of Annaba, within a 40 km radius from the Mediterranean coast (Fig. 1). This region, influenced by the Mediterranean climate, is characterized by unevenly distributed precipitations that fall most often in the form of showers of varying duration and intensity.

Based on a probabilistic approach, DDF curves illustrate the frequency distribution of the maximum values of rainfall depth (or intensity) observed over a fixed duration. These curves are obtained in two steps: the transformation of raw data into a series of annual maximum values for different durations and the consolidated, or not, probability distribution fit to these series of extreme values [3].

From rainfall charts, available at the National ANRH (Agency for Water Resources), the entire rainfall records in a year are analyzed to find the maximum depths for various storm events of constant duration, with moving time origins and whether the rain falls continuously or not [4]. Thus each storm gives one value of maximum depth for a given duration. The largest of all such values is taken to be the maximum depth in that year for that duration. Likewise the annual maximum depth is obtained for durations ranging from 5 minutes to 24 hours. Nineteen series

that behave as random variables are obtained and subject to a frequency analysis.

3. Frequency Analysis of Extreme Rainfall Events

Empirical data, collected over a long period of observations are subject to reliability tests. Indeed, the Wald-Wolfowitz randomness test [5], the Mann-Whitney homogeneity test in Ref. [6] and the test for outliers [7-11] are performed and show that the observed data are, practically, well suited to a frequency analysis.

Due to the space limitation, it is not possible to accommodate all the rain gauging sites. Table 2 presents the performance of some selected tests for the Ain Berda recording gauge taken as an example to illustrate the followed method in assessing original data. Basic descriptive statistics of the empirical frequency distributions of heavy rains in the region of Annaba (mean, standard deviation, range and skewness) are provided in Table 3.

In order to give more credibility to frequency analysis results, a stochastic extension of each time series is conducted using a Gamma data generator integrated to the Statgraphics Centurion XV software. Being supported by “goodness of fit” tests, the Gamma distribution is best suited to model heavy storms in general [12] and in the extreme north-eastern parts of Algeria, in particular [13]. For

Fig. 1 Location of the study area.

Table 2 Test statistics for Ain Berda (N = 28).

Test	Statistic	Duration in minutes									
		5	10	15	30	60	120	180	360	720	1440
Wald-Wolfowitz	Median	4.3	7.5	9.9	13.2	16.7	20.3	24.5	29.8	38.9	53.5
	N ₊	14	16	14	14	14	14	14	14	14	14
	N ₋	14	12	14	14	14	14	14	14	14	14
	R	14	14	14	16	15	16	12	12	17	13
	Z _{obs}	0.38	0.51	0.38	1.15	0.77	1.15	-0.38	-0.38	1.54	0.0
Decision: accept the randomness hypothesis at the 5% significance level if $-1.96 < Z_{obs} < 1.96$											
Mann-Whitney	R _{1adj}	188.5	197.5	187.0	198.5	197.0	186.5	177.0	173.5	198.5	194.5
	U _{1adj}	83.5	92.5	82.0	93.5	92.0	81.5	72.0	68.5	93.5	89.5
	Decision:	accept the homogeneity hypothesis at the 5% significance level if U _{obs} is within the range of critical values U _{0.05, 14/14} = 55-141									
Grubbs-Beck	X _L	1.5	3.5	4.7	5.7	7.6	9.6	11.0	13.8	16.4	20.1
	X _H	12.4	15.1	20.6	30.6	38.2	46.4	55.3	65.3	97.0	128.3
	Decision:	any sample values greater than X _H are considered to be high outliers and those less than X _L are considered to be low outliers.									

N₊: number of positive signs; N₋: number of negative signs; r: number of runs; Z_{obs}: reduced normal score; R₁ and U₁: adjusted small sample statistics and critical values: (U_{a, n1/n2}); a = significance level. Grubbs-Beck: WRC version with K_{α, N} = K_{0.1, 28} = 2.535.

each duration (d), 100 variates are generated. These synthetic series are again subject to frequency analysis and the 10, 50 and 100 year rainfall depths are finally calculated by the Pearson type III probability model (Table 4).

4. DDF Curves Calculation

To be more expressive, the results given in Table 4 are used to establish the theoretical laws that best fit the DDF of heavy rains at the calibration stations: Ain

Berda, Pont Bouchet and Chafia-Dam. Selected from several models that reproduce with different accuracies the DDF and/or the IDF relationships [14-16], a Montana type model is adopted in this study. This multiplicative model takes the form:

$$H(d, T) = a(T) \times d^{b(T)} \quad (1)$$

In Eq. (1), H(d, T) is the rainfall depth (mm) over a duration d (min) for a T year recurrence interval, a(T) and b(T) are the Montana adjustment coefficients. The least squares method results are given in Table 5

Table 3 Statistical summary of heavy rainfall data (mm).

Rain gauge code	Statistics	Rainfall duration (minutes)									
		5	10	15	30	60	120	180	360	720	1,440
		Calibration recording rainfall gauges									
140606	Minimum	1.6	4.0	4.5	7.5	9.6	15.0	13.5	15.5	19.0	19.0
	Mean	4.4	7.4	10.2	14.5	17.8	21.9	24.9	30.4	41.6	52.9
	Maximum	9.1	14.5	22.5	33.3	33.3	38.3	53.0	66.5	86.5	103.5
	Standard deviation	1.8	2.3	3.6	6.0	6.5	7.7	9.6	11.1	16.1	19.7
	Skew coefficient	0.9	1.3	1.9	1.6	0.9	0.9	1.5	1.7	1.0	0.6
140631	Minimum	2.0	3.5	4.0	5.0	8.5	11.9	13.5	17.0	19.5	23.5
	Mean	5.6	9.0	11.2	15.0	18.1	21.2	24.0	32.2	41.5	54.2
	Maximum	13.5	14.0	20.7	27.5	29.0	44.0	48.5	84.0	104.5	128.5
	Standard deviation	2.4	3.2	4.0	5.8	6.7	7.4	8.3	15.9	19.4	26.8
	Skew coefficient	1.5	1.0	1.1	1.2	1.3	1.4	1.5	2.3	2.0	1.6
031501	Minimum	3.3	5.0	5.0	9.0	9.5	11.3	14.8	20.5	22.5	32.0
	Mean	7.1	9.6	12.3	17.1	22.1	27.0	30.2	38.5	48.6	62.9
	Maximum	16.0	19.0	21.0	24.6	43.5	50.0	56.0	79.4	106.0	116.1
	Standard deviation	4.0	4.5	6.2	5.4	9.0	10.9	12.3	17.3	23.2	24.5
	Skew coefficient	1.4	1.0	1.6	1.0	1.4	1.1	1.3	1.6	1.8	0.9
Validation recording rainfall gauges											
140402	Maximum	20.5	22.8	23.9	23.9	32.0	41.7	47.7	82.1	104.1	113.2
031601		8.5	13.5	32.4	52.7	91.1	108.2	127.3	142.9	149.9	154.3
030905		10.0	16.0	16.0	16.6	27.1	41.0	45.0	54.8	73.5	75.9
030903		9.0	11.3	13.6	14.0	16.5	24.3	33.3	52.0	91.5	145.4
100711		-	-	15.00	17.3	25.6	48.3	53.00	62.2	80.4	99.2

Table 4 Maximum rainfall depth frequency (mm).

Rainfall duration (minutes)		5	10	15	30	60	120	180	360	720	1,440
Ain Berda (140606)	T = 10 years	11.1	14.4	16.7	21.6	27.9	36.1	41.9	54.1	69.9	90.4
	T = 50 years	14.9	19.2	22.2	28.5	36.6	47.1	54.5	70.0	89.9	115.4
	T = 100 years	16.5	21.2	24.6	31.7	40.9	52.7	61.2	78.8	101.6	130.9
Pont Bouchet (140631)	T = 10 years	11.3	14.9	17.5	23.1	30.4	39.9	46.9	61.7	81.2	106.9
	T = 50 years	14.6	19.4	22.9	30.5	40.5	53.9	63.7	84.8	112.8	150.1
	T = 100 years	15.3	20.5	24.4	32.7	44.0	59.0	70.2	94.2	126.6	170.0
Chafia-Dam (031501)	T = 10 years	12.2	15.8	21.5	24.7	34.1	41.6	46.6	60.6	78.4	96.6
	T = 50 years	21.1	24.0	32.4	32.6	45.1	54.9	66.4	93.6	118.3	132.7
	T = 100 years	26.1	28.1	37.5	42.7	49.6	60.4	76.0	110.9	138.2	148.8

and Fig. 2; R^2 and SEE being the determination and the standard error of estimate, respectively. In practice, such relationships are preferred as they synthesize the characteristics of intense rainfall events in the region of Annaba.

Being very significant, the results obtained for recording rain gauges can further be extended to calculate dimensionless DDF curves. Likewise, these

curves can be described by an equation of the form:

$$\frac{H(d,T)}{H(24,T)} = a'(T) \times \left[\frac{d}{24} \right]^{b'(T)} \quad (2)$$

in which d is the duration in hours, $H(24, T)$ is the T year maximum daily rainfall depth (mm), $a'(T)$ and $b'(T)$ are adjustment coefficients. The results of the least square analysis are reproduced in Table 6 and Fig. 3.

This mode of graphical representation that best fits

Table 5 Regression analysis results of the relation $H(d, T) = f(d, T)$.

Rain gauge name	Ain Berda (140606)			Pont Bouchet (140631)			Chafia (031501)		
T (years)	10	50	100	10	50	100	10	50	100
A (T)	6.14	8.36	9.14	6.00	7.50	7.67	7.45	11.00	12.46
B (T)	0.369	0.361	0.366	0.395	0.412	0.426	0.358	0.351	0.351
R ² (%)	97.48	96.46	97.16	98.46	97.60	96.50	99.50	98.54	96.53
SEE (mm)	0.108	0.126	0.116	0.08	0.112	0.150	0.045	0.077	0.121

Fig. 2 Theoretical DDF curves for the calibration stations.

Table 6 Results of regression analysis of the dimensionless DDF relationship.

Rain gauge name	Ain Berda (140606)			Pont Bouchet (140631)			Chafia (031501)		
T (years)	10	50	100	10	50	100	10	50	100
a'(T)	0.994	0.994	0.993	1.012	1.012	1.013	1.034	1.061	1.070
b'(T)	0.366	0.357	0.362	0.402	0.418	0.423	0.354	0.347	0.346
R ² (%)	99.97	99.97	99.96	99.8	99.8	99.97	98.58	98.30	96.02
SEE	0.012	0.011	0.013	0.037	0.038	0.041	0.042	0.084	0.129

Fig. 3 Theoretical dimensionless DDF curves for the calibration stations.

the data shows that the theoretical curves for the 10, 50 and 100 year frequencies are more or less confused. Presumably, major storm intensities are uniformly distributed over time in the region of Annaba. Thus, it may be possible to extrapolate the results using an

envelope curve (or a master curve) that reflects the distribution of maximum daily rainfall over time. Close examination of the dimensionless regression results shows that the constants $a'(T)$ could be taken as unity. By trial and error, the constant $b'(T)$ that

closely overlaps and best fits the theoretical data is approximately equal to 0.36 (Fig. 4).

In practice, such a model is a valuable tool to estimate heavy rainfall depths for various durations and frequencies in non recording rain gauge stations from the daily storm depth. It provides the basic input for urban and agricultural drainage projects as well as flood hazard mapping in the region.

5. Model Validation

Given that the performances of the model calibration are less indicative of its actual simulation capabilities, these are best expressed through validation, an absolutely essential step in the modelling process of random phenomena. A model is said to be valid if it is able to correctly reproduce the data. To quantify the performance of a model, there is no universal method. The basic principle is to compare calculated (or simulated) values with sampled data. To appreciate the efficiency of the model, calculations are performed on data that were not used in its calibration. In the literature, many criteria are used to assess the model sensitivity in hydrology, including the correlation coefficient, the coefficient of determination, the mean squared error,

the Nash criterion of efficiency and the Willmott index of agreement [17-19]. In this paper, three “goodness-of-fit” measures are used for model validation: the coefficient of correlation (R), the Nash criterion of efficiency (E) and the Willmott index of agreements (d_1') which are briefly described below.

The Pearson’s product-moment or correlation coefficient, a measure of the strength and direction of the linear relationship between two variables with N paired observations, is given by:

$$R = \frac{\sum_1^N (x_i - \bar{x})(y_i - \bar{y})}{[\sum_1^N (x_i - \bar{x})^2 \sum_1^N (y_i - \bar{y})^2]^{1/2}} \quad (3)$$

where, x and y are the explicative and explained variables with means $\bar{x}$ and $\bar{y}$ respectively. It (R) indicates how closely data in a scatter plot fall along a straight line. The closer that the absolute value of R is to one, the closer that the data are described by a linear equation.

The coefficient of efficiency has been widely used to evaluate the performance of hydrologic models. Nash and Sutcliffe (1970) defined this coefficient, which ranges from minus infinity to 1.0, with higher values ($E \geq 0.6$) indicating better agreement, as:

$$E = 1 - \frac{\sum_1^N (O_i - P_i)^2}{\sum_1^N (O_i - \bar{O})^2} \quad (4)$$

Fig. 4 Reduced DDF curve for Annaba region.

Table 7 Statistics comparing the observed and simulated series.

Rain gauges code	Calibration stations			Validation stations				
	140606	140631	031501	031601	140402	30903	30905	100711
Intercept	0.187	9.582	2.106	5.266	3.065	25.954	0.006	4.961
Slope	1.028	0.899	0.905	0.698	0.897	0.899	0.873	0.898
R (Pearson correlation)	0.993	0.992	0.990	0.901	0.979	0.961	0.979	0.986
Sum of squared errors	124.8	203.0	197.6	3312.4	402.8	1202.6	178.1	150.1
Ficher F	537.76	474.04	396.36	34.60	180.56	96.20	183.76	205.93
Nash criterion	0.982	0.964	0.967	0.698	0.949	0.729	0.908	0.966
Willmott index of agreement	0.934	0.901	0.927	0.734	0.898	0.671	0.873	0.903

in which, O_i are observed data with mean $\bar{O}$ and the P_i are simulated values.

Physically E , is the ratio of the mean square error,

$$MSE = N^{-1} \times \sum_1^N (O_i - P_i)^2 \quad (5)$$

to the variance in the observed data, subtracted from unity.

The Willmott index of agreement (d_r), is another widely used dimensionless indicator of model “goodness-of-fit” given by the expression below:

$$d'_1 = \frac{\sum_1^N |P_i - O_i|}{2 \times \sum_1^N |O_i - \bar{O}|}, \text{ if}$$

$$\sum_1^N |P_i - O_i| \leq 2 \times \sum_1^N |O_i - \bar{O}| \quad (6)$$

The index of agreement varies from $-\infty$ to 1 with higher values indicating that the model predicted values have better agreement with the observations [18].

In this work, the model-predicted data are compared with the observed data on heavy rainfall events (i.e., the absolute maximum rainfall depths recorded over a given duration during the observations period) at the three calibration stations (Ain Berda, Pont Bouchet and Chafia-Dam) and five control stations located in the North-east of Algeria, namely Settara, Zardézas, Bousnib, Guelma and Ain Assel. Table 7 presents the model validation process results.

Performances, expressed in terms of Nash-Sutcliffe criterion and Willmott index of agreement obtained by applying the multiplicative type model are adequate to good ($0.698 \leq E \leq 0.982$ and $0.671 \leq d_1 \leq 0.934$) in calibration and in validation phases. Furthermore, the correlation coefficient values being close to one for both calibration and validation cases indicate a strong

linear relationship between observed and simulated values. In other words, the three “goodness of fit” criteria imply that the multiplicative model works sufficiently well and provides satisfactory answers as to simulate heavy rainfalls observed in the region of Annaba and in the North-east of Algeria as well.

6. Conclusions

This paper presents a 2-parameter multiplicative model to overcome the lack of information on short duration rainfall data at sites with non recording rainfall gauges in the Annaba region and the extreme North-east of Algeria as well. The capability of this model to provide a reliable estimate of the short-duration design storm depth is tested by computing the correlation coefficient for the linear relationship between predicted and observed values, the Nash efficiency criterion and the Willmott refined index of agreement. Results of this evaluation indicate the feasibility of the proposed procedure for deriving the DDF curves relations. In its reduced form, the model is used to estimate, with sufficient accuracy, the T-year design rainfall depth for any duration from the corresponding 24 duration T-year rainfall for the cases where recording rainfall data are missing in the extreme North-east of Algeria.

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