INNSPUB

Journal of Biodiversity and Environmental Sciences (JBES)
ISSN: 2220-6663 (Print) 2222-3045 (Online)
Vol. 11, No. 4, p. 209-219, 2017
http://www.innspub.net

RESEARCH PAPER OPEN ACCESS

Modelling and mapping of short duration storms in Northeastern Algeria

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Article published on October 30, 2017

Key words: Northeastern Algeria, Design storm, Frequency analysis, Model validation, Isohyets map

Abstract

One of the natural phenomena that have the greatest impact on humans is heavy rainfall. Thus, knowledge of spatial and temporal distribution of short duration rainfall is of great interest in hydro-technical studies. This work has two objectives: calculating the *Depth-Duration-Frequency (DDF)* relationships and drawing isohyetal maps for short duration heavy rains in northeastern Algeria. Digitized charts for more than 5000 rainfall events recorded at 18 sites and daily rainfall for 74 rain gauges that spread over the main hydrographic basins in the region are the raw data. Several formulations are tested to assess the DDF laws. The sensitivity analysis validated, with sufficient accuracy, two nondimensional 2-parameter models (geometric and semi-logarithmic) to analytically describe these laws. Using previous and newly produced results and the kriging method for interpolation, we were able to shift from a point estimate to a spatial evaluation of the rainfall hazard by drawing isohyetal maps of the 10 and 100-year events for the 15, 30, 60 minute and 24 hour rainfall durations. This mapping made it possible to reconstruct the great disparities in quantities and durations of heavy rainfall events in the northeastern Algeria watersheds. Moreover, the results allow to answer, for a well-informed user, many questions in hydraulics, sol conservation fields as well as in rainfall-runoff-sol loss modelling.

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Introduction

Heavy rains are natural phenomena with the greatest impact on humans and their environment. Rainfall characteristics (depth and intensity, duration, frequency and geographic extent) are largely explained by geographic factors (spatial position: altitude, exposure, distance to the sea, etc.).

The purposes of this study consists of (1) searching for analytical relationships to calculate maximum short-duration rainfall from the maximum daily rainfall and (2) drawing isohyet contour maps for the 10 and 100 year rainfalls of 15, 30, 60 minute and 24 hour durations in order to get an overview of the spatial and temporal variability of rain in northeastern Algeria.

The database contains records of 18 recording rain gauges (more than 5000 events) and 74 non recording ones that span over the study area. To achieve these goals, exploratory data analysis, frequency analysis, curvilinear regression and interpolation techniques, especially kriging, play a key role. This form of regionalization permits to localize zones of maximum rainfall intensities and to visualize their geographical extension. From a practical point of view, the results of this study will answer many questions in water engineering (design storm calculation) and soil conservation, on one hand, and in Rainfall-Runoff-Erosion modeling (as input variable), on the other hand.

Materials and methods

Study area

Located in the North-east of Algeria, the study area represents an intermediate zone between the Tellian domain, with a strong mediterranean influence in the North, and the High plains domain with a broad continental influence in the South. Combined action of topography, geology and climate gives the Northeastern Algeria very important water possibilities that are renewed, to a large extent, by the rains.

Although annual and seasonal rainfall depths maintain the sustainability of groundwater and superficial flows in the five major hydrographic basins: Côtiers constantinois, Hauts plateaux constantinois, Kébir-Rhumel, Medjerda-Mellegue et Seybouse (Fig. 1), they cannot solely explain the unpredictable character of heavy rains because they tend to smooth the variability in rainfall duration and hence to mask the energy characteristics of rain showers.

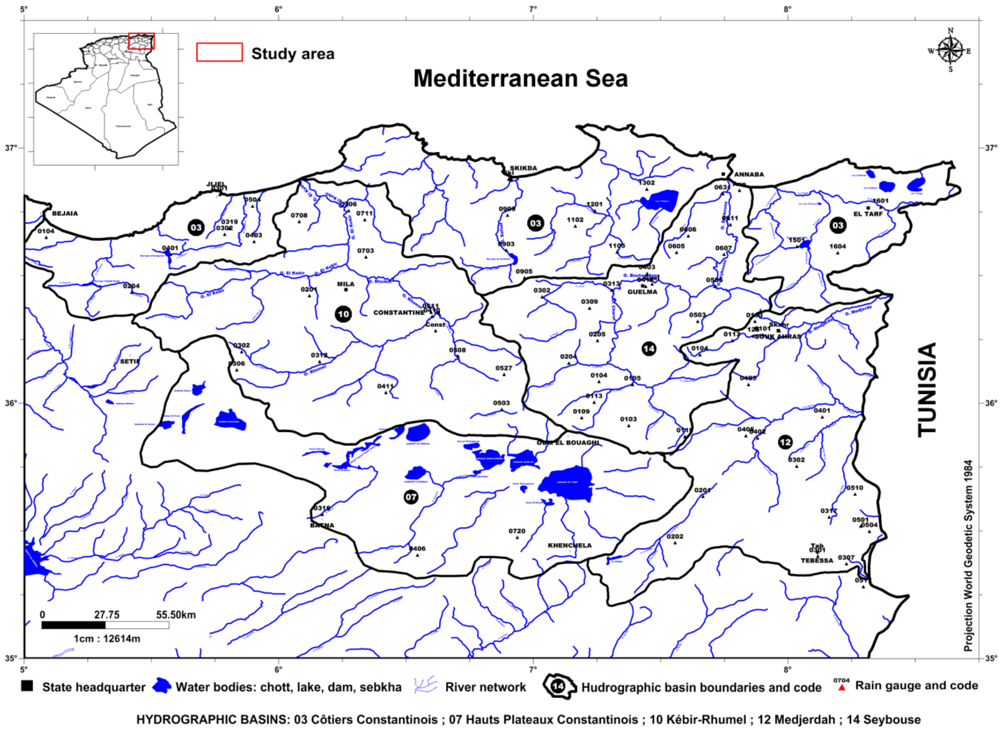


Fig. 1. Study area and location of rainfall stations.

Rains those are more abundant in the North (700-1600 mm/year) than in the South (300 mm/year) of the study area, fall in the form of short duration, sometimes violent, showers due to local or generalized weather disturbances. Sometimes, the brutality of extreme rainfall events causes floods and landslides that increase property and human damages in Algeria as well as elsewhere (the generalized floods of December 1984 in the eastern part of the country and the landslides of February 2012 in Skikda city).

Rainfall Depth-Duration-Frequency modelling

Extreme rainfall modelling can be very useful in hydro-technical structures design or in any other project requiring some knowledge on rainfall events. In this work, we attempt to explore and describe the Depth-Duration-Frequency (DDF) relationships by analytical models and to provide an objective evaluation of the capacity of these models to generate realistic DDF relationships that allow to synthesizing the information on the heavy rains characteristics in the study area. On site data recorded by 18 tipping bucket rainfall gauges with annual series containing 7 to 32 years of observations were subjected to a classical frequency analysis (exploratory data analysis, probability distribution fitting, goodness of fit testing and frequency model choice) to provide, for seventeen time series of various durations (D), ranging from 5 minutes to 24 hours, the T-year event for 16 arbitrarily selected return periods (T). The T-year maximum rainfall events were estimated using the generalized extreme values distribution (GEV).

Dispersion diagrams describing the H(D, T) = f (D) relationships, showed that:

- at equal frequencies, the rainfall depth is the greater the longer its duration.
- at equal durations, the rainfall depth is greater the greater the return period.

These observations suggest the use of increasing curvilinear models whose parameters are to be estimates by least squares methods. Several empirical models, implemented in *STATGRAPHICS CENTURION XV* software, were tested.

For regionalization purposes, the dimensionless data were preferred and instead of calculating the relationship R = f (D, T), we worked on the reduced form described by the equation (Beloulou *et al.*, 2015; Guechi *et al.*, 2017):

$$\frac{R(D,T)}{R_{24}(T)} = \varphi\left(\frac{D}{24}\right) \quad (1)$$

Where R (D,T) is the T-year rainfall depth of duration D, R_{24} (T) is the T-year maximum daily precipitation and φ is some function. The reduced time series have been subjected to a simple linear regression analysis. The analysis of variance results, permitted to retain in the calibration phase, the multiplicative and semi-logarithmic model types:

-Semi-logarithmic: $y = \beta_0 + \beta_1 \ln(x)$ (2)

− Multiplicative: $y = \beta_0 x^{\beta_1}$ (3)

As an example, Table 1 below summarizes the least squares regression results (model parameters and goodness of fit) of the non-dimensional DDF relationship expressed by the above equation for some representative stations in the northeastern Algeria. In this table, the constants a and b are respectively the estimators of β_0 and β_1, r^2 is the coefficient of determination and MAE corresponds to the mean absolute error between the observed and predicted values.

Table 1. Adopted models parameters.

	Multiplicative model					Semi-logarithmic model				
Parameters	Return period in years					Return period in years				
	2	10	25	50	100	2	10	25	50	100
Jijel (Côtiers constantinois basin: 03) – Sample size : 18 - Observations period : 1984/2002										
a	1,12	1,02	0,98	0,96	0,95	0,89	0,87	0,86	0,85	0,85
b	0,41	0,32	0,29	0,27	0,25	0,16	0,14	0,13	0,12	0,12
r^2 (%)	97	94	91	87	81	97	96	93	90	86
MAE	0,11	0,11	0,12	0,14	0,16	0,04	0,04	0,05	0,06	0,07

Multiplicative model							Semi-logarithmic model				
Parameters	Return period in years						Return period in years				
	2	10		25	50	100	2	10	25	50	100
Foum Toub (Hauts plateaux constantinois basin : 07) – Sample size : 29 - Observations period : 1969/2004											
a	1,09	0,98		0,95	0,94	0,93	0,93	0,88	0,87	0,87	0,87
b	0,35	0,28		0,26	0,25	0,23	0,16	0,14	0,13	0,13	0,12
r^2 (%)	97	99		99	98	97	96	96	96	96	95
MAE	0,07	0,03		0,03	0,05	0,07	0,05	0,04	0,03	0,03	0,04
Settara (Kébir-Rhumel basin : 10) – Sample size : 31 - Observations period : 1972/2002											
a	1,12	1,14	1,16	1,18		1,12	0,90	0,93	0,96	0,98	1,01
b	0,46	0,41	0,41	0,39		0,46	0,20	0,2	0,19	0,19	0,19
r^2 (%)	99	98	97	95		99	95	96	97	97	97
MAE	0,06	0,08	0,09	0,11		0,06	0,06	0,05	0,04	0,04	0,04
Tebessa (Medjerda-Mellegue basin :12) : Sample size : 31 - Observations period : 1974/2005											
a	1,14	1,03		1,01	0,99	1,02	0,97	0,93	0,91	0,91	0,90
b	0,33	0,26		0,26	0,25	0,25	0,16	0,14	0,13	0,13	0,13
r^2 (%)	96	98		99	99	99	99	99	98	98	97
MAE	0,09	0,05		0,04	0,03	0,04	0,02	0,02	0,04	0,03	0,03
Guelma (Seybouse basin : 14) - Sample size : 27 - Observations period : 1974/2001											
a	1,02	1,01	1,01	1,03	1,05	1,02	0,87	0,91	0,93	0,96	0,98
b	0,35	0,31	0,30	0,30	0,30	0,35	0,15	0,15	0,16	0,16	0,16
r^2 (%)	97	98	95	94	92	97	94	91	90	89	87
MAE	0,06	0,07	0,10	0,12	0,13	0,06	0,06	0,07	0,08	0,08	0,09

Being present at all probability levels with practically acceptable coefficients of determination and mean residuals, the two models are retained. Moreover, these models are well prepared for a generalization insofar as the constant a is close to one and only the parameter b varies from one station to another. Therefore, DDF relationships are described by the following analytical formulations:

- Multiplicative model: $R(D,T) = R_{24}(T) \times \left(\frac{D}{24}\right)^b$ (4)

- Semi-logarithmic model: $R(D,T) = R_{24}(T) \times \left[1 + b \times \ln\left(\frac{D}{24}\right)\right]$ (5)

Both models have to be validated. In the literature, there is a variety of metrics to evaluate the sensitivity of a model (Servat and Dezetter 1990, Legates and McCabe 1999; Hingray *et al.*, 2009, Biondi *et al.*, 2012). The most widely used by hydrologists are the correlation coefficient (r), the coefficient of determination (r^2), the mean absolute error (MAE), the mean square error (MSE) and the Nash-Sutcliffe (NSE), the Willmott (d) and the Kling-Gupta KGE (2009) criteria. A comprehensive study of these criteria is beyond the scope of this paper. In practice, the search for the optimal set of parameters for the given model with respect to a given sensitivity criterion is to find the set of parameters which gives the best value of the criterion.

For the case of the selected DDF models (equations 4 and 5), the parameter set relates only to the constant b while remaining close to the value found during the calibration phase.

Results and discussion

Although the time series are very short for some recording rain gauges, the agreement between predicted and experimental values (efficiency criterion > 0.6 in all cases), as shown in Table 2, allowed to take advantage of these rainfall reduction empirical models to estimate extreme short-duration precipitation from daily data. From a spatial point of view, observations from 18 rainfall recording gauges are insufficient to draw a more or less precise map for rainfalls of less than 24 hour duration. Moreover, the constant b values vary in space with no precise spatial organization or trend; elevation, latitude (or distance from the sea) and the nature of the probability distribution law seem to play an important role in the variability of the b parameter of the DDF models.

For regionalization purposes, maximum short-duration storms are obtained using the rainfall reduction equations (4 and 5) developed previously. Given that the regional constants values are somewhat different, a zoning based mainly on the geographic neighborhood and hydro-climatic affinities between the reference rainfall gauges (recording rain gauges) and the target ones (daily rain gauges), was carried out. It was thus possible to easily estimate the short-duration storm depth at the remaining 74 daily rainfall gauges. For each duration, the T-year value corresponds to the average value of the predicted estimates by both models. Table 3 illustrates the results obtained for some representative rainfall sites. This new database is necessary to construct isohyets maps in northeastern Algeria.

Table 2. Model sensitivity analysis results for some rain gauges.

Rain gauge	Model parameters		Willmott et al. (2012)			Nash and Sutcliffe (1970)	R^2
	a	b	d	d_1	d_1'	NSE	(%)
Multiplicative model							
Jijel	1	0,31	0,97	0,88	0,88	0,89	93
Foum Toub	1	0,2	0,96	0,80	0,8	0,85	95
Settara	1	0,34	0,96	0,84	0,84	0,83	92
Tebessa	1	0,26	0,98	0,89	0,90	0,94	94
Guelma	1	0,3	0,98	0,89	0,89	0,91	93
Pont Bouchet	1	0,3	0,98	0,89	0,89	0,91	93
Semi-logarithmic model							
Jijel	1	0,14	0,96	0,82	0,82	0,86	96
Foum Toub	1	0,16	0,96	0,82	0,80	0,82	95
Settara	1	0,16	0,96	0,82	0,80	0,82	95
Tebessa	1	0,14	0,96	0,82	0,82	0,86	96
Guelma	1	0,14	0,96	0,82	0,82	0,86	96

Table 3. DDF calculation results (mm).

Rain gauge identification		Coordinates			Storm duration (minutes)			
Code (03)	Name	Latitude (°N)	Longitude (°E)	Elevation (m)	15	30	60	1440
T = 10 years								
0301	Jijel	36,82	5,77	5	23	32	40	93
0406	Foum Toub	35,41	6,55	1102	20	25	31	74
0711	Settara	36,72	6,34	280	11	15	21	82
0301	Tebessa	35,40	8,12	890	16	22	29	58
0412	Guelma- ONM	36,47	7,47	-	28	35	43	92
T = 100 years								
0301	Jijel	36,82	5,77	5	45	60	65	125
0406	Foum Toub	35,41	6,55	1102	31	38	53	109
0711	Settara	36,72	6,34	280	21	24	31	105
0301	Tebessa	35,42	8,12	-	31	38	46	93
0412	Guelma-ONM	36,47	7,47	-	55	69	85	180

According to Bloschl and Sivapalan (1995), regionalization implies the transfer of information from one place to another. It consists in determining processes that best synthesize the point rainfall information (Descroix *et al.*, 2001) and estimating the cumulative rainfall, and therefore, the intensity, at any point in a region defined as an area within which the statistical behavior of rainfall events is assumed to be homogeneous (Hingray *et al.*, 2009). One goal of regionalization is mapping (Lebel and Slimani, 1987). Since DDF estimates vary from point to point in the study area, direct regionalization of the T-year storm requires elaborating maps for each rainfall duration unless we work with multi-duration laws (Ghanmi, 2015).

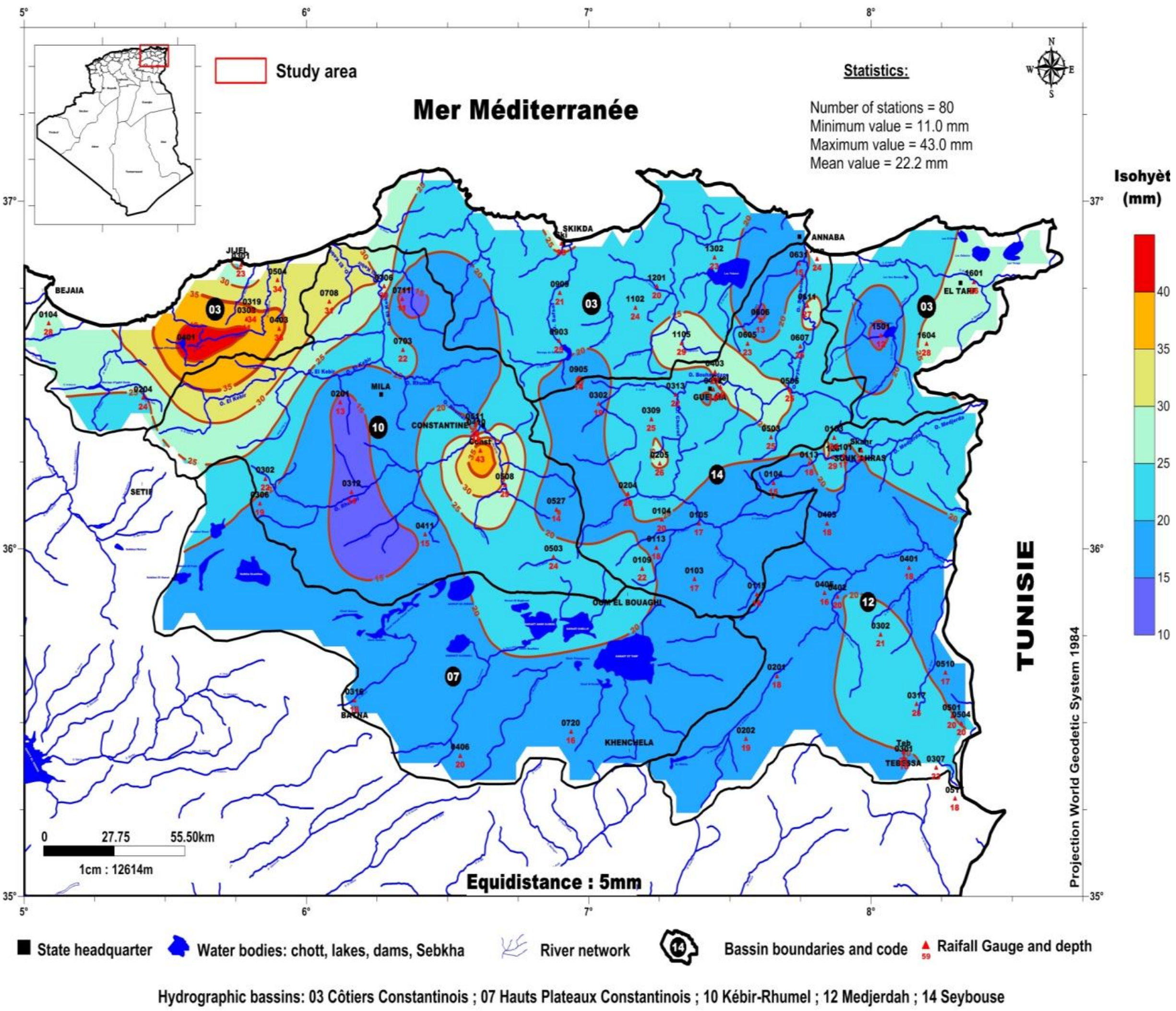
Thus, information in the new database must be transformed into maps, which will provide an estimate of the Depth-Duration-Frequency characteristics of rainfall at any point in the study area.

After calculation of maximum short-rainfall according to the applied zoning, isohyet maps for 15, 30, 60 and 24-hour durations corresponding to the 10 and 100-year heavy storm events were established. These maps were constructed using the simple kriging interpolation method built into the Golden Software LLC *Surfer 11* tools. Whatever the recurrence interval and the storm duration are, a close look at the different isohyetal maps allows to draw the following lessons:

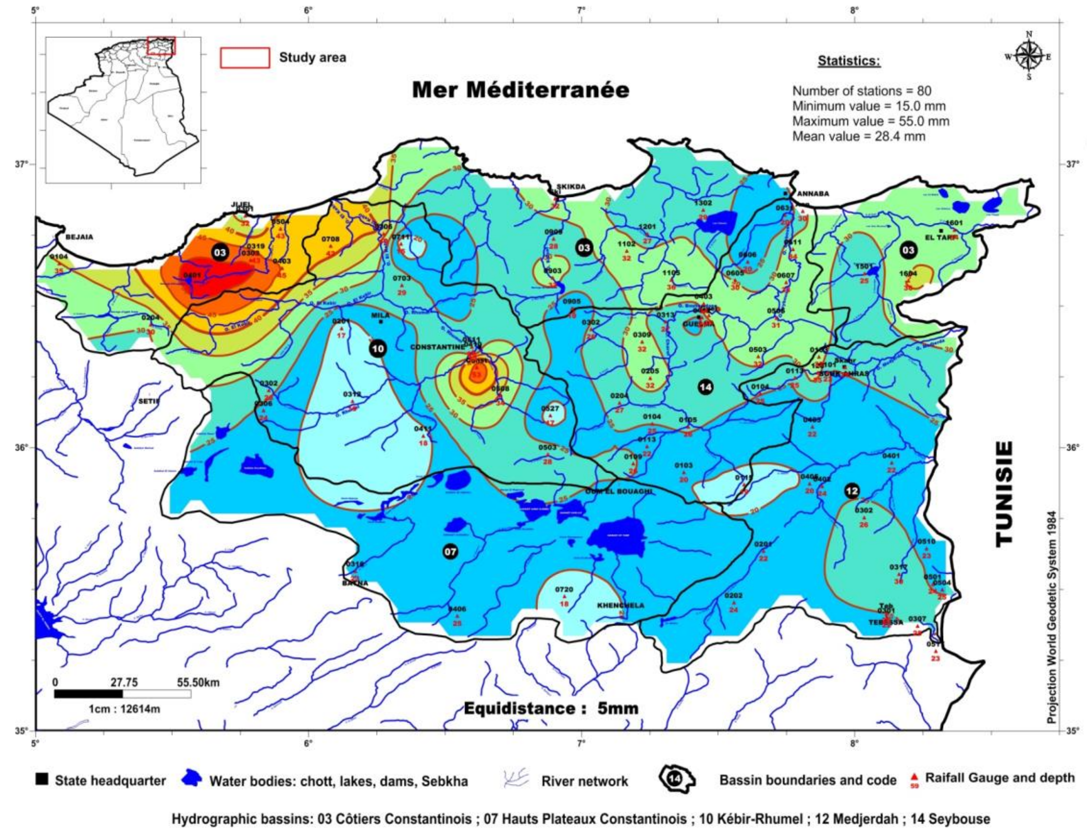
- the most heavy rains fall on the Côtiers constantinois West basin (Jijel-Collo region), the Constantine (Airport) region and the Côtiers constantinois Est basin (humid zones: Ain Assel and Chaffia mountains). In these areas the 10-year and 100-year isohyets reach or exceed 90 and 150mm in 24 hours, respectively. In the same zones, the hourly rains of the same frequencies vary from 40 to 70mm and from 60 to 90mm, respectively. Events of such intensities are also observed along the Zardezas-Boukhamouza axis with some discontinuities in space.
- the rainfalls follow roughly a decreasing gradient from North to South. The 10-year 24-hour isohyets decrease from 140 mm at Erraguene to less than 60mm in the semi-arid zones and the chotts region.

The most severe storms (the 100-year isohyets) decrease from more than 200 mm in El Milia in the North to less than 90mm to the South. It is possible that storms of higher intensity may be encountered in the Hauts plateaux constantinois basin along the Foum Toub-Khenchela-Tebessa axis. It should be noted that short duration rainfalls (less than 60 minutes) follow approximately the same spatial distribution.

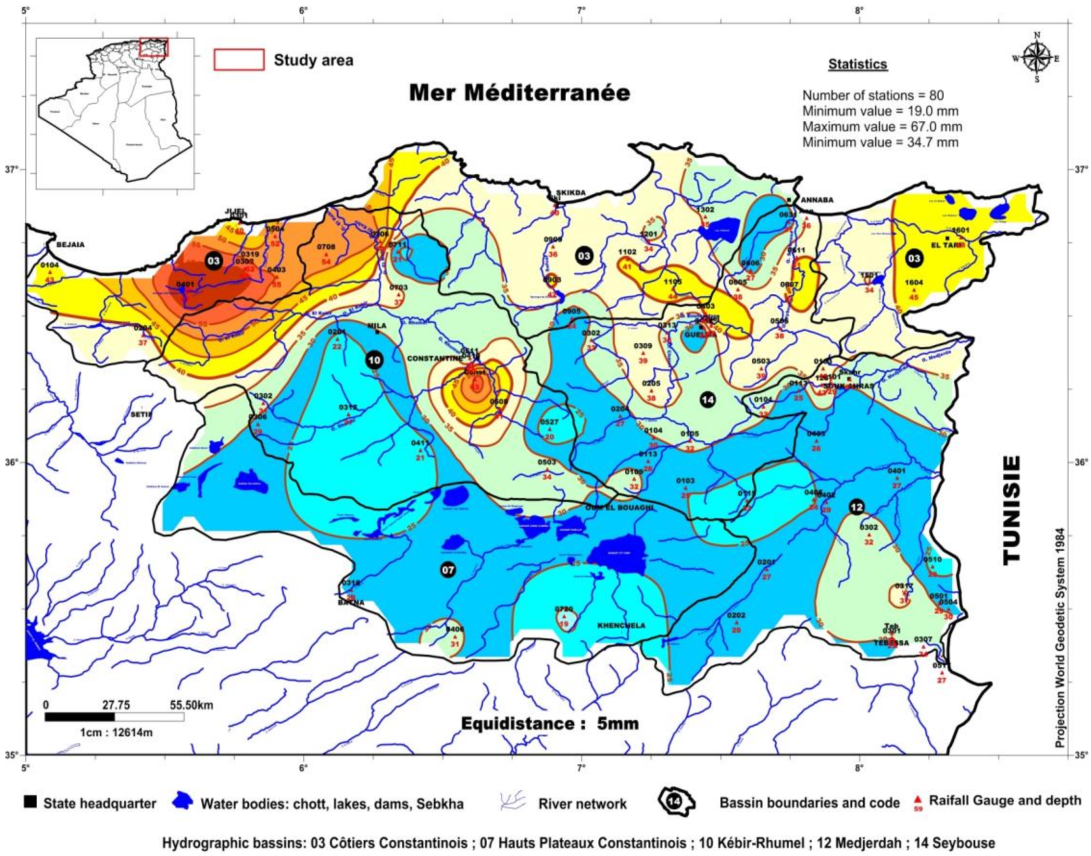
These disparities are closely related to the differences in geo-morphological and climatic characteristics, which are highly variable, in northeastern Algeria (see maps 1 to 8).



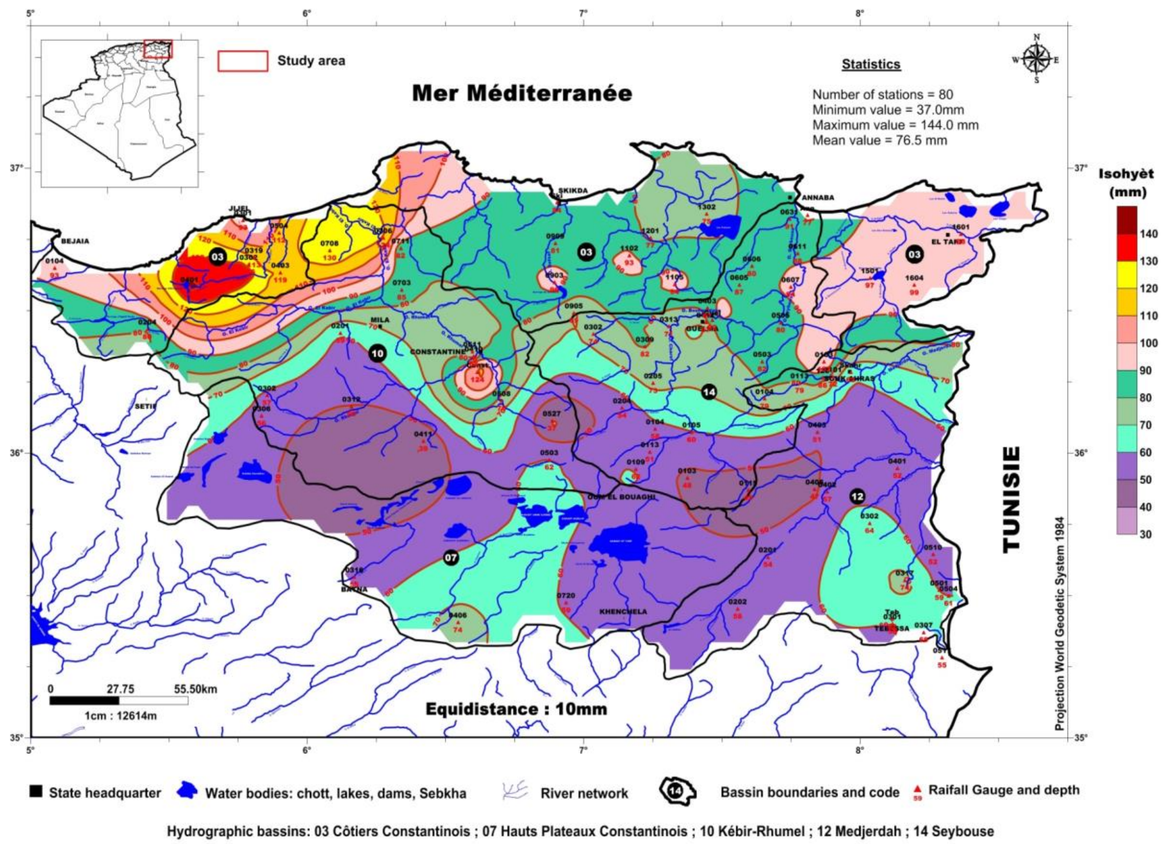
Map 1. Northern algeria 10-year, 15-minute extreme rainfall map



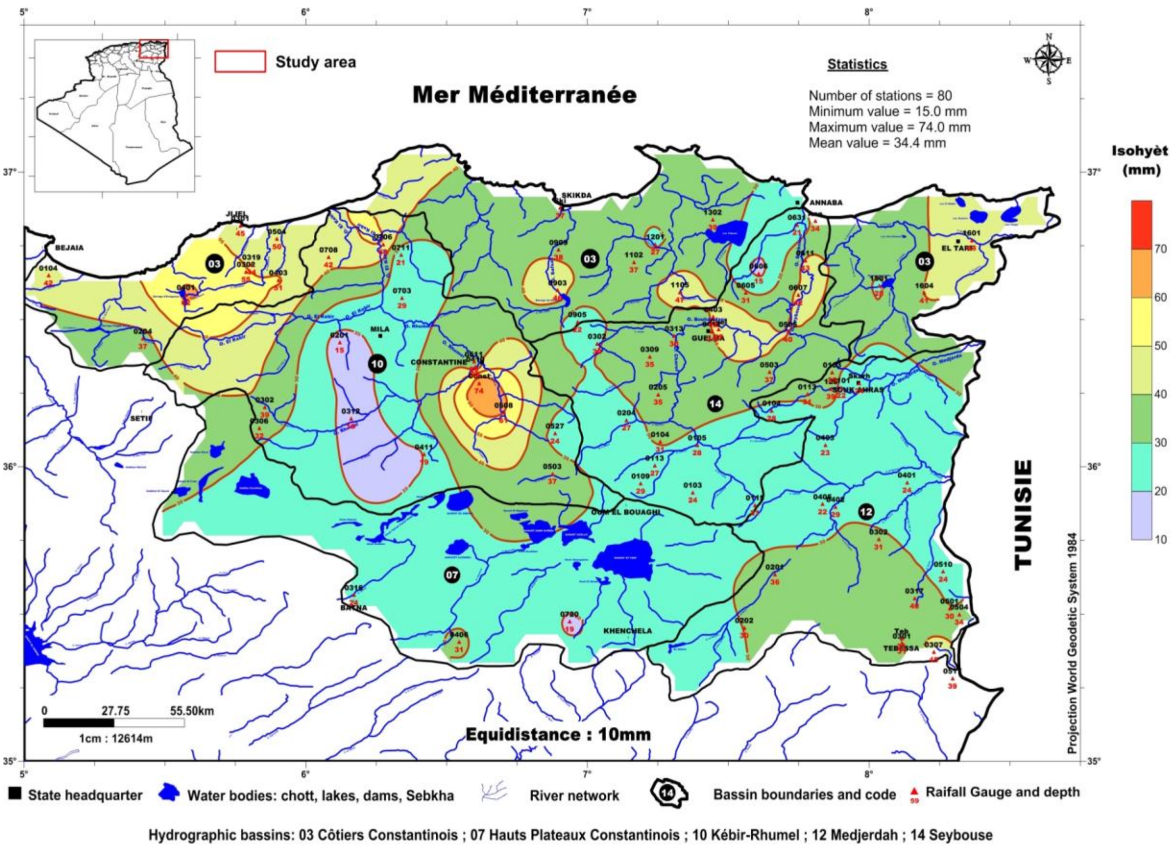
Map 2. Northern algeria 10-year, 30-minute extreme rainfall map



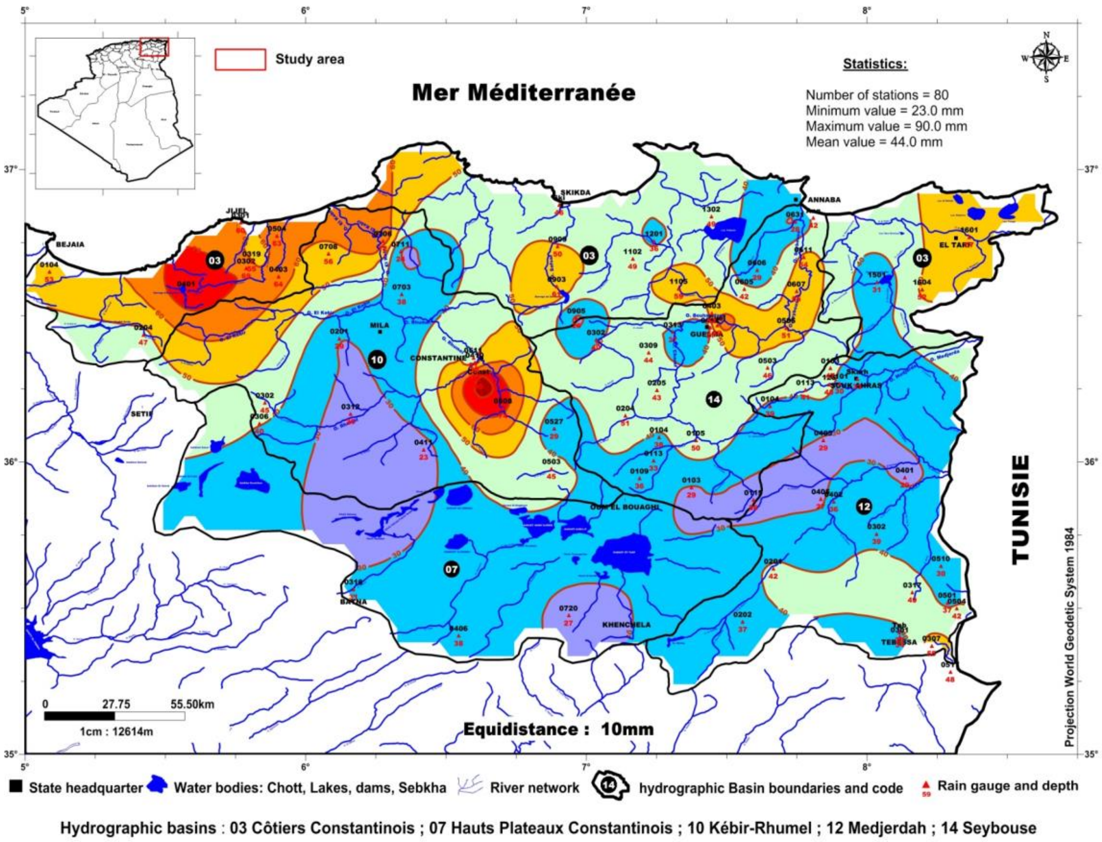
Map 3. Northern algeria 10-year, 60-minute extreme rainfall map



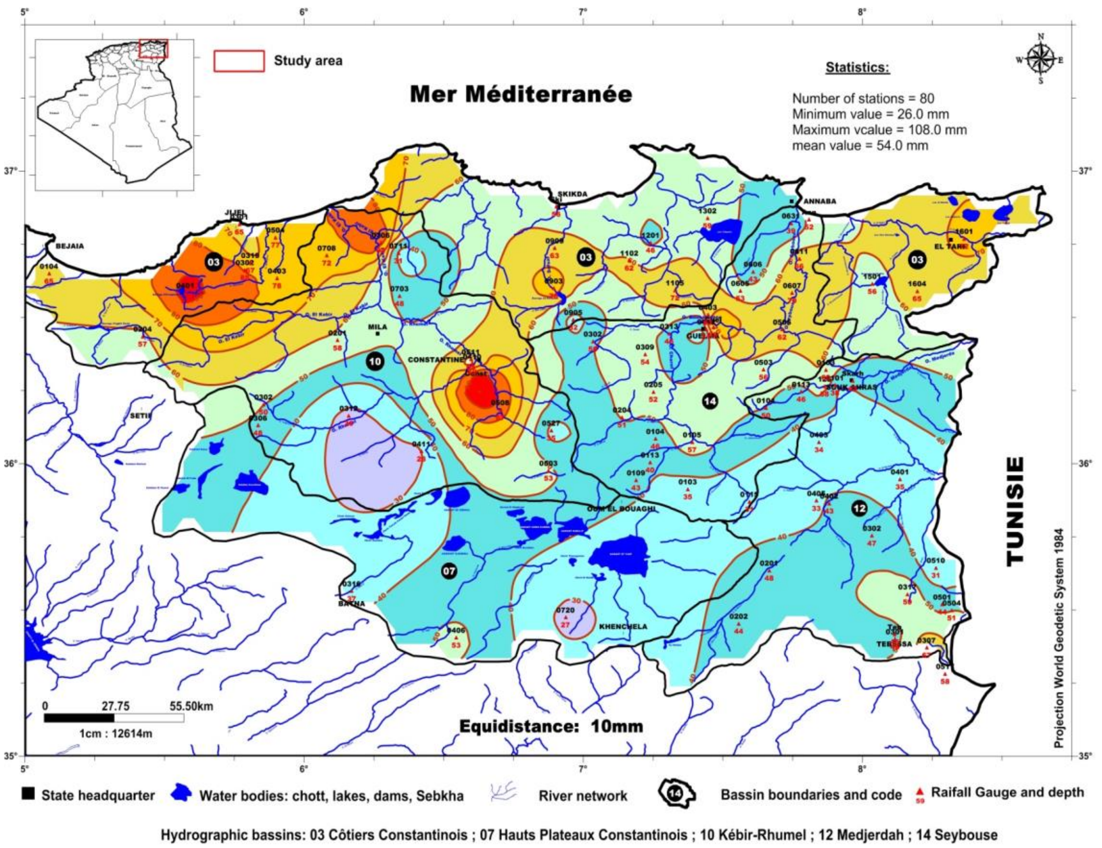
Map 4. Northern algeria 10-year, 24-hour extreme rainfall map



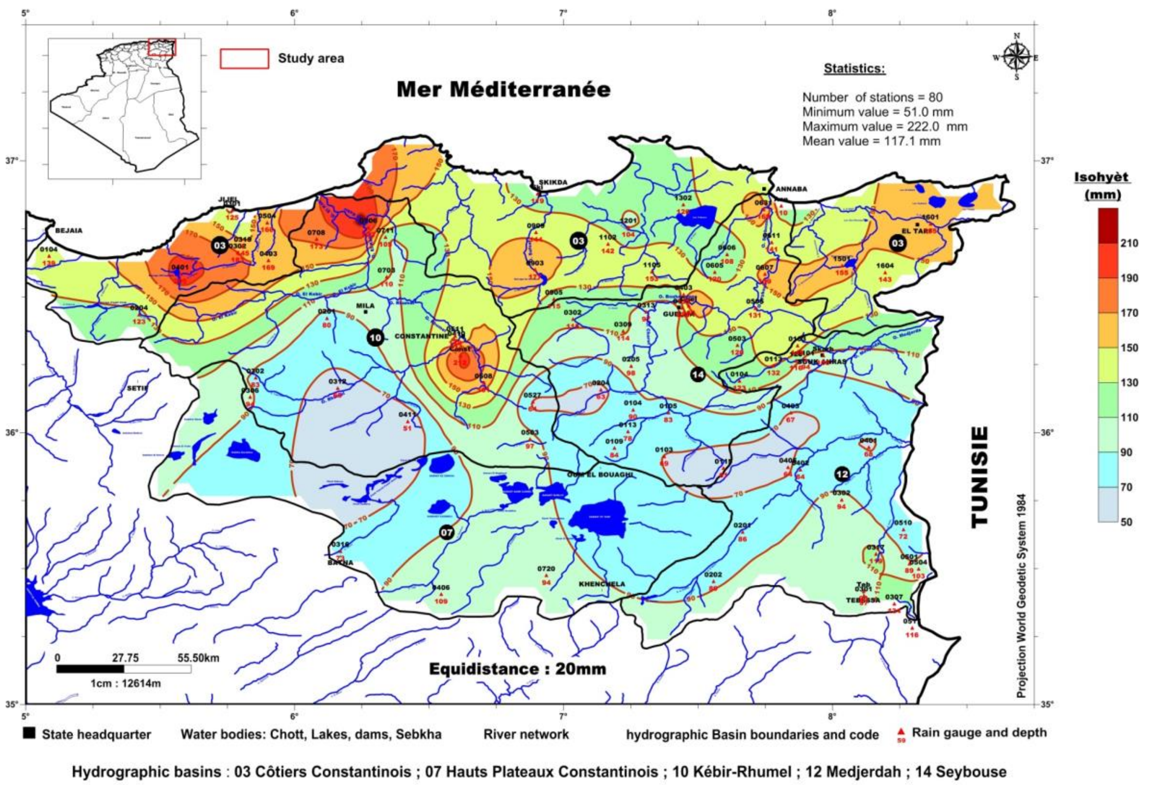
Map 5. Northern algeria 100-year, 15-minute extreme rainfall map



Map 6. Northern algeria 100-year, 30-minute extreme rainfall map



Map 7. Northern algeria 100-year, 60-minute extreme rainfall map



Map 8. Northern algeria 100-year, 24-hour extreme rainfall map

Conclusion and recommendations

At the end of this work, it must be recognized that heavy storm events are random phenomena characterized by complex structures and, hence, difficult to precisely reproduce. Thus, the preparation of isohyetal maps for different durations and frequencies is a delicate operation that requires a rigorous and well-defined procedure in which frequency analysis, regression and interpolation techniques play a central role. The mapping of the severe storm events at different time scales and frequencies allows to move from a point estimate to a spatial knowledge of the phenomenon that helps to estimate rainfall depths and volumes for the design rainfall in hydraulic engineering works. Furthermore, developed maps in this study enables to assess the spatial and temporal variability of extreme rains intensity in northeastern Algeria. Apart from some restrictions, these maps show that the rainfall severity, defined by the largest isohyets, is greater on the coastal strip, especially in the western and eastern parts of the study area and, to a lesser degree, on the summit parts of internal zones such as the Constantine and Souk Ahras mountains. From a practical point of view, these maps give satisfactory results for small return periods events.

However, they must be used with caution for very low frequency events estimates, especially when dealing with the 100-year values because the percentiles used to establish these maps are determined from samples of limited size (less than 50 years of observations).

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