



Spatial and temporal variability of rainfall: case of Bizerte-Ichkeul Basin (Northern Tunisia)

Hiba Jemai¹ · Manel Ellouze¹ · Habib Abida¹ · Benoit Laignel²

Received: 13 September 2017 / Accepted: 15 March 2018 / Published online: 19 April 2018
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Abstract

This study examines spatial and temporal variability of rainfall in Bizerte-Ichkeul Watershed. The basin, located in the extreme north of Tunisia, covers an area of 3084 km². Thirteen rainfall stations, with continuous monthly precipitation records over the period (1970–2011), were considered in the analysis. Two methods were used. In the first, the dimensionless standardized precipitation ratio is applied to examine precipitation temporal variation. The second method is represented by continuous wavelet analysis for the precipitation spatial analysis and the identification of the origin of its variability. The study of temporal variability of annual rainfall showed severe persistent and recurrent drought episodes over the period (1977–2001). Wavelet analysis resulted in detecting the modes and origins of precipitation variability. Three energy bands were clearly identified: (1, 2–4, and 4–8 years) for the entire watershed. The visualization of the power distribution showed that the observed modes of variability are different in their power distributions from one station to another. The approach adopted allowed the identification of two groups with the same precipitation frequency and temporal variation. These groups were defined according to the difference in occurrence of the frequency band for each station.

Keywords Bizerte-Ichkeul Basin · Precipitation · Standardized precipitation ratio · Continuous wavelets

Introduction

Identifying the impact of climate change on hydrological systems and water resources (greenhouse effect, increase in temperature, reduction of rainfall, etc.) is a major challenge for scientists. Climate change is considered the greatest challenge for coastal areas (Nicholls and Klein 2005; Najjar et al. 2000), forestry (Easterling et al. 2000), and many economic and social sectors such as agriculture (Albert and Shortle 2000) and

ecosystems (Scavia et al. 2002; Hammer 1999). Several recent large-scale climatic events have pushed the global community to address climate change and understand the irregular distribution of precipitation in space and time (Khoualdia et al. 2014).

The results of various studies (from 1991 to 2010) on the evolution of precipitation show that climate change resulted in an intensification of precipitation and a more perceptible recurrence of extreme events (New et al. 2001; Solomon et al. 2007; Planton et al. 2005). Among these studies are those interested in the drought sequence that has affected the Central Maghreb Region (Algeria, Morocco, Tunisia) since the 1970s (Djellouli and Daget 1993; Nouaceur 2011; Nouaceur et al. 2013a, b).

Currently, Morocco has the longest dry period in its modern history, characterized by a decrease in precipitation and a marked increase in temperature (Khomsi et al. 2013; Driouech et al. 2010; Zamrane et al. 2016). Algeria experienced during its history many periods of variable scale droughts, which had impacts on living conditions particularly on rural population (1943–1948); the most severe and persistent drought events are those recorded during the years 1980s and 1990s. In that period, the rainfall deficit was estimated to be 50% for the

✉ Hiba Jemai
h.jemai@hotmail.fr

Manel Ellouze
manel.ellouze@hotmail.com

Habib Abida
habibabida62@gmail.com

Benoit Laignel
benoit.laignel@univ-rouen.fr

¹ Faculty of Sciences of Sfax, Road Sokra, 3000 Sfax, Tunisia

² UMR CNRS 6143 Continental and Coastal Morphodynamics 'M2C' University of Rouen, 76821 Mont-Saint-Aignan Cedex, France

central and western regions of Algeria and 30% in the east. The year 1988/1989 was classified as the driest year in Algeria (Djellouli and Daget 1993).

During the twentieth century, Tunisia has experienced several severe droughts. These droughts had different frequencies in the different decades. The years 1950 and 1970, for instance, are distinguished by infrequent appearance of dry years. In the years 1920, 1940, 1960, and 1980, multiyear droughts were recorded with a large spatial extension and a high rainfall deficit (Hénia 2001).

Maritime influences, geographical position, climate, and topographical arrangements (Dorsal in the North, Sahara in the South) attribute to Tunisia several local climates whose characters are sometimes very distinct. This results in a distinguished spatial variability of rainfall throughout the country. Indeed, the north is characterized by an important rainfall and a humid to sub-humid climate while the south is subjected to an arid climate, with very scarce downpours. The study basin, located in the extreme North of the country, is marked by important rainfall and important surface water resources, which have significant hydrological, environmental, and economic impacts on the whole region.

Most research carried out in the study area dealt with the ecological and biological fields, such as studies conducted by Bouzouita (2003), Bejaoui et al. (2005), and Brahim et al. (2008). Nevertheless, studies examining temporal and spatial variability of precipitation are rare. In the following, some of these few studies are briefly described. First, Mathlouthi and Lebdi (2008) showed that dry events of 57 days were identified, during the rainy season in the Ghezala Subwatershed of the Ichkeul Basin. Another study by Mathlouthi and Lebdi (2010), in the same basin, resulted in the calibration of a lumped hydrological model relating runoff to daily rainfall and antecedent precipitation index. Moreover, Mathlouthi et al. (2011) showed that the extreme rainfall events of 2005 are responsible for the generation of landslides in Ichkeul Basin. Finally, Feki et al. (2007) showed, based on GIS and remote sensing, that the development of the vegetation cover in Kroumirie and Mogods (Bizerte region) is mainly related to seasonal rainfall variation.

In this context, the objective of this work is to explore the spatial and temporal variability of precipitation over Bizerte-Ichkeul Basin (Northern Tunisia). First, we examine the trend of rainfall variability in the Bizerte-Ichkeul Basin based on the general shape of the dimensionless standardized precipitation ratio curves, to identify the inter-annual variability as well as the periods of deficit and excess of rainfall. The obtained results are then analyzed by the continuous wavelet method to identify the origin of the precipitation temporal variations (dry and wet periods). Thirteen monthly rainfall time series, registered over a period of 42 years (1970 to 2011), were considered in the analysis.

Description of the study area and data used

The Bizerte-Ichkeul Basin, located in the extreme north of Tunisia, covers an area of 3084 km² (Fig. 1). The watershed has a stretched form. It has a well-developed stream network and drains a rather strong relief. This basin is part of the cold and rainy Talien natural region. The region contains several important watercourses, locally known as wadis, such as wadi Sejnane and wadi Joumine and various hydraulic structures such as dams and hilly lakes.

Bizerte Lagoon, Lake Ichkeul, and the lagoon of Ghar el Melh represent three depressions which form remarkable landscapes belonging to the basin. The plain of Mateur and Lake Ichkeul are separated, to the southwest by the Djebel Ichkeul (510 m of altitude). Lake Ichkeul is the receptacle of the wadis Joumine, Sejnane, Ghezala, Douimis, Tine, and El Meleh. It is linked to Bizerte Lagoon by the Tinja Canal which was endowed with a lock in the 1980s. This lake is supplied with fresh water in the winter period by six main wadis namely: wadis Doumiss, Sejnane, Melah, Ghezala, Joumine, and Tine, causing an increase in water levels in Lake Ichkeul. This results in a large volume of water flowing from the lake to Bizerte Lagoon. During wet years, it pours three times its volume during winter and spring. The situation is reversed in summer, when a drop in the water level of the lake causes the arrival of salt water from Bizerte Lagoon by Wadi Tinja. Several hydraulic developments (dams and hilly lakes) were implemented in the watersheds of Lake Ichkeul and Lagoon of Bizerte, which led to major changes in liquid and solid flows to the lagoon.

Data used in this study are mainly monthly precipitation time series that were obtained from the DGRE (General Directorate of Water Resources in Tunisia) and Tunisian monographs. Thirteen rainfall stations, with continuous monthly precipitation records over a period of 42 years (1970 to 2011), were considered in the analysis (Fig. 1). The rainfall stations are evenly distributed over the entire catchment (Fig. 1).

A preliminary statistical study of the rainfall data was first established. Indeed, the series of observations must be independent, random, homogeneous, and without tendency. These hypotheses were verified using the HYFRAN Software. The considered tests were accepted at a significance level of 5%. Next, the mean, minimum, and maximum annual precipitations, as well as other statistical characteristics (median, standard deviation, coefficients of variation, skewness, and kurtosis) were computed. The corresponding results are presented in Fig. 2 and Table 1.

Methodology

Different statistical methods, such as principal component analysis, kriging, and standardized precipitation index, were

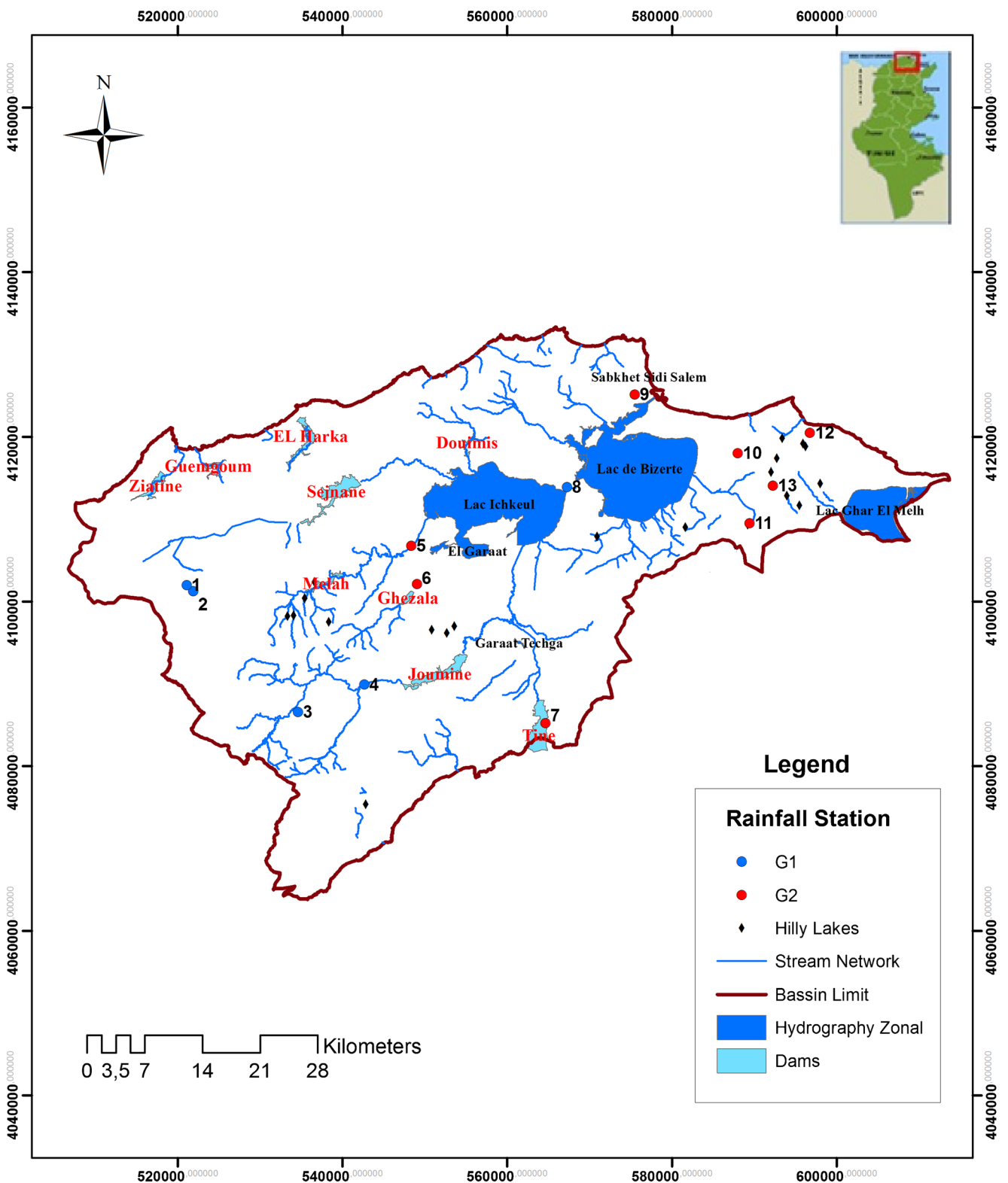
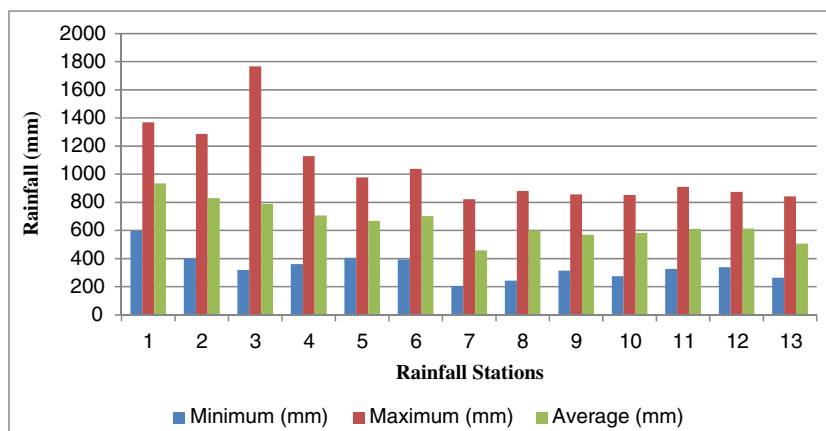


Fig. 1 Study basin

used to examine the variability of precipitation in time and space (Gocic and Trajkovic 2013; Jemai et al. 2016). Other indices used to identify drought and to show temporal fluctuations of precipitation are available in the literature. These

include Mean Deviation Index, Rainfall Index, and Relative to Normal Precipitation (Khaladi 2005) among others. Other methods such as the Palmer Drought Severity Index, Quintiles and Tertiary Rainfall Index have also been used to study the

Fig. 2 Minimum, maximum, and average rainfall variability



frequency of drought periods and their severity (Khaladi 2005).

The variance and variability of precipitation were amply analyzed in the literature using quantum perturbation method (QPM) (Willems 2013), Non-parametric Anomaly Inlay Method (NAIM) (Onyutha 2016a, b), autocorrelation spectral analysis (ASA (Blackman and Turkey 1958), and many other methods. However, statistical methods have several limitations due to the complexity of the precipitation variability, taking into account their non-linearity and non-stationarity. The method of wavelet transforms was introduced as an alternative due to its capacity to capture temporal variability at multiple scales. This robust mathematical device, which yields a timescale signal representation, is primarily useful in the study of non-stationary associations using time series data. Wavelet transform provides the decomposition of precipitation time series inside time–frequency spaces by identifying the principal variability modes and their temporal distribution into spectra (Jemai et al. 2017).

Two methods were used to examine both spatial and temporal variability of precipitation in the Bizerte-Ichkeul Watershed. In the first, the dimensionless standardized precipitation ratio is applied in order to examine the temporal variation of precipitation. The second method is represented by continuous wavelet analysis to examine the structure of the variability. Obtained data were processed via the R Software (R Development Core Team 2011) and Sowas Package in order to perform continuous wavelet transform and wavelet coherence analysis (Massei et al. 2009; Maraun and Kurths 2004, 2007). Spatial variation was also examined by comparing the results obtained for the different stations.

Standardized precipitation ratio

The dimensionless standardized precipitation ratio was computed in order to standardize the series of precipitation, making it possible to compare different data series. This method results in characterizing the evolution of annual rainfall

Table 1 Statistical characteristics of the annual rainfall data series

Station number	Latitude	Longitude	Altitude (m)	Standard deviation (mm)	Median (mm)	(Cv)	(Cs)	(Ck)
1	37.07	9.24	145	194.4	953.65	0.21	0.09	2.23
2	37.06	9.25	135	214.7	809.45	0.26	0.03	2.28
3	36.93	9.39	109	309.2	687.25	0.39	1.39	4.58
4	36.96	9.48	109	174.3	717.65	0.25	0.22	2.25
5	37.11	9.54	28	154.2	670.35	0.25	0.21	2.17
6	37.07	9.55	75	177.2	702.85	0.25	0.13	2.00
7	36.91	9.73	70	140.1	440.25	0.31	0.22	2.51
8	37.17	9.76	8	146.8	587.95	0.25	0.08	2.65
9	37.27	9.85	50	154.7	578.75	0.27	0.13	1.77
10	37.21	9.99	55	155.0	576.60	0.27	0.07	2.08
11	37.13	10.01	80	153.1	603.25	0.25	0.22	2.1
12	37.23	10.09	20	141.0	587.65	0.23	0.21	1.93
13	37.17	10.04	120	143.0	514.6	0.28	0.23	2.41

CV coefficient of variation, *CS* coefficient of skewness, *Ck* coefficient of kurtosis

compared to the average of the period considered, identifying thereby the periods of deficit and excess of rainfall. An inter-annual rainfall index, defined as a dimensionless standardized precipitation ratio, was determined for each station (Servat et al. 1998). This method was widely used in Africa (Kingumbi et al. 2000; Zamrane et al. 2016; Nouaceuret al. 2013a; Ellouze et al. 2009; Ellouze 2010).

The dimensionless standardized precipitation ratio (rainfall index) is the ratio of the deviation from the inter-annual mean to the standard deviation of annual rainfall (Eq. (1)).

It is described as follows

$$I_p = (P_i - P) / \sigma \quad (1)$$

Where

- P_i Rainfall for a given study year;
- P Average rainfall during a given study period;
- σ Standard deviation of rainfall for the same period.

The index is positive for wet years and negative for dry years (Lubès et al., 1994, b). Examining the different graphs representing the variation of this index allowed the identification of regions with similar temporal characteristics. The results obtained were then analyzed by the continuous wavelet method to identify the origin of temporal variation.

Continuous wavelet analysis

The wavelet spectra allow the observation of the data structure as a function of time. The parameterization in scales and the translation of the daughter wavelets make it possible to detect the different frequencies composing the signal. Moreover, these frequency components can be detected and studied over time, allowing a better description of non-stationary processes (Schneider and Farge 2006; Torrence and Compo 1998). Labat (2008) showed that wavelet analysis is an alternative method to classical correlative and spectral analyses and is more informative. According to Torrence and Compo (1998), Perrier et al. (2007), and Mesquita (2009), the wavelet is a function containing a temporal parameter and a shape parameter. The first allows to stretch the wavelet for the analysis of the desired frequencies while the second allows to translate the wavelet on the times axis to analyze this frequency close to a given moment of the signal. The reference wavelet is called mother wavelet, and the modification of its parameters is used to produce daughter wavelets. The wavelet transform is thus made by decomposing the signal into defined signals over a certain period of time (or space), which makes it possible to analyze the variations of the frequency content over time. Furthermore, the wavelet spectrum of the signal

makes it possible to visualize the presence of frequencies temporally localized.

Compared to other methods, wavelet analysis has often been used for hydrological variability of major world rivers (Gauchere 2002; Labat 2005). In particular, applications of wavelets to discharge time series allow describing signals of climatic oscillation (Massei et al. 2009, 2011; Labat et al. 2000; Lafrenieresa and Sharp 2003). The continuous wavelet method (WCT) is used to analyze and quantify each temporal feature of the main spectral components in the time series. The wavelet transformation is used to follow the time course of the process at different scales in the signal (Daubechies 1990; Zamrane et al. 2016). Turki et al. (2016) showed that continuous wavelet method was not amply used to study hydrological variability in North Africa. The continuous wavelet analysis was used in Algeria (Turki et al. 2016) and Morocco (Zamrane et al. 2016).

In this study, Continuous Wavelet Transformation (CWT) was used in order to obtain reasonably accurate results for low and high frequencies. Three types of mother wavelets are available in the literature, namely Morlet, Gaussian, and Paul wavelets. However, the Morlet mother wavelet was adopted in this study as it was shown to be more appropriate for the study of rainfall variability (Torrence and Compo 1998; Perrier et al. 2007 among others). The Morlet wavelet consists of a Gaussian-modulated sine, characterized by a high-frequency resolution. The wave number of the mother wavelet controls its basic frequency resolution: the higher the wave number, the more rapid the oscillation of the wavelet, and the higher the frequency resolution. The wave number used here was six for all spectra. In particular, applications of wavelets to discharge time series allow the description of signals of climatic oscillation (Massei et al. 2009, 2011; Labat et al. 2000; Lafrenieresa and Sharp 2003).

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The mother wavelet includes two parameters: scaling “a” and temporal location “b” (Eq. (2)):

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \quad (2)$$

$\psi_{a,b}(t)$ Wavelet daughter;
 a Scale parameter;
 b Time-localization parameter.

The continuous wavelet transforms the signal $S(t)$ to generate a wavelet spectrum. It is expressed as follows (Eq. (3)):

$$S_{(a,b)} = \int_{-\infty}^{+\infty} S(t) \times \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \times dt \quad (3)$$

Wavelet transform can play an important role in analyzing precipitation data, since its local analysis and multiresolution decomposition make the analysis process more efficient and accurate (Kuo and Sheng 2010; Jun et al. 2016). Continuous wavelet analysis, described in details by Schneider and Farge (2006), is used to evaluate and characterize the evolution of the short and long-term variability of the precipitation data series in the Bizerte-Ichkeul Basin. They may also detect possible temporal ruptures in the structuring of this variability. Temporal variability can be expressed as “energy spikes” or “energy bands,” covering certain timescales. The local wavelet spectrum allows description and visualization of the power distribution (z -axis), from low power (dark blue) values to high power (red) values, depending on the different frequencies (y -axis) during time (x -axis). In all continuous wavelet spectra, the color scale used represents increasing power (variance) from blue to dark red. The continuous wavelet spectrum of the time series highlights the existence of several modes of variability in the form of energy bands covering certain ranges of frequencies.

Continuous wavelet analyses were used to identify the main modes of precipitation variability in Bizerte-Ichkeul Watershed. They may also detect possible temporal ruptures in the structuring of this variability. The questions that arise are for what characteristic timescales do rainfall evolve? Is the structure of the variability the same or does it evolve over time and on a spatial scale?

Results and discussion

Descriptive statistical analysis

A preliminary statistical analysis of annual rainfall data over the period 1970–2011 was established for the 13 rainfall stations spread all over the study basin. In the study area, the average annual rainfall is around 637 mm. Figure 2 shows a large variation of rainfall throughout the study area from northwest to southeast. The study area is characterized by rainfall ranging from 935 mm in the extreme northwest of the basin (station no. 1) to less than 460 mm in the south (station no. 7) (Figs. 1 and 2). Standard deviations of annual rainfall indicate a high inter-annual variability in the Bizerte-Ichkeul catchment.

The standard deviations are greater than 141 mm per year and sometimes reach more than 300 mm per year. Statistics of annual rainfall data, such as the coefficient of variation (CV), coefficient of skewness (CS), and coefficient of kurtosis (Ck) are presented in Table 1. The mean values of CV, CS, and Ck for the study region are 0.27, 0.21, and 2.38, respectively. The maximum value for the different statistical parameters CV, CS, and Ck were obtained for station no. 3 (mountainous region). CV values are generally higher than 25%, except for stations 12 and 1, which are located in the northeast and the southwest regions, respectively. The CV is considered to follow the evolution of the rainfall from 1 year to the next. The obtained CV values do not show a large variation. They vary from 0.21 (station no. 1) to 0.39 (station no. 3), implying a slight decrease in the west-east direction.

The values of (CS) for all time series are positive. They are close to zero for most stations, which implies a symmetrical distribution of rainfall data. The values of (Ck) for most stations varied between 1.7 and 2.65. The exception is made for station 3 with a (Ck) value close to five, indicating that low rainfall is more frequent than high rainfall values (Amrutha and Shreedhar 2014). In general, CV slightly decreases, CS remains constant, and Ck slightly increases with an increase in annual rainfall (Modarres and Rodrigues da Silva 2007).

A mixture of increasing and decreasing trends of rainfall is noted (Fig. 2). This result suggests that the rainfall trends may be attributed to local changes in the rainfall regime rather than the large-scale patterns of atmospheric circulation. Indeed, according to Jemai et al. (2013), rainfall variability in the Bizerte-Ichkeul Basin is governed by the effect of topography in the northwestern regions while for the southeastern regions, other factors such as latitude, longitude, proximity to the sea, and direction of wind speed affect rainfall characteristics and are the principal sources of variation.

Inter-annual rainfall of the Bizerte-Ichkeul basin

The comparative analysis of the evolution of the dimensionless standardized precipitation ratio applied to the annual rainfall data over the period 1970–2011 was established for the 13 rainfall stations belonging to the study basin. The temporal evolution of precipitation is based on the trend of the curves representing the distribution of the dimensionless standardized precipitation ratio. Three periods were distinguished according to the trend of the curves of variation of the dimensionless standardized precipitation ratio (Fig. 3).

- The first, from 1970 to 1976, is considered normal to wet. There is a deficit with negative rainfall indices (from 0 to –1.01).

- A long dry period of 26 years begins in 1977 and ends in 2001. This period is interspersed with short wet periods (1990–1992, 1996–1997). A significant drop in wet and very humid years occurs at all stations. This interval is marked by a greater severity of drought. The years 1982, 1987, 1988, 1993, 1994, 2000, and 2001 have a very high percentage of stations characterized by dry to very dry conditions. A deficit condition was observed for standardized precipitation ratio varying between 0 and -2.45 .
- The last period, from 2002 to 2011, is characterized by an increase of humid and very humid years and normal years; only the year 2008 recorded a negative rainfall index.

The results obtained showed similar statistical characteristics for the different rainfall stations, with a mild rainfall gradient increasing from east to west. For the southeastern regions, other factors such as latitude, longitude, proximity to the sea, and direction of wind affect rainfall characteristics and are the principal sources of variation (Jemai et al. 2013). For convenience, only the results of four reference stations were selected in this study with a homogeneous distribution within the study area, namely stations 2, 7, 8, and 12, located in the west, south, north, and east, respectively (Fig. 3).

These results are in agreement with those found in shorter series by Laborde (1993) which shows that the decline in rainfall in northern Algeria was observed after the 1970s in a significant way. Mahe et al. (2011) identified a rupture in annual rainfall in Morocco between 1979 and 1988. The findings of Kingumbi et al. (2000), who examined rainfall series of Central Tunisia using the standardized precipitation ratio, confirm the results obtained (decrease in annual totals between 1977 and 1989). Nouaceur et al. (2014) and Laignel et al. (2014) showed that drought affected the Moroccan and Tunisian regions over a long period compared to the Algerian Region, where droughts were identified in the period (1988–2002). These results are also in agreement with the conclusions of the regional report of the United Nations on climate change in North Africa and the findings of the Intergovernmental Panel on Climate Change of 2001 and

2007 (IPCC 2007). These periods can be used as reference periods to represent drought in the study area. The results obtained were then analyzed by the continuous wavelet method to identify the origin of temporal variations.

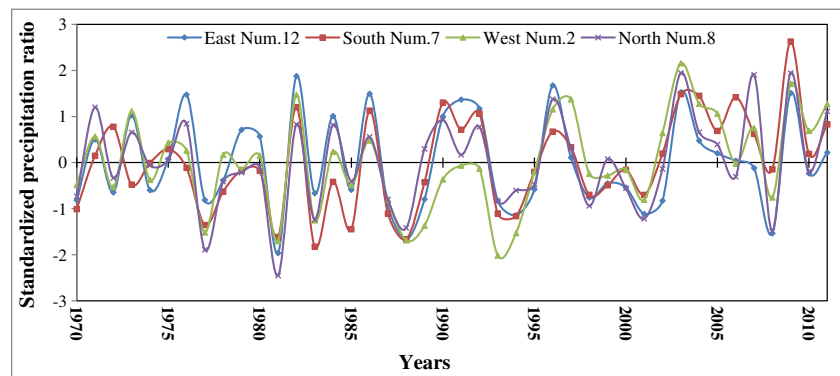
Spatial characterization of precipitation

Continuous wavelet analysis is used to evaluate and characterize the evolution of the short and long-term variability of the precipitation data series in Bizerte-Ichkeul Basin. Temporal variability can be expressed as energy spikes or energy bands, covering certain timescales. The local wavelet spectrum allows description and visualization of the power distribution (z -axis), from low power (dark blue) values to high power (red) values, depending on the different frequencies (y -axis) during time (x -axis) (Fig. 4).

The spectra of precipitation wavelet analyses applied to the monthly rainfall data series over the period 1970–2011 were analyzed. The results obtained made it possible to identify three energy bands (1 (year), 2–4 (years), and 4–8 (years)) for the entire watershed. In addition, Fig. 3 shows several modes of frequency variability based on the shape of the energy bands. From an annual cycle perspective, the global spectral energy is not constant over time and varies according to three main periods for the 13 stations studied (1970–1977, 1978–2001: 2002–2011). These periods have already been detected by the temporal analysis of precipitation by means of the dimensionless standardized precipitation ratio.

For the 1-year mode, the alternating high- and low-energy bands reflect the succession of wet and dry years. The power of this energy showed differences between all records of the Bizerte-Ichkeul Basin, explained by the local conditions related to the geographic characteristics. Based on high-power spectral energy, five sub-periods were identified: The first begins in 1970 and ends in 1973, showing only the mode of 1 (year). The second spreads over the period between 1974 and 1987, where modes 1 (year) and 2–4 (years) were detected. The third phase begins in 1988 and ends in 1993, when modes 1 (years) and 4–8 (years) were detected. The fourth (from 1995 to 2001) shows only the mode of 1 (year) while the fifth

Fig. 3 Variation of the standardized precipitation ratio for the considered stations



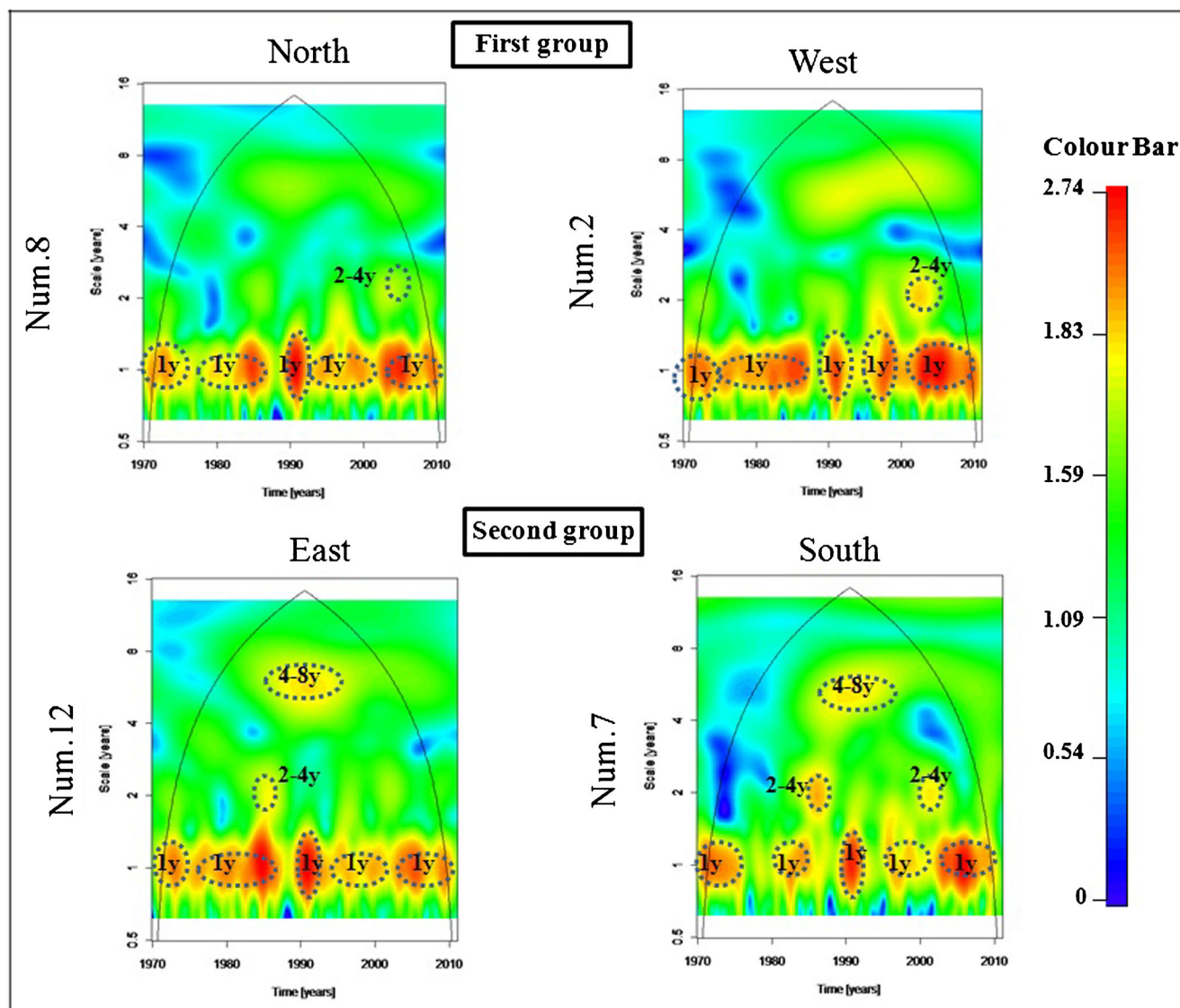


Fig. 4 Local spectra of wavelet analysis of monthly precipitation of the Bizerte-Ichkeul watershed

(2002–2011) presents modes 1 (year) and 2–4 (years). These periods are defined by four main discontinuities corresponding to the mid-1970s, late 1980s, mid-1990s, and early 2000s (Fig. 4, Table 2). The second and third interruption periods may be related to the drought periods that occurred in Tunisia between 1980 and 2001. These results are in agreement with those found by Kutiel et al. (1996), showing that the late 1980s and the early 2000s witnessed intense drought in a wider part of the Mediterranean Region. Jemai et al. (2016) found that severe drought periods were registered at the end of 1980 and 2000 in Southern Tunisia (Gabes Basin). Moreover, Ellouze (2010) showed that dry conditions became more repetitive and frequent since the second half of the twentieth century (from 1935 to 2001) in central and southern Tunisia.

The visualization of the power distribution shows that the observed modes of variability are different in their power

distributions from one station to another. The annual cycle mode (1 year) of rainfall variability was observed in the majority of the rainfall stations, where the hydrological cycle presents an alternation of seasonal variation in precipitation (Fig. 4). The annual variation of high frequency is identified during this period. Southern stations also presented important annual frequencies but less pronounced than those observed in the NW and the NE. It is also important to note that rainfall variability may be related to a change in the probability law of the time series at a given time, which is most often unknown (Lubès et al. 1998). The annual cycle mode (1 year) of rainfall variability was observed in all rainfall stations for the identified periods while inter-annual scale fluctuations of 2–4 (years) and 4–8 (years) seem to be more specific to certain stations. The mode (2–4 years) was observed during the periods (1980–1987, 2002–2011). Concerning the second

Table 2 The time variation of the rainfall variability modes, extracted from the continuous wavelet analysis

Station number	1 year	2–4 years	4–8 years
1	1970–1973	2002–2004	–
	1980–1987		
	1990–1993		
	1995–2001		
2	1970–1973	–	–
	1980–1987		
	1990–1993		
	1995–2001		
3	1970–1973	2001–2003	–
	1980–1987		
	1990–1993	2008–2001	
	1995–2001		
4	1970–1973	2002–2004	–
	1980–1987		
	1990–1993		
	1995–2001		
5	1970–1973	–	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		
6	1970–1973	–	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		
7	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993	2002–2004	
	1995–2001		
8	1970–1973	2002–2004	–
	1980–1987		
	1990–1993		
	1995–2001		
9	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993	2002–2004	
	1995–2001		
10	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		
11	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		
12	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		
13	1970–1973	1983–1987	1986–1995
	1980–1987		
	1990–1993		
	1995–2001		

period, the frequency band 2–4 years is observed more precisely from 1983 to 1987. During the fifth period the 2–4 years mode is observed in two different sequences of 2002–2004 and 2008–2011. The mode of 4–8 years is observed in most stations during the third period (1990–1993) (Table 2).

The modes of cycles 2–4 and 4–8 years reflect the influence of global climate represented by indices such as ENSO (El Niño/Southern Oscillation), PDO (Pacific Decadal Oscillation), or NAO (North Atlantic Oscillation). These two modes are observed in most stations during the second interval detected by the annual cycle (1977–2001). The results obtained by the dimensionless standardized precipitation ratio shows that this interval is characterized by a long period of drought, interspersed with short wet periods. These results are in agreement with those found in the flow series in the Mississippi River basin (USA) by Massei et al. (2011), which showed that the dominant modes of current flow variability during the inter-annual periods in the 2–4, 4–8, and 10–16 age brackets are related to climatic fluctuations in the Southern Oscillation (SOI). Laignel et al. (2010) showed that high modes of variability are correlated with the NAO in the Northwest region of France and North Africa and with the SOI in the USA. The results obtained by the continuous wavelet analysis of the precipitation regime show that the variability modes observed are different from one station to another by their power distribution. For convenience, only the results of four reference stations studied in the first part are presented in this section.

The structure of the variability of continuous wavelet precipitation spectra varies from one station to another. Indeed, the approach adopted allowed the identification of two families or groups with the same characteristics of temporal and frequency variation of precipitation. These two groups were defined according to the difference in appearance of the frequency band at each station (Fig. 1).

The first group is composed of five rainfall stations (1, 2, 3, 4, and 8) (Fig. 1), located in the mountain chain beside the sea which stretches to the extreme north of the study area, preventing the spread of the disturbances of the northwest and the north. This group is characterized by the existence of frequency bands of 1 year and few bands of 2–4 years. This annual periodicity was already confirmed by the results obtained in the temporal analysis of precipitation by means of the dimensionless standardized precipitation ratio. Unlike stations 1, 2, 3, and 4, which are all located in the western mountainous region, station 8 is rather located in the eastern plane of the watershed. The specificity of this particular series is rather its particular geographical position, as it is located between Ichkeul Lake and Bizerte lagoon, which affected its spatial and temporal rainfall variability. This clearly shows that rainfall may be affected by local conditions, such as the proximity to the sea or the presence of relief.

The second group is represented by eight stations (5, 6, 7, 9, 10, 11, 12, and 13) (Fig. 1), located in the extreme south-east, where the disturbances of the Mediterranean air masses represent the main source of rainfall which is moderated by both topography and the proximity of the sea and Bizerte Lagoon. This group presents several annual and inter-annual

frequency bands (2–4 and 4–8 years), implying the influences of large-scale climatic factors on rainfall variance.

The representation of station groups with similar characteristics shows that the spatial variability may be explained by local climatic factors, such as disturbances of the Mediterranean winds, topography, proximity to the sea, Lake Bizerte, depressions, and the effect of the sea. These results are in agreement with those found by Jemai et al. (2016) in the Gabes Basin (Southern Tunisia), indicating that drought severity was important in western and Northern Tunisia, while the east (along the coast) and the southern regions were characterized by mild droughts. They proved that rainfall variability was governed by the effects of altitude and the Mediterranean Sea in Southern Tunisia (Gabes Basin). Merzougui and Slimani (2012) showed that the monthly isohyets maps throughout the Tunisian territory present a rainfall gradient, varying with time and space. According to Benzarti and Habaieb (2001) rainfall varied with the effect of altitude, proximity to the sea (longitude and latitude), continental effects, and regional and local climate factors, from the north to the south of Tunisia. Nevertheless, it is important to examine the potential relationships between climate change and hydrological systems and their impacts on water resources.

Conclusions

Temporal analysis of the evolution of precipitation by means of a dimensionless standardized precipitation ratio applied to the annual rainfall series over the period 1970–2011 for 13 rainfall stations belonging to the Bizerte-Ichkeul Basin resulted in the identification of three different periods: (1970–1976), (1977–2001), and (2002–2011). The period (1970–1976) is considered normal to wet. There is a deficit with negative rainfall indices (from 0 to -1.01). The period (1977–2001) is characterized by alternating dry and normal years. The years (1987, 1988, 1993, 1994, 1996, 1999, and 2001) are dry years marked by severe. However, the interval (2002–2011) is characterized by an increase in wet or very humid years and normal years.

A continuous wavelet analysis resulted in detecting the modes and origins of precipitation variability. Three energy bands were clearly identified: (1 year), 2–4 (years), and 4–8 (years) for the entire watershed. Moreover, the visualization of the power distribution showed that the modes of variability observed are different in their power distributions from one station to another. Indeed, the approach adopted allowed the identification of two groups with the same characteristics of temporal and frequency variations of precipitation. These two groups were defined according to the difference in occurrence of the frequency band for each station.

The first group, which includes five stations, is characterized by the existence of 1-year frequency bands and few 2- to

4-year bands. The second group, formed by eight stations, presents several bands of annual and inter-annual frequencies (2–4 and 4–8 years). The modes of cycles 2–4 and 4–8 years are two modes that reflect the influence of global climate.

In order to determine and quantify the origin of the differences between the observed modes of precipitation in the Bizerte-Ichkeul Watershed, a verification of the relationship between the spatial and temporal variation of precipitation and the climate change models is recommended.

Acknowledgements Bizerte-Ichkeul Basin data used in this study were provided by the General Directorate of Water Resources (DGRE) in Tunisia. The authors also would like to thank the editors and the anonymous reviewers for their constructive comments, which improved the quality of this paper.

References

- Albert DG, Shortle JS (2000) Climate change and agriculture in the Mid-Atlantic Region. *Clim Res* 14:185–194. <https://doi.org/10.3354/cr014185>
- Amrutha R, Shreedhar R (2014) Study of rainfall trends and variability for Belgium. *Int J Res Eng Technol* 3:148–155 <http://esatjournals.net/ijret/2014v03/i18/IJRET20140318024.pdf>
- Bejaoui B, Ben charrad R, Moussa M, Ben hamadou R, Harzalla A, Chapelle A (2005) Caractérisation hivernale de la lagune de Bizerte. *Bulletin de l'Institut National des Sciences et Technologies de la Mer de Salammbô* 32:79–71. <https://www.oceandocs.org/bitstream/handle/1834/3748/article%2011.pdf?sequence=1&isAllowed=y>
- Benzarti Z, Habaieb H (2001) Etude de la persistance de la sécheresse en Tunisie par utilisation des chaînes de Markov (1909–1996). *Sécheresse* 12(4):215–220. http://www.jle.com/fr/revues/sec/edocs/etude_de_la_persistance_de_la_secheresse_en_tunisie_par_utilisation_des_chaines_de_markov_1909_1996_230048/article.phtml?tab=texte
- Blackman RB, Tukey JW (1958) The measurement of power spectra from the point of view of communications engineering. *Bell Labs Tech J* 37:185–282. <https://doi.org/10.1002/j.1538-7305.1958.tb03874.x>
- Brahim M, Bejaoui B, Atoui A (2008) Etude de l'hydrodynamique sédimentaire de la lagune de Bizerte. *Bulletin de l'Institut National des Sciences et Technologies de la Mer de Salammbô* 35:149–160. <https://www.oceandocs.org/bitstream/handle/1834/4160/16.pdf?sequence=1>
- Bouzouita Z. (2003) Les échanges Lac Ichkeul-Lac de Bizerte” Mémoire de DEA-MHE, Ecole Nationale d'ingénieurs de Tunis. (95 pages)
- Daubechies I (1990) The wavelet transform time-frequency localization and signal analysis. *IEEE Trans Inf Theory* 36:961–1005. <https://doi.org/10.1109/18.57199>
- Djellouli Y, Daget P (1993) Conséquences de la sécheresse des deux dernières décennies sur les écosystèmes naturels algériens. *Publ Assoc Int Climatol* 6:105–114
- Driouech F, Déqué M, Gómez E (2010) Weather regimes—Moroccan precipitation link in a regional climate change simulation. *Glob Planet Change* 72:1–10. <https://doi.org/10.1016/j.gloplacha.2010.03.004>
- Easterling D, Evans J, Groisman P, Karl T, Kunkel K, Ambenje P (2000) Observed variability and trends in extreme climate events: a brief review. *Bull Am Meteorol Soc* 81(3):417–425. <https://doi.org/10.1175/1520-0477>

- Ellouze M, Azri C, Abida H (2009) Spatial variability of monthly and annual rainfall data over Southern Tunisia. *Atmos Res* 93:832–839. <https://doi.org/10.1016/j.atmosres.2009.04.005>
- Ellouze M (2010) Development of a triangular model for the generation of synthetic hyetographs and spatio-temporal characterization of drought in central and southern Tunisia. PhD Thesis, Faculty of Sciences of Sfax, Tunisia, pp 182
- Fekai M, Douguedroit A, Dobreuil V (2007) Réponse de la végétation de Kroumirie et des Mouds à la variation saisonnière et interannuelle du climat. Apport de la Teledetection et des SIG
- Gauchere C (2002) Use of wavelet transform for temporal characterisation of remote watersheds. *J Hydrol* 269:101–121. [https://doi.org/10.1016/S0022-1694\(02\)00212-3](https://doi.org/10.1016/S0022-1694(02)00212-3)
- Gocic M, Trajkovic S (2013) Analysis of precipitation and drought data in Serbia over the period 1980–2010. *J Hydrol* 494:32–42. <https://doi.org/10.1016/j.jhydrol.2013.04.044>
- Hammer DA (1999) *Creating freshwater wetlands*, 2nd edn. CRC Lewis Publishers, Boca Raton, FL, p 406
- Hénia L (2001) Les grandes sécheresses en Tunisie au cours de la dernière période séculaire. *Eau Environnement et milieux méditerranéens*. ENS éditions. 25–36.
- IPCC (2007) *Climate change 2007: impacts, adaptation and vulnerability*. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ and Hanson CE (eds). Cambridge University Press, Cambridge, p 976
- Jemai H, Ellouze M, Abida H (2013) Caractérisation annuelle de la sécheresse dans le bassin de Bizerte- Ichkeul (Tunisie), Séminaire International: La Gestion Durable des Ressources en Eaux et en Sols: Situation, Défis et Perspectives. (Hammamet, 19–20 novembre 2013 PHCMaghreb2013). Page 135
- Jemai S, Ellouze M, Agoubi B, Abida H (2016) Drought intensity and spatial variability in Gabes Watershed, south-eastern Tunisia. *J Water Land Dev* 31:63–72. <https://doi.org/10.1515/jwld-2016-0037>
- Jemai S, Ellouze M, Abida H (2017) Variability of precipitation in arid climates using the wavelet approach: case study of the watershed of Gabes in South-Eastern Tunisia. *Atmosphere* 8:178. <https://doi.org/10.3390/atmos8090178>
- Jun S, Jun W, Sunyun L, Jianping B (2016) Spatial and temporal variability of seasonal precipitation in Poyang Lake basin and possible links with climate indices. *Hydrol Res* 47(S1):51–68. <http://hr.iwaponline.com/content/ppiwahydrores/47/S1/51.full.pdf>
- Khaladi A (2005) Impacts de la sécheresse sur le régime des écoulements souterrains dans les massifs calcaires de l'Ouest Algérien "Monts de Tlemcen—Saida", THESE Présentée à la faculté des Sciences de la terre, de Géographie et l'Aménagement du Territoire, UNIVERSITE D'ORAN, p 239
- Khoms K, Mahe G, Sinan M, Snoussi M (2013) Hydro-climatic variability in two Moroccan basins: a comparative analysis of temperature, rainfall and runoff regimes. In: *Climate and land surface changes in hydrology* (Proceedings of IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013). IAHS Publ. 362. IAHS Press, Wallingford
- Khoualdia W, Djebbar Y, Hammar Y (2014) Caractérisation de la variabilité climatique: cas du bassin versant de La Medjerda (Nord-Est algérien). *Rev Sci Tech* 29:6–23
- Kingumbi A, Bergaoui Z, Bourges J, Hubert P, Kallel R, (2000) Etude de l'évolution des séries pluviométriques de la Tunisie centrale. In: Servat Eric, Albergel Jean (eds), *Hydrologie des régions méditerranéennes*, Montpellier (FRA); Montpellier: UNESCO; IRD, 2001, (51), p. 341–350, (Documents Techniques en Hydrologie; 51), *Hydrologie des Régions Méditerranéennes: Séminaire International*, Montpellier (FRA), 2000/10/11–13. <http://medhycos.mpl.ird.fr/doc/kin.pdf>
- Kutieli H, Maheras P, Guika S (1996) Circulation and extreme rainfall conditions in the eastern Mediterranean during the last century. *Int J Climatol* 16:73–92. [https://doi.org/10.1002/\(SICI\)1097-0088\(199601\)16:1<73::AID-JOC997>3.0.CO;2-G](https://doi.org/10.1002/(SICI)1097-0088(199601)16:1<73::AID-JOC997>3.0.CO;2-G)
- Kuo CH, Sheng TL (2010) Clustering spatial-temporal precipitation data using wavelet transform and self-organizing map neural network. *Adv Water Res* 33(2):190–200. <https://doi.org/10.1016/j.advwatres.2009.11.005>
- Labat D, Ababou R, Mangin A (2000) Rainfall-runoff relations for karstic springs—Part II: continuous wavelet and discrete orthogonal multiresolution analyses. *J Hydrol* 238:149–178. [https://doi.org/10.1016/S0022-1694\(00\)00322-X](https://doi.org/10.1016/S0022-1694(00)00322-X)
- Labat D (2005) Recent advances in wavelet analyses: part 1. A review of concepts. *J Hydrol* 314:275–288. <https://doi.org/10.1016/j.jhydrol.2005.04.003>
- Labat D (2008) Wavelet analysis of the annual discharge records of the world's largest rivers. *Adv Water Resour* 31(1):109–117. <https://doi.org/10.1016/j.advwatres.2007.07.004>
- Laborde J (1993) Carte pluviométrique de l'Algérie du Nord à l'échelle de 1/500000, Agence Nationale des Ressources Hydrauliques, projet PNUD/ALG/88/021, une carte avec notice explicative, p 44
- Lafrenieres M, Sharp M (2003) Wavelet analysis of inter-annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta. *Hydrol Process* 17:1093–1118. <https://doi.org/10.1002/hyp.1187>
- Laingel B, Nouaceur Z, Jemai H, Abida H, Ellouze M, Turki I (2014) Vers un retour des pluies dans le Nord-Est Tunisien? In Proceedings of the Actes du XXVIIe Colloque de l'Association Internationale de Climatologie-2 au 5 Juillet 2014, pp. 727–732, Dijon, France, 2014
- Lubès H, Masson JM, Servat E, Paturel JE, Kouame B, Boyer JF (1994) Caractérisation de Fluctuations dans une Série Chronologique par Applications de Tests Statistiques-Etude Bibliographique Etude bibliographique. Programme ICCARE. Rapport n°3. ICCARE. ORSTOM, Montpellier, France
- Lubès-Niel H, Masson JM, Paturel JE, Servat E (1998) « Variabilité climatique et statistiques. Etude par simulation de la puissance et de la robustesse de quelques tests utilisés pour vérifier l'homogénéité de chroniques ». *Rev Sciences Eau* 3:383–408. <https://doi.org/10.7202/705313ar>
- Mahe G, Singla S, Driouech F, Khoms F (2011) Analyse de la persistance de ruptures dans des séries pluviométriques au Maroc en fonction de l'échelle spatiale et de la reconstitution des données. In Proceedings of the Conférence CIREDD4, Blida, Algeria, 22–23
- Maraun D, Kurths J (2004) Cross wavelet analysis: significance testing and pitfalls. *Nonlinear Process Geophys Eur Geosci Union (EGU)* 11:505–514. <https://hal.archives-ouvertes.fr/hal-00302384/document>
- Maraun D, Kurths J, Holschneider M (2007) Nonstationary Gaussian processes in wavelet domain: synthesis, estimation and significance testing. *Phys Rev E* 75:016707(1)–016707(14). <https://doi.org/10.1103/PhysRevE.75.016707>
- Massei N, Laingel B, Deloffre J, Mesquita J, Motelay A, Lafite R, Durand A (2009) Long-term hydrological changes of the Seine River flow (France) and their relation to the North Atlantic Oscillation over the period 1950–2008. *Int J Climatol* 30: 2146–2154. DOI: <https://doi.org/10.1002/joc.2022>
- Massei N, Laingel B, Rosero E, Motelay-Massei A, Deloffre J, Yang ZL, Rossi A (2011) A wavelet approach to the short-term to pluridecadal variability of streamflow in the Mississippi river basin from 1934 to 1998. *Int J Climatol* 31:31–43. <https://doi.org/10.1002/joc.1995>
- Mathlouthi M, Lebdi F (2008) Event in the case of a single reservoir: the Ghèzala dam in Northern Tunisia. *Stoch Environ Res Risk* A 22: 513–528. <https://doi.org/10.1007/s00477-007-0169-3>
- Mathlouthi M, Lebdi F (2010) Modélisation de la relation pluie-ruissellement par durée d'épisode pluvieux dans un bassin du nord de la Tunisie. *Hydrol Sci J* 55:1111–1122. <https://doi.org/10.1080/02626667.2010.512471>

- Mathlouthi M, Ghali A, Lebdi F (2011) Impact des pluies extrêmes sur la genèse et l'amplification des glissements de terrain dans le Nord de la Tunisie. *Rev Sci Tech LJEJ* 19:79–89. http://www.ensh.dz/files/ljee/19/Article_Mathlouthi.pdf
- Mesquita (2009) Facteurs de contrôle climatique et géomorphologique de la variabilité hydrologique de bassins versants en substrat carbonaté: Comparaison Haute Normandie (FR) et Région d'Austin, Texas (USA) Thèse à l'UMR CNRS 6143 « M2C » Morphodynamique continentale et Cotière
- Merzougui A, Slimani M (2012) Régionalisation des lois de distribution des pluies mensuelles en Tunisie. *Hydrol Sci J* 57:668–685. <https://doi.org/10.1080/02626667.2012.670702>
- Modarres R, Rodrigues da Silva VP (2007) Rainfall trends in arid and semi-arid regions of Iran. *J Arid Environ* 70:344–355. <https://doi.org/10.1016/j.jaridenv.2006.12.024>
- Najjar R, Walker H, Anderson P, Barron E, Bord R, Gibon J, Kennedy V, Knight C, Megonigal J, Rober E, Connor O, Polsky C, Psut N, Richards B, Sorenson L, Steele E, Swanson R (2000) The potential impacts of climate change on the mid-Atlantic coastal region. *Clim Res* 14:219–233. <https://doi.org/10.3354/cr014219>
- New M, Todd M, Hulme M, Jones P (2001) Precipitation measurements and trends in the twentieth century. *Int J Climatol* 21:1899–1922. <https://doi.org/10.1002/joc.680>
- Nicholls R, Klein R, (2005) Climate change and coastal management on Europe's coast. *Managing European Coasts Environmental Science*, pages 199–226. http://link.springer.com/chapter/10.1007/3-540-27150-3_11#page-1
- Nouaceur Z (2011) Vers un retour des pluies sur la rive sud du bassin méditerranéen occidental: analyse et évaluation de la tendance pluviométrique sur plus d'un demi-siècle en Algérie, *The Annals of Valahia University of Târgoviște, Geographical Series, Tome 11 / 2011*. <https://fsu.valahia.ro/images/avutgs/1/2011/2011111204.pdf>
- Nouaceur Z, Laingel B, Turki I (2013a) Changements climatiques au Maghreb: vers des conditions plus humides et plus chaudes sur le littoral algérien? *Géogr Phys Environ* 7:307–323
- Nouaceur Z, Laingel B, Jemai H (2013b) Climate change and rainfall trend: towards the end of the drought in central Maghreb 2013 *Actes colloque de Fes Maroc changement climatique et tendance pluviométrique*, 27–28 November 2013. http://aerapa.conference.ubbcluj.ro/2014/PDF/07-Nouaceur_at_all.pdf
- Nouaceur Z, Laingel B, Turki, Jemai H (2014) Climate in Northern Africa: towards a return of rain on the Southern Mediterranean Basin. *Conference proceeding Air and Water components of the environment, CLUJ Napoca 21–22 Mars pp 48–55 2014*. http://aerapa.conference.ubbcluj.ro/2014/PDF/07-Nouaceur_at_all.pdf
- Onyutha C (2016a) Variability of seasonal and annual rainfall in the River Nile riparian countries and possible linkages to the ocean-atmosphere interactions. *Hydrol Res* 47(1):171–184. <https://doi.org/10.2166/nh.2015.164>
- Onyutha C (2016b) Statistical uncertainty in hydro-meteorological trend analyses. *Adv Meteorol* 2016:1–26. <https://doi.org/10.1155/2016/8701617>
- Perrier V, Bilgot A, Le Cadet O, Desbat L (2007) Transformée en Ondelettes Continue Directionnelle. *Appl Imagerie Med ESAIM Proc* 18:216–228. <https://doi.org/10.1051/proc:071816>
- Planton S, Deque M, Douville H, Spagnoli B (2005) Impact du réchauffement climatique sur le cycle hydrologique. *Compt Rendus Geosci* 337:193–202. <https://doi.org/10.1016/j.crte.2004.10.003>
- R Development Core Team (2011) R: a language and environment for statistical computing. the R Foundation for Statistical Computing, Vienna, Austria ISBN: 3–900,051–07-0. Available online at <http://www.R-project.org/>
- Scavia D, Field J, Boesch D, Buddemeier R, Burkett V, Cayan D, Fogarty M, Harwell M, Howarth R, Mason C, Reed D, Royer T, Sallenger A, Titus J (2002) Climate change impacts on US coastal and marine ecosystems. *Estuar Coasts* 25:149–164. <https://doi.org/10.1007/BF02691304>
- Schneider K, Farge M, (2006) Wavelet: Mathematical Theory, *Encyclopedia of Mathematics Physics*, Françoise J,P,Naber G,Tsun T,S, ed, Elsevier,426–438. <http://wavelets.ens.fr/PUBLICATIONS/ARTICLES/PDF/208.pdf>
- Servat E, Paturel J, Kouamé B, Travaglio M, Ouedraogo M, Boyer J, Lubès-Niel H, Fritsch, J, Masson JM, Marieu B (1998) Identification, caractérisation et conséquences d'une variabilité hydrologique en Afrique de l'Ouest et Centrale, In: *Water resources variability in Africa during the 20th century (Abidjan'98 Conference)*, Publication IAHS, n° 252, pages 323–337. http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers09-04/010017941.pdf
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and HL Miller (2007) Regional climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Eds., Cambridge University Press, Cambridge, pages 847–940. https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
- Torrence C, Compo G (1998) A practical guide to wavelet analysis. *Bull Am Meteorol Soc* 79(1):61–78. [https://doi.org/10.1175/1520-0477\(1998\)079<0061:APGTWA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2)
- Turki I, Laingel B, Laftouhi N, Nouaceur Z, Zamrane Z (2016) Investigating possible links between the North Atlantic Oscillation and rainfall variability in Marrakech (Morocco). *Arab J Geosci* 9: 1–14. <https://doi.org/10.1007/s12517-015-2174-z>
- Zamrane Z, Turki I, Laingel B, Mahe G, Laftouhi N (2016) Characterization of the interannual variability of precipitation and streamflow in Tensift and Ksob basins (Morocco) and links with the NAO. *Atmosphere* 2016(7):84. <https://doi.org/10.3390/atmos7060084>
- Willems P (2013) Multidecadal oscillatory behavior of rainfall extremes in Europe. *Clim Chang* 120:931–944. <https://doi.org/10.1007/s10584-013-0837-x>