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The frequency distribution and stochastic analysis of the hydrological drought in northern Algeria

Brahim Habibi[1,*], Mohamed Meddi[2], Mohamed Abdelkader[3]

[1] *Faculty of Natural and Life Sciences, Hassiba Benbouali University of Chlef and GEE Laboratory, Blida, Algeria*
[2] *National School of Hydraulics and GEE Laboratory, Blida, Algeria*
[3] *Department of Civil, Environmental, and Ocean Engineering (CEOE), Stevens Institute of Technology, Hoboken, NJ, USA*
*Corresponding author. Email: habibibrahime7@gmail.com

Abstract. The objective of this study was to examine drought using the Streamflow Drought Index (SDI) at various time scales and its temporal evolution using monthly streamflow data from 1973 to 2009. Streamflow records were collected from a network of 14 hydrometric stations distributed throughout the study area. The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were used to assess the quality of the adjustment. According to these criteria, the gamma law better suited the time scales of 3, 6, and 12 months, whereas the log-normal law was better suited to the scale of 9 months. The analysis of the Streamflow Drought Index in the three study basins (Middle and Upper Cheliff, Lower Cheliff, and the Mina) revealed that different classes of drought among 3, 6, 9, and 12-month time scales in the period of 1973 to 2009 had occurred, notably beginning in 1980. The frequency of 19 to 54% was found at all stations and in years marked by a mild drought. The moderate years had a frequency of 6 to 19%, while the severe and extreme years had a lower percentage (about 3 to 6%) in the study area. Two consecutive years of drought (D-D) were more likely in the Middle and Upper Cheliff basins (> 60%) for the 6, 9, and 12-month time scales, according to the transition of probability of first-order non-stationary Markov chain. On a three-month time scale, the transition probabilities (D-D) were greater than 50% in the Coastal basin and Lower Cheliff basin, as well as the Mina basin, and less than 50% in the Middle and Upper Cheliff basins.

Keywords: monthly stream flow, hydrological drought, frequency, Markov chain, North of Algeria.

INTRODUCTION

Climate change in arid and semi-arid regions is marked by a decrease in precipitation as well as a deprivation due to drought; this phenomenon is one of the most extreme climate conditions, affecting more people than any other natural disaster (Wilhite, 2000). Algeria is one of the countries in the Mediterranean basin that suffers from water scarcity from one season to the next and year to year. Water runoff is characterized by significant seasonal and interannual irregularities, as well as the severity and rapidity of the floods. In addition, the climate is characterized by lengthy periods of drought and irregular precipitation patterns in terms of both time and space. The lack of precipitation has resulted in evaporation deficits ranging from 37 to more than 70% from the east to the west of the country (Meddi and Hubert, 2003). Algeria, like the rest of the North African region, has been suffering from a persistent drought for more than three decades (Meddi and Meddi, 2009; Ghenim et al., 2013). The hydrological drought is the reduction of surface flow in watercourses and, consequently, it leads to a decrease in the volume stored in hydraulic structures and a natural drop in the water level in underground wetlands (Bergaoui and Alouini, 2001). The economic impact of hydrological drought on a country can be significant. For example, higher average temperatures in winter than in summer, has an impact on snow and ice tourism in particular (Yuan et al., 2022). Hydrological drought is defined by reduced river flow, dam fill rates, and groundwater recharge (Soro et al., 2011). Drought is a prolonged dry period in the natural climate cycle that can occur anywhere in the world. It is a slow on-set phenomenon caused by a lack of rainfall (WMO, 2014). Meteorological drought is characterized by the absence of precipitation or lower precipitation heights than those generally recorded in the same period and signaled by a lack of precipitation over time (WMO, 2014). Between 1970 and 2012, severe African droughts caused nearly 680,000 deaths (OMM, 2014). Thierry (2020) and Faye et al. (2015) defines agricultural drought as the influence of meteorological or hydrological droughts on crop yield. There are several indices for assessing the hydrological and meteorological drought at different scales (3, 6, 9 and 12 months), including the Palmer Drought Severity Index (PDSI, Palmer, 1965), The Standard Precipitation Index (SPI, McKee et al.,1993), the Standardized Stream Flow Index (SSFI, Modarres, 2007), the Standardized Runoff Index (SRI, Shukla and Wood, 2008), the Surface Water Supply Index (SWSI, Shafer and Dezman, 1982) and the Streamflow Drought Index (SDI, Nalbantis and Tsakiris, 2009) . The SPI, SDI and SSFI indices were used to generate drought intensity at time scales of 3, 6, 9 and 12 months. According to the time scale, the 3-month SPI index provides a seasonal estimate of precipitation; the 6- and 9-month SPIs indicate the medium-term precipitation trend. As for SPIs of 12 months and more, they reflect the long-term trend. They are generally related to stream flows, reservoir filling rates and even static groundwater levels (Khan et al., 2008). Modarres (2007), the SSFI provides the benefit of controlling hydrological drought and/or water supply on a short, medium, and long term basis. Standardized streamflow index (SSFI) was utilized by Hosseinzadeh Talaee et al. (2014) to characterize hydrological drought in the west of Iran for the hydrological years of 1969/1970 to 2008/2009 through 29 rainfall stations.

Nalbantis and Tsakiris (2009) proposed the Streamflow Drought Index (SDI) method, which is used to evaluate dryness over time. The SDI method, developed by Nalbantis and Tsakiris (2009), includes a similar calculation to the Standardized Precipitation Index (SPI) method (McKee et al. 1993). Zamani et al. (2015) determined the hydrological droughts through the SDI index in the Karkheh river basin in southwest Iran at time scales of 3, 6, 9, and 12 months. Several researchers around the world have used the SDI index to analyze hydrological drought, for example, Tabari et al.,2013; Rezaeian-Zadeh and Tabari (2014); Yeh et al.,2015; Hong et al., 2015; WMO and GWP , 2017; Kavianpour et al., 2018 ; Akkurt Eroğluer and Apaydin, 2020 ; Jahangir and Yarahmadi, 2020; Zaki, 2020; Zhao et al., 2020 ;Koffi et al.,2020 ; Tareke and Awoke, 2022 ; Elbeltagi et al., 2023). Meteorological and hydrological droughts have been analyzed by many researchers around the world on the basis of SPI and SDI indices (Sardou and Bahramand, 2014; Arya Akbari et al., 2015; Pathak et al., 2016; Koudamiloro Olivier et al., 2017; Dabanli, 2018 ;Melhaoui et al., 2018; Boudad et al., 2018; Zulfiqar et al., 2019; González-López et al., 2020; Benlabiod et al., 2020; Sun et al., 2020; Zhong et al., 2020; Jiang et al., 2020; Minea et al., 2021; Ngoc Quynh Tram et al., 2021; Prajapati et al., 2022). Bartczak et al. (2015) applied the Box-Cox transformation to identify drought events through the Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI).

In Algeria, there are researchers who have used the SDI index and the SSFI index to analyze and characterize hydrological drought. Filali (2004) investigated medium and long-term dryness using (SPI) and (SSFI) over two time scales of 6 and 12 months. Ghenim and Megnounif (2011) used the SPI and SSFI indices between September 1946 to August 2009 to study drought variability. The results showed that the drought severity values by SPI -12 for the two sub-basins vary within the same range [-2.24; 1.79], i.e. from extreme drought to severe humidity. On the other hand, the drought severity of the SSFI index over 12 months varied between -2.3 (extreme drought) and 1.8 (severe humidity) in Mefrouche and Beni Bahdel from -1.99 (severe drought) at 2.39 (extreme humidity). Ghenim and Megnounif (2013) used two indices, SSFI and SPI, to show that the Meffrouche sub-basin in northwestern Algeria had experienced periods of moderate humidity and drying, with a drying trend. Meddi et al. (2013) used the Streamflow Drought Index (SDI) to study drought in the Tafna river basin during periods of 3, 6, 9, and 12 months in the northeast of Algeria between 1941 and 2010. In this regard, some researchers have applied the Standardized Streamflow Index (SSFI) and the SDI Index in Algeria, such as Bendjema (2019) and Atallah et al (2021). They discovered that precipitation decreased by 26% in the Tafna basin after 1975, with a notable reduction in runoff of around 62%. In comparison, the three basins of Middle and Upper Cheliff, Lower Cheliff , and the Mina, which belong to the grand basin of Cheliff-Zahrez, have had severe and moderate droughts since 1980 (Habibi et al., 2018; Habibi and Meddi, 2021).

The Markov chain methodology may be used to determine the likelihood of having a dry year following a dry year. This procedure expresses conditional probabilities of transiting from the previous year's state to the current year's state. Because the stochastic process X_n (n = 0, 1, 2...) is a Markov chain (Medhi, 1994), the probabilities of transitions are only dependent on the current and future states (Meddi and Meddi, 2009; Meddi et al., 2013; Tokarczyk and Szaliska, 2014; Meddi et al., 2014; Tabari et al., (2015) :Lazri et al., 2015; Merabti and Meddi, 2016;Tettey et al., 2017; Habibi et al., 2018; Santos et al., 2019; Sattar et al., 2020).

The aim of this study is to provide quantitative information on hydrological drought (SDI) in semi-arid climatic conditions in northern Algeria using random Markov chain models and to

obtain probabilistic hydrological information. The SDI index was chosen to describe hydrological drought. The SDI (Nalbantis and Tsakiris, 2009) index has been widely used to describe and characterize hydrological drought. It is also simple in its use and allows a good description of this type of drought, which has been shown by several researchers around the world (Jahangir and Yarahmadi, 2020; Zhang et al., 2022; Katipoğlu, 2023). We have chosen this indicator for the efficient service and management of surface water (dams) and for the control of groundwater levels in the Cheliff-Zahrez basin, which is considered as an important agricultural area in the north of Algeria. The information on the probability of occurrence of drought is an important challenge for making short- and long-term decisions on water management.

This research motivates researchers and policymakers to use the most accurate and representative temporal characterization of drought risk in a semi-arid region.

STUDY AREA

The study area is located in the midwest of northern Algeria which includes three hydrographic basins (Lower Cheliff and the Mina, Middle and Upper Cheliff, and Coastal Dahra) (Figure 1). These three basins extend over 132,411 km^2. Lower Cheliff and the Mina, and Middle and Upper Cheliff are crossed by the Cheliff River. These basins have a very dense hydrographic network (Figure 2) with around 2, 2 km of permanent wadis and 5,600 km of temporary wadis. The Cheliff River's main watercourse of 349 km long results from the junction of the two large wadis of Nahr Touil and Nahr Ouassel (ABH CZ, 2004). The drainage density varies between 0.57 and 1.54 km/km^2. The low values characterize low-pitched terrain, which is mainly located on the high plains and results from low rainfall on permeable formations.

Data and methodology

The data used in this study is made up of a series of monthly flows. The characteristics of hydrometric stations, in terms of geographical location and observation periods, are summarized in Table 1. The largest moving sub-basin is that of El Abtal, which covers 5,400 km2 (Table 1), while the second largest sub-basin is that of Ammi Moussa, which covers 1,890 km2, and they are followed by the sub-basin of Takhemaret, which covers 1,550 km2. The fourteen stations in the study area are not regulated by the dam waters. We chose 14 sites to cover the study area completely. The operating period of the selected stations was 37 years, beginning with the hydrological year 1973/74 and ending with the year 2009/10. September is considered the beginning of the hydrological year in Algeria.

Hydrometric data relating to monthly flows was collected from the National Agency for Hydraulic Resources (ANRH) Algeria.

Streamflow Drought Index (SDI)

Nalbantis (2009) developed the SDI method for the detection of the onset of hydrological drought in two river basins in Greece. The SDI is calculated using several time scales. Furthermore, according to Nalbantis (2008), the calculation of SDI is based on monthly flows, which are then accumulated based on the duration k. For a k-year hydrological period, the cumulative flow volume is obtained. It is necessary to understand the circumstances, magnitude, extent, and frequency of the drought (Tabari et al., 2013). Other researchers used the

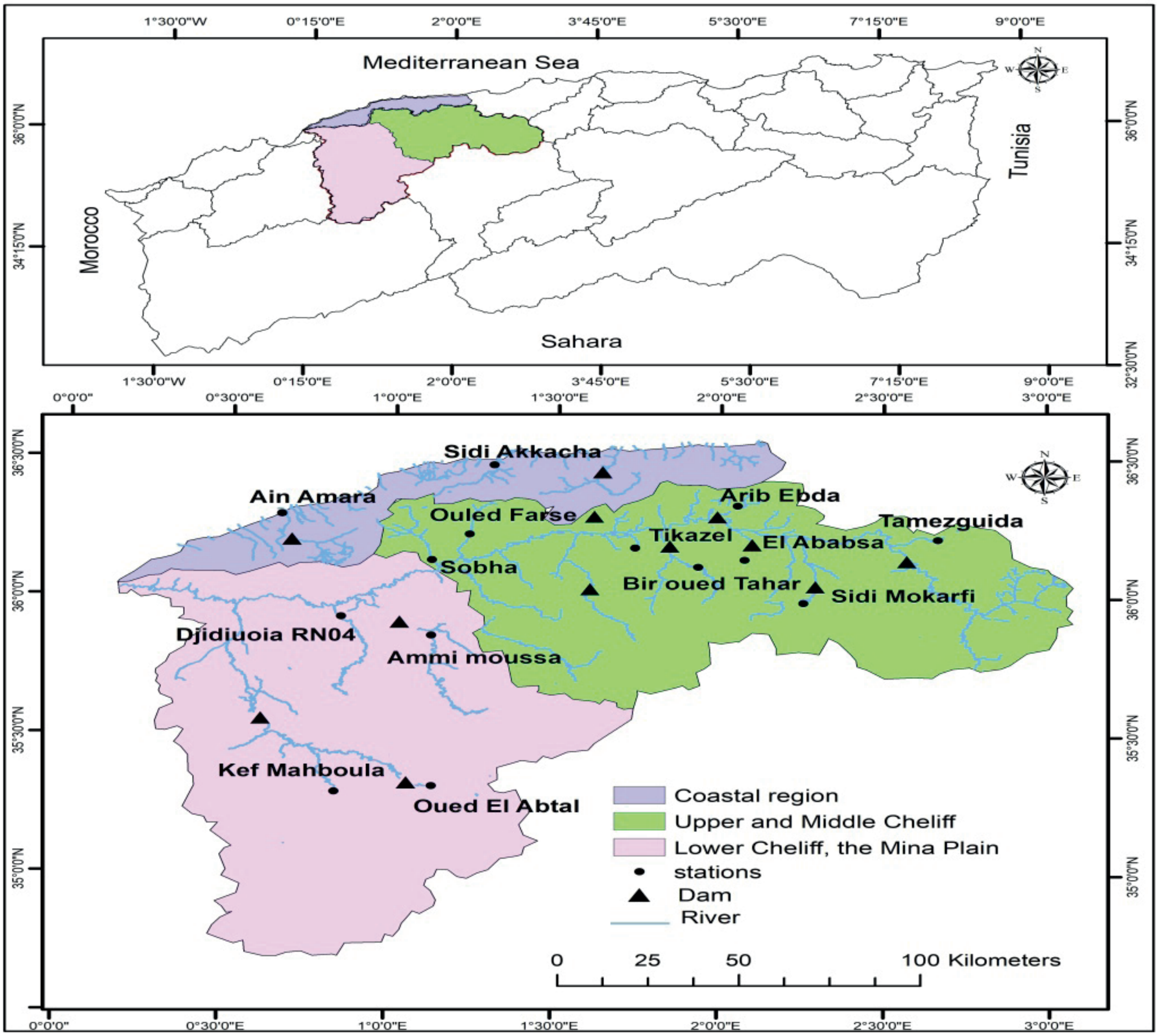

Figure 1. Geographical location of the study area.

SDI index to calculate hydrological drought (e.g., Tabari et al., 2013; Manikandan and Tamilmani, 2015; Yeh et al., 2015). According to the impact studied, SDI values of 3 months or less are useful for routine drought monitoring, SDI values of 6 months or less are useful for agricultural impact monitoring, and SDI values of 12 months or more are useful for hydrological impact detection (WMO, 2012).

The SDI is calculated as follows using the cumulative flow $V_{i,\,k,}$ in which *i* denotes the hydrological year and *j* the month within that hydrological year (j = 1 for September et j = 12 for August), $V_{i,k}$ can be obtained based on Equation (1): for the i-th hydrological year and the reference period k:

$$V_{i,\,k} = \text{Sum}\,(Q_{i,j})\ i=1, 2..T, J=1, 2, ...12, k=1, 2, 3, 4 \quad (1)$$

Q_{ij} is the monthly flow, and $V_{i,k}$ is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 is used for the period of September to November, k = 2 is used for the period of November to February, k = 3 is used for the period of September to May, and k = 4 is used for the period of September to August.

After calculating $V_{i,\,k}$, the SDI is calculated for each reference period k of i years:

Table 1. Characteristics of the hydrometric stations studied.

Name	Basin	X (m)	Y (m)	Z (m)	Observation period
Sidi Akkacha	Coastal Dahra	375000	354300	120	1973-2009
Ain Amara		316450	335120	775	1973-2009
Tamesguida	Middle and Upper Cheliff	497000	323899	490	1973-2009
El Ababsa		443950	318050	313	1973-2009
Arib Ebda		439600	335600	280	1973-2009
Bir Oued Tahar		431000	313250	245	1973-2009
Tikazel		413668	320905	215	1973-2009
Ouled Fares		368100	326650	370	1973-2009
Sobha		357649	316399	375	1973-2009
Ammi Moussa	Lower Cheliff and the Mina	357400	286150	140	1973-2009
Djidiuoia RN04		332600	293899	550	1973-2009
Kef Mahboula		330500	223800	620	1973-2009
Sidi Mokarfi		463000	302600	425	1973-2009
Oued El Abtal		357350	225849	490	1973-2009

$$\mathrm{SDI}_{i,k} = \frac{V_{i,k} - V_k}{S_k} \quad i=1, 2\ldots \quad k=1, 2, 3, 4. \tag{2}$$

where
$\overline{V}_k$ and S_k are the long-term average and standard deviation of the cumulative flow volumes of the reference period k, respectively. In this definition, the truncation level is set to $\overline{V}_k$, although other values based on rational criteria can also be used (Nalbantis and Tsakiris, 2009).

In general, flow data for small basins does not follow a normal distribution and has an asymmetric probability distribution. In accordance with Nalbantis and Tsakiris (2009), Tabari et al. (2013), and Zamani et al. (2015), a log-normal distribution is used as follows to fit the flow data for the SDI calculation:

$$\mathrm{SDI}_{i,k} = \frac{y_{i,k} - \bar{y}_k}{s_{y,k}} \quad i=1, 2\ldots \quad k=1, 2, 3, 4. \tag{3}$$

In such case:

$$y_{i,k} = \ln(V_{i,k}) \quad i=1, 2\ldots,T \quad k=1, 2, 3,4. \tag{4}$$

where
$\overline{y}_k$ and $S_{y,k}$ represent the mean and standard deviation values of V_i, and T is the number of years. According to Nalbantis and Tsakiris, 2009, hydrological drought classification using SDI is shown in Table 2.

The first-order Markov process

Hydrological drought and Markov chains have been studied by many authors, we can cite among them Nalbantis and Tsakiris (2009) ; Meddi and Meddi, 2009; Meddi et al., 2013; Tabari et al., (2015); Lazri et al., 2015; Merabti and Meddi, 2016; Tettey et al., 2017; Habibi et al., 2018; Santos et al., 2019; Sattar et al., 2020 and recently Rahmouni et al., (2021).

Table 2. Hydrological drought based on the SDI (Nalbantis and Tsakiris, 2009).

State description	Criterion	Probability (%)
Non-drought	≤ 0.0	50
Mild drought	-1.0 ≥ SDI <0.0	34.1
Moderate drought	-1.5 ≥ SDI <-1.0	9.2
Severe drought	-2.0 ≥ SDI <-1.5	4.4
Extreme drought	SDI <-2.0	2.3

Markov chains are the simplest example of stochastic processes, when in the study of a series of random variables, one abandon the assumption of independence. It is a non-memory discrete time process.

The first order Markov Chain takes into account only the actual state (present) of the process and not the previous states (past).

Formally, we model with Homogeneous Markov chains the evolution over time of quantities X which can take a finite number of states $X = x_1$, $X = x_2$,… $X = x_n$, and which pass from the state i at time t at state j at the next time t + 1 with a given probability p_{ij}.

$p_{ij} = \mathrm{P}(X_{T+1} = x_j/X_t = x_i$ therefore satisfy $0 \le p_{ij} \le 1$ and $\sum_{j=0}^{n} p_{ij} = 1$ (since if the chain is in state xi at a time, it will necessarily be in one of the possible states x1,…, xn the next instant and therefore $p_{i1} + p_{i2} + \ldots + p_{in} = 1$; The expression $P(X_{t+1} = j/X_t = i)$ is called a conditional probability and represents the "probability that the quantity X will be j at time t + 1 knowing that it is i at time t".

To define a Markov chain, two basic ingredients are therefore needed:

1. The state space S:={$x_1 \ldots x_n$} known that we will assume finite
2. The transition (or passage) matrix

$$P=(p_{ij})_{1\le i\le n, 1\le j\le n} = \begin{pmatrix} & x_1 & x_2 \cdots x_n \\ p_{11} & p_{12} \cdots p_{1n} \\ & \vdots & \\ p_{n1} & p_{n2} & p_{nn} \end{pmatrix} \tag{5}$$

Two-state, first-order Markov chain

A two state-, first-order Markov chain is illustrated schematically in figure 2. The two states wet ("1") and dry ("0"). were considered in this study as at each time t, the random variable X can be in one state. First order time dependence implies that there are $2^2 = 4$ transition

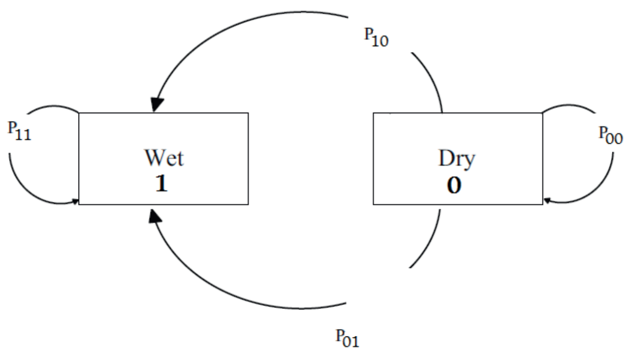

Figure 2. Transitions diagram of two-state, first-order Markov chain.

probabilities, p_{ij}, with $p_{i1} + p_{i2} = 1$ with i = 1, 2. Estimation of the transition probabilities for two-state Markov chains are obtained from the conditional relative frequencies of the transition counts (n_{ij}):

$$\hat{p}_{ij} = \frac{n_{ij}}{\sum_{k=0,1} n_{ik}}, i, j = 0,1. \tag{6}$$

We used the following hypothesis: the model is non-stationary order lag-one Markov chain, i.e $P(X_n=0)$ is not constant over time. Furthermore, it was assumed that transition probabilities were constant across time.

The transition from one state to another at any moment was determined by a P transition matrix of size nxn with the following properties:

$$P = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \tag{7}$$

In order to calculate the probabilities of a higher-order transition, we used the Chapman-Kolmogorov (Ross, 2014; Lakshmi and Manoj, 2020). equations given by the following matrix product:

$P^{k+1} = P^k P$, where k = 1, 2 ... n.

The limit law of the steady state (which is stationary) exists and is unique because the Markov chain is aperiodic and irreducible in the space of finite states, and it is invariant in determining the limit equation:

$$\begin{bmatrix} 1\text{-} p & p \end{bmatrix} \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} = \begin{bmatrix} 1\text{-} p & p \end{bmatrix}; \tag{8}$$

Let $p_0 = P(X_0 = 1)$. Here p_0 is the probability that the initial year was wet year in our data.

Solving equation 7 gives the following solution:

$$p = \frac{P_{01}}{1 - (P_{11} - P_{01})} \tag{9}$$

p is the probability of remaining in state “1,” and $1/p$ is the average time to return to that state.

The law of probabilities of sojourn time in the state “1: Wet” noted by W, which follows the geometric law of a parameter (P_{11}), i.e.

$$P(W = k) = (1 - P_{11})\, P_{11}^{K-1} \tag{10}$$

As a result, the transition probabilities of Wet sequences of lengths greater than k are:

$$P(W > k) = \sum_{t=k+1}^{\infty} P(W = t) = P_{11}^{K} \tag{11}$$

Similarly, the probability of a dry episode of a length m is

$$P(D = m) = (1 - P_{00})\, P_{00}^{m-1} \tag{12}$$

and the probability of dry sequences of lengths greater than “m” is:

$$P(D > m) = (P_{00})^m \tag{13}$$

The criteria for comparison

The Akaike Criteria (AIC) was proposed by Akaike (1974) and the Bayesian Criteria (BIC) was proposed by Schwarz (1978). Akaike’s Information Criterion (AIC) and Bayesian Information Criterion (BIC) are two of the most widely used criteria for model selection and performance measures (Qi et al., 2001). Lower AIC and BIC values indicate better model fit. Akaike (1974) formula is given in equation (14):

$$AIC_c = \left[\frac{2n}{n-k-1}\right] k - 2\ln[L_{max}] \text{ (for n>≈40).} \tag{14}$$

The Bayesian Criteria (1978) is defined by equation (15) as follows:

$$BIC = \ln[n]k - 2\ln[L_{max}] \quad \text{(for n>≈20)} \tag{15}$$

DISCUSSION AND RESULTS

The frequency analysis of flows at different scales was carried out on data from 14 hydrometric stations from 1973 to 2009. The laws used are: gamma, Gumbel, log-normal and Halphen type A. According to Nalbantis 2008; Shukla and Wood 2008 the log-normal distribution is the most adequate distribution for flow adjustment. In our work, we adapt the flow series to both the gamma law and the log-normal distribution and we determine the validity of the law by the criteria of AIC and BIC.

The analysis of the results showed that the log-normal is better adjusted with the Coastal Dahra stations at different scales of 3, 6, 9 and 12 months according to the AIC and BIC criteria. On the other hand, the Gamma law appears better with the stations Middle and Upper Cheliff and Lower Cheliff and the Mina for the scale 6, 9 and 12 (tables 3 and 4).

Knowledge of SDI classes for different time scales plays an important role in drought identification. It then allows better control of the water supply which generates the proper functioning of the system of forecasting and management of water resources in the short, medium and long term.

The results of an SDI analysis for 14 sites for the period from 1973 to 2009 (September-October-November) showed that three basins had experienced a variety of droughts, with the most severe occurring during the 1980s.

The duration of drought episodes (Fig. 3) showed that variations were occurring from one time scale to another and from one station to another. The Coastal basin had a longer period of non-drought (six years) from 1996 to 2001, and the same class was recorded in the basins of the Lower Cheliff and the Mina from 1992 to 1995, 1999 to 2001, and 2006 to 2008. In the meantime, the Middle and Upper Cheliff basins faced

Table 3. Results of the AIC and BIC criteria (3 months).

Basin	Station names	Criteria	Gamma	Log-normal
Coastal Dahra	Ain Amara	AIC	319.2	301.3
		BIC	323.8	305.9
	Sidi Akacha	AIC	65.8	64.8
		BIC	69	68
Middle and Upper Cheliff	Tamezghuida	AIC	176.7	172.8
		BIC	179.9	176.1
	El Ababsa	AIC	157.1	119.4
		BIC	150.3	122.6
	Arib Ebda	AIC	129.4	127.1
		BIC	132.6	130.3
	Bir Ouled Tahar	AIC	176.3	175.1
		BIC	179.6	178.3
	Tikazel	AIC	136.4	125
		BIC	139.6	128.3
	Ouled Fares	AIC	54.7	52.8
		BIC	57.9	56
	Sobha	AIC	74.5	70.9
		BIC	77.8	74.2
Lower Cheliff and the Mina	Ammi Moussa	AIC	172.7	175.1
		BIC	175.9	178.3
	Djediouia RN 04	AIC	37.6	39.9
		BIC	40.8	43.1
	Kef Mahboula	AIC	79.2	84.3
		BIC	82.4	87.5
	Oued El Abtal	AIC	236.3	284.7
		BIC	239.5	287.9
	Sidi Mokarfi	AIC	90.3	91
		BIC	93.5	94.3

Table 4. Results of the AIC and BIC criteria (12 months).

Basin	Station names	Criteria	Gamma	Log-normal
Coastal Dahra	Ain Amara	AIC	227,4	226,6
		BIC	230,6	229,8
	Sidi Akacha	AIC	197,3	193,5
		BIC	200,5	196,8
Middle and Upper Cheliff	Tamezghuida	AIC	272,1	277,9
		BIC	275,3	281,2
	El Ababsa	AIC	86,5	91,6
		BIC	89,7	94,8
	Arib Ebda	AIC	277,2	279,9
		BIC	280,5	283,1
	Bir Ouled Tahar	AIC	173,6	175,3
		BIC	176,8	178,5
	Tikazel	AIC	93,6	106,1
		BIC	96,8	109,3
	Ouled Fares	AIC	238,1	248,5
		BIC	241,3	246,8
	Sobha	AIC	188,1	189,9
		BIC	191,3	193,2
Lower Cheliff and the Mina	Ammi Moussa	AIC	296	297,5
		BIC	299,2	300,7
	Djediouia RN 04	AIC	200	200.6
		BIC	203,8	203,8
	Kef Mahboula	AIC	137,8	140,3
		BIC	141	143.6
	Oued El Abtal	AIC	262,2	263,2
		BIC	265,1	266,5
	Sidi Mokarfi	AIC	239,1	242,5
		BIC	236,3	248,7

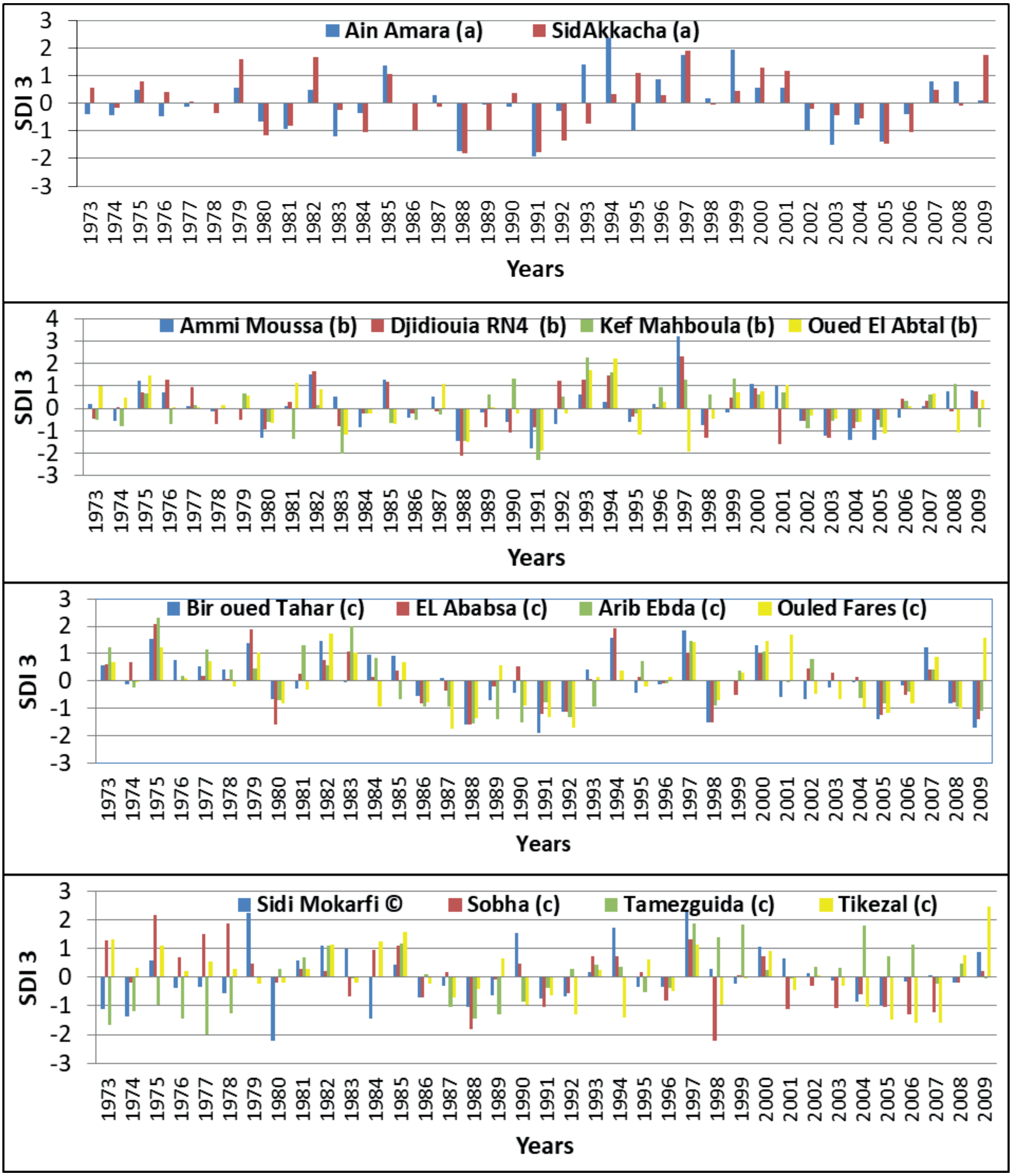

Figure 3. The evolution of the 3-month SDI for (a) Coastal, (b) Lower Cheliff and the Mina, and (c) Middle and Upper Cheliff.

wet periods from 1974 to 1978 and from 1981 to 1984 in the months of September, October, and November. On a three-month scale, the hydrological drought in the Coastal basin consisted of a number of mild episodes between 13 to 14, 2 to 5 moderate episodes, 2 to 3 severe episodes and 0 extreme episodes with a maximum intensity of -1 .9. In terms of the Lower Cheliff and the Mina basins, they recorded 10 to 15 mild episodes, 2 to 5 moderate episodes, 0 to 2 severe episodes, and 1 to 2 extreme episodes with a maximum intensity of -2.3. Furthermore, hydrometric stations in the Middle and Upper Cheliff basins recorded 9 to 17 mild episodes, 2 to 6 moderate episodes, 1 to 4 severe episodes, and 0 to 1 extreme episode with a maximum intensity of -2.2.

The three basins are distinguished by different types of drought based on a six-month analysis of the SDI. The results are depicted in the figures below.

During the 6-month period (September, October, November, December, January, and February), the three basins (Fig. 4) experienced extreme drought with maximum intensities of -2.2 (Coastal), -2.2 (Lower Cheliff and the Mina), and -2.4 (Middle and Upper Cheliff). They were observed between 1988 and 1989, and between 1990 and 1991. A mild drought of flow supplies (-1.0 < SDI < 0.0) was noted at most of study sites between 1980 and 1985. A mild drought was marked by the occurrence of 13 to 15 episodes in the Coastal basin, 9 to 12 episodes in the Middle Cheliff and the Mina basins, and 9 to 20 episodes in the Upper Cheliff basin. However, from September to February, the Coastal and Lower Cheliff faced moderate droughts of 2 to 4 episodes, while the Mina experienced moderate droughts of 2 to 6 episodes. The Middle and Upper Cheliff basins faced 2 to 7 Moderate drought episodes.

During a 6-month period, the basins of Lower Cheliff and the Mina recorded 2 to 3 severe episodes and 0 to 2 extreme episodes. Furthermore, the hydrometric stations in the Middle and Upper Cheliff basins recorded 0 to 4 severe episodes and 0 to 1 extreme episode. And the Coastal basin recorded 2 to 3 severe drought episodes and 1 extreme episode.

Considering all the study stations, the evolution of the 9-months SDI in Figure 5 shows successive occurrences of moderate, mild, and severe droughts, which were observed between 1980 and 1986, 1985 and 1993, and 1995 and 2006. For instance, a 9-month drought was recorded in 1983 at Oued El Abtal (-2.2) and Kef Mahboula (-2.2), in 1988 at Kef Mahboula (-2.6), in 1991 at Bir Oued Tahar (-2.2), in 1992 at Arib Ebda (-2.3), and in 2006 at Tikazel (-2.9).

In terms of mild drought episodes, 13 episodes were observed in the Coastal basin, 9 to 12 episodes in the Lower Cheliff and the Mina basins, and 9 to 18 episodes in the Middle and Upper Cheliff basins. Comparable moderate droughts of 9 months duration are counted in the order of 5 to 7 sequences in the Coastal basin. The Bas Chéliff and Mina basin recorded 2 to 6 drought sequences and the Middle and Upper Chéliff 3 to 5 sequences. On the other hand, in terms of severe drought episodes, 0 to 2 episodes were observed in the Coastal basin, 0 to 3 episodes in the Lower Cheliff and the Mina basins, and 1 to 4 episodes in the Middle and Upper Cheliff basins. In addition, the 9-month evolution of droughts revealed 5 extreme episodes in three study basins: Arib Ebda, Bir Oued Tahar, Kef Mahboula, Oued El Abtal, and Tikazel.

The variability of the evolution of the 12-month SDI in Figure 6 was studied, and it was discovered that it varied in terms of both time and region. The results of a 12-month SDI analysis (from September to August) are depicted in the figures, which show the various classes, and they particularly occurred in the 1980s. It is also noted that the driest years during the study period were recorded from 1999 to 2006 at the stations of Sidi Akkacha and Ain Amara and from 1985 to 1990 at the stations of Bir Oued Tahar, El Ababsa, Arib Ebda and Ouled Fares. On the same time scale, the stations in the Coastal basin had 13 episodes of mild drought with a maximum intensity of -0.5. From 1973 to 2009, 9 to 12 mild drought episodes were observed in the Lower Cheliff and the Mina basins, and 9 to 18 mild drought episodes were observed in the Middle and Upper Cheliff basins, based on 12-month records. In the three study basins, a 12-month moderate drought was observed with a number of episodes between from 2 to 7, with maximum intensities of -1.4 (Coastal), -2 (the Lower Cheliff and the Mina), and -2 (the Middle and Upper Cheliff). Severe and extreme drought episodes occurred in two basins (the Lower Cheliff and the Mina, and the Middle and Upper Cheliff), with the number of episodes ranging from 0 to 3. The maximum intensity was recorded at the Middle and Upper Cheliff basins (e.g. -2.9 (Tikazel), -2.4 (Arib Ebda)) as well as at two stations in the Lower Cheliff and the Mina basins (Kef Mahboula (-2.4) and Oued El Abtal (-2.4)).

Comparison of the number of episodes in each of the three basins at various time scales

The graphs below show the number of extreme, severe, and moderate drought sequences that occurred in three basins in northern Algeria between 1973 and 2009. The analysis revealed that the number of episodes varied from one time scale to another and from one station to another.

The number of drought episodes in each of the three basins was determined using the SDI (shown in Figure 7) at various time scales, allowing us to identify the periods of extreme drought (ED), severe drought (SD), and moderate drought (MD) in the Middle and

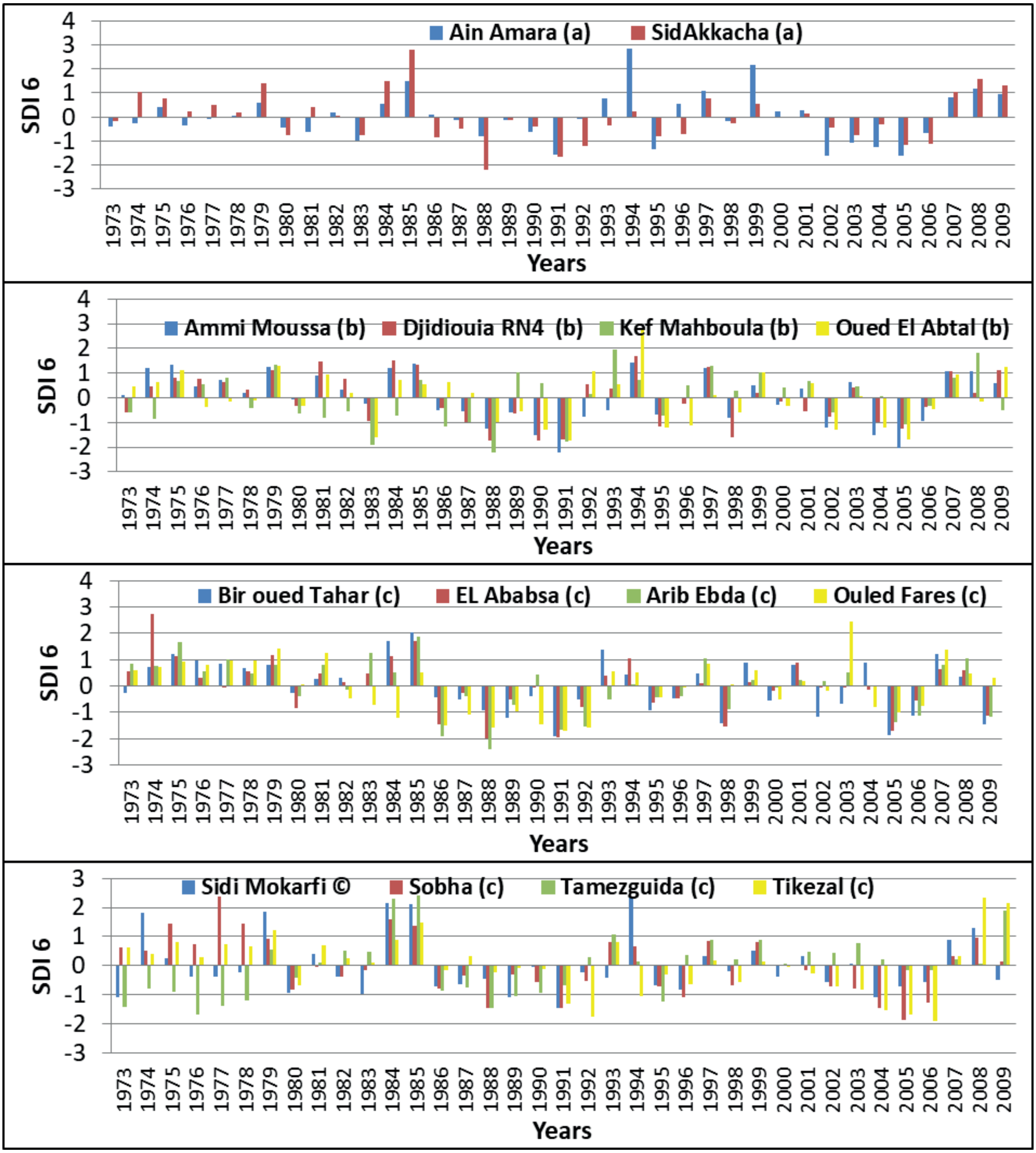

Figure 4. The evolution of the 6-month SDI for (a) Coastal, (b) Lower Cheliff and the Mina, and (c) Middle and Upper Cheliff.

Upper Cheliff basins, the Lower Cheliff basin, and the Mina basin. Extreme drought episodes were observed at 14 hydrometric stations across the study area, with episodes ranging from 1 to 2 months in length. On the other hand, the four stations of the Bas Cheliff and Mina basins were confronted with two extreme episodes of drought on a time scale of 9 months. Ammi Moussa (Lower Cheliff and the Mina), Bir Oued Tahar,

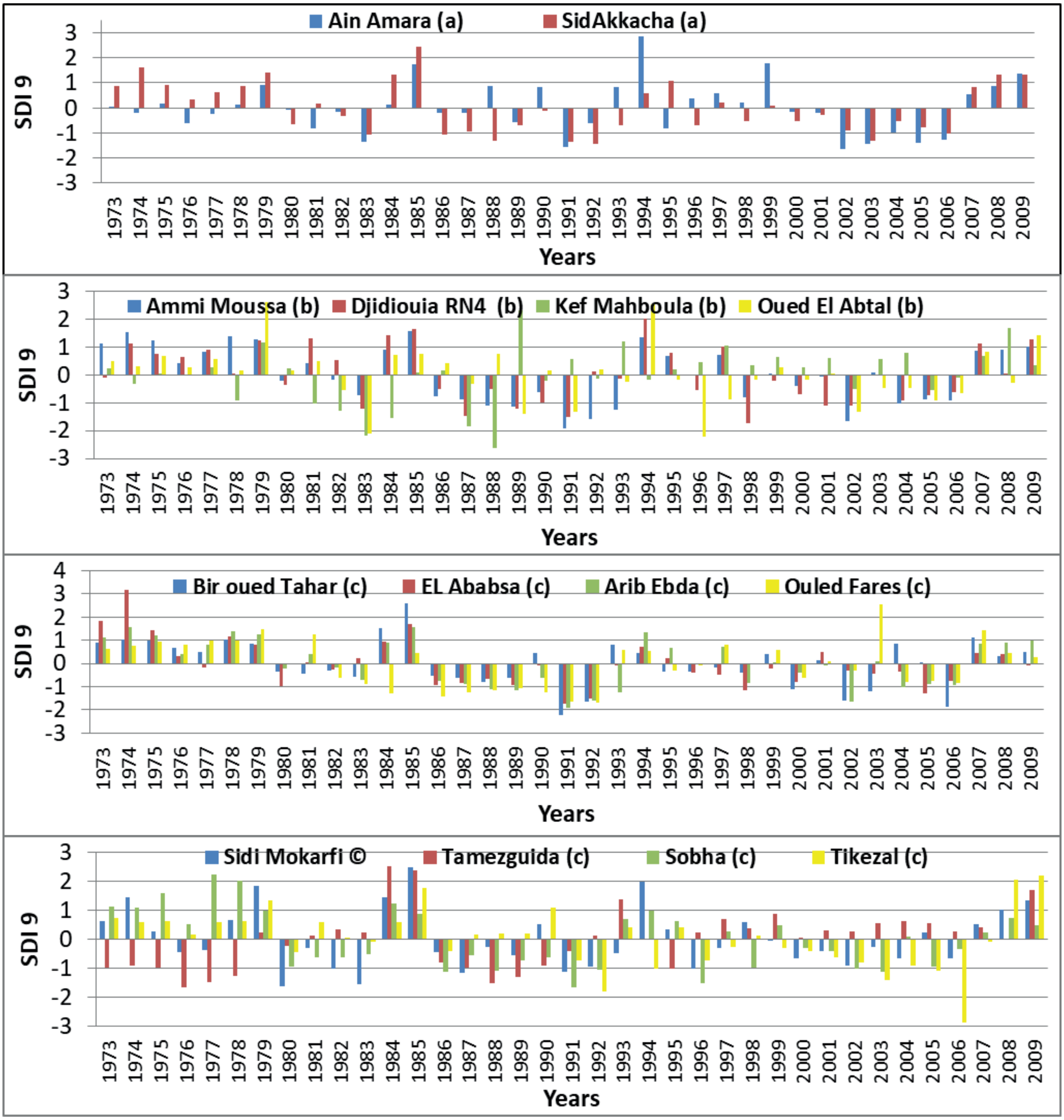

Figure 5. The evolution of the 9-month SDI for (a) Coastal, (b) Lower Cheliff and the Mina, and (c) Middle and Upper Cheliff.

El Ababsa, and Tikazel (Middle and Upper Cheliff) had all experienced severe drought, with a maximum of four episodes. The obtained results suggest that moderate drought periods can be classified into three main categories. Each category can be distinguished by the length and frequency of the drought event occurrence. This condition is the result of the dry climate trend that has been seen in northern Algeria since the 1980s (Meddi and Meddi, 2009).

Frequency mapping of the SDI

We used a histogram that represents through a bar the frequency of drought classes at each interval for the

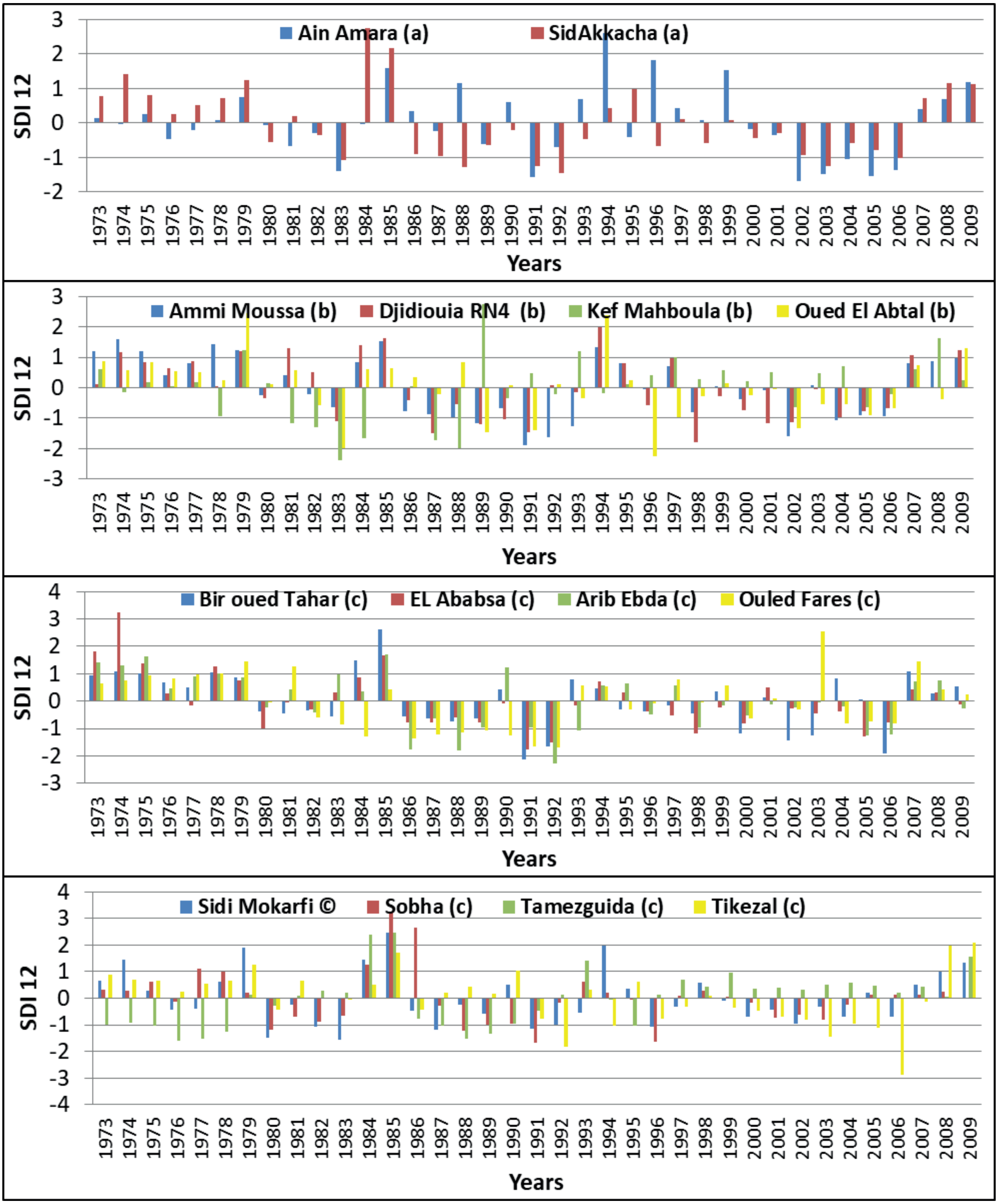

Figure 6. The evolution of the 12-month SDI for (a) Coastal, (b) Lower Cheliff and the Mina, and (c) Middle and Upper Cheliff.

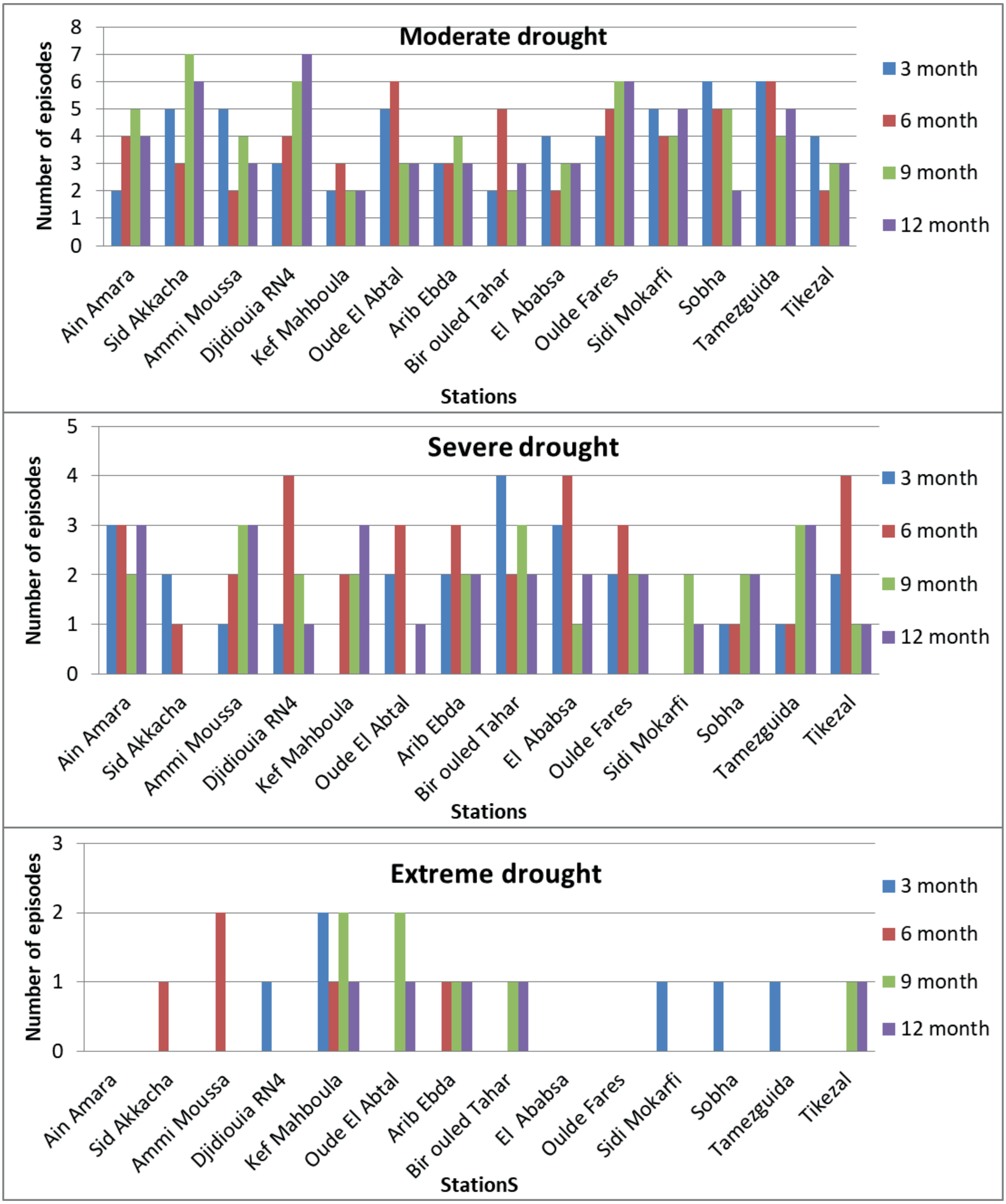

Figure 7. the number of episodes in each of the three basins at various time scales.

description and analysis of the variability of relative frequencies at different time scales in the three basins. Figure 8 shows the frequency distribution, which takes into account the continuous nature of variables and the fact that the classes have different amplitudes. In the meantime, the relative frequency provides the percentage for each drought class in a range of 0 to 1. The distribution of drought classes for all three basins was represented by projecting the results of the SDI frequencies onto the map of the studied region. This type of representation makes the distribution of frequencies of stations in the study area more visible.

Figure 8 depicts the spread of five different kinds of hydrological drought throughout the whole catchment basin. The non-drought class (ND) was found at all the stations in the study area, with a peak at El Ababsa (62%), and a nadir at Oued El Abtal, Tamesguida, and Ferme-Farhat (45%). At Ferme-Farhat, a mild drought (MLD) with a maximum trend (17%) was recorded. And then, 15% frequency was recorded at the levels of Sidi Mokarfi, Kef Mahboula, Bir Oued Tahar, and Djidiuoia RN04. A minimum mild drought (MLD) of 7% was recorded at the El Ababsa station. The maximum frequency of moderate drought (MD) was observed at the stations of Ammi Moussa and Sobha, which reached 27%. Except for the station at Bir Oued Tahar, which recorded an 11% frequency of severe (SD) and extreme (ED) droughts, the whole study area was characterized by very low values ranging from 0% to 8%.

The non-drought frequency (6-month) of the fourteen hydrometric stations was found to be between 62 % and 44%, and they are shown in Figure 8. The repetition of the mild drought (MLD) of high frequency at the level of three basins (Middle and Upper Cheliff basin, Coastal and Lower Cheliff basin, and the Mina basin) was of the order of Sidi Mokarfi (54.1%), Sobha (37.8%), Sidi Akkacha (40.5%), and Ferme-Farhat (29.7%).

Analysis of the 9-months frequency distribution map (Fig. 9) of the study basin shows that the non-drought (ND) frequency was between 45% and 60% in all hydrometric stations such as Tamesguida (56.8%), Kef Mahboula (59.6%), Ferme-Ferhat (54.1%), and Sidi Akkacha (46%). In addition, the mild drought was quite strong in the Middle and Upper Cheliff basins with a maximum value at the station of Sobha (32.4%). Moreover, stations in the Coastal and Lower Cheliff basins were marked by a rather low frequency (Ammi Moussa (32.4%), and Kef Mahboula (24.3%). Severe drought (SD) was recorded in the upper part of Tamesguida (8.1%) and in the upper part of Ferme-Farhat (10.8%). Extreme drought (ED) was detected at the stations of Kef Mahboula (5.4%) and Oued El Abtal (5.4%).

Between 1973 and 2009, the 12-month non-drought class frequencies (Fig.9) reflected the most significant trend in the study area, ranging between 59 % and 38%. The highest non-drought (ND) frequency was discovered in the east and southeast. In the mild class (MLD), the sub-basin of Lower Cheliff had relatively low frequencies, averaging 32.4%, whereas the other basins had quite high frequencies, ranging from 48% to 19%. In the whole study basin, frequencies ranging from 11% to 0 were found for the two severe and extreme drought classes.

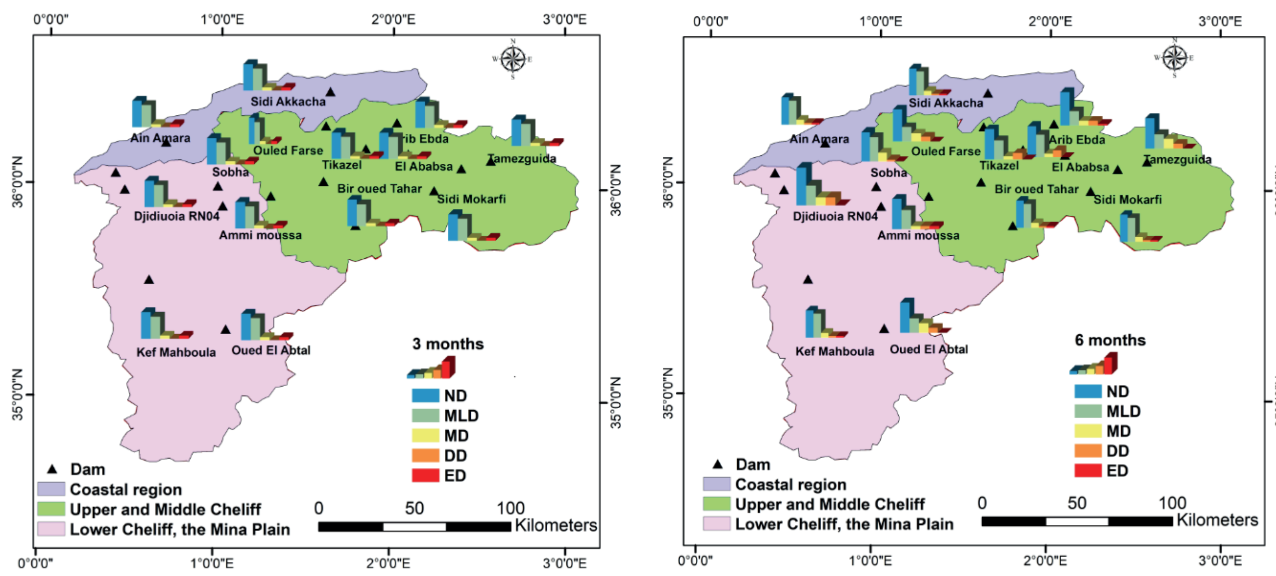

Figure 8. Frequency distribution of the SDI-3 (left) and SDI-6 (right).

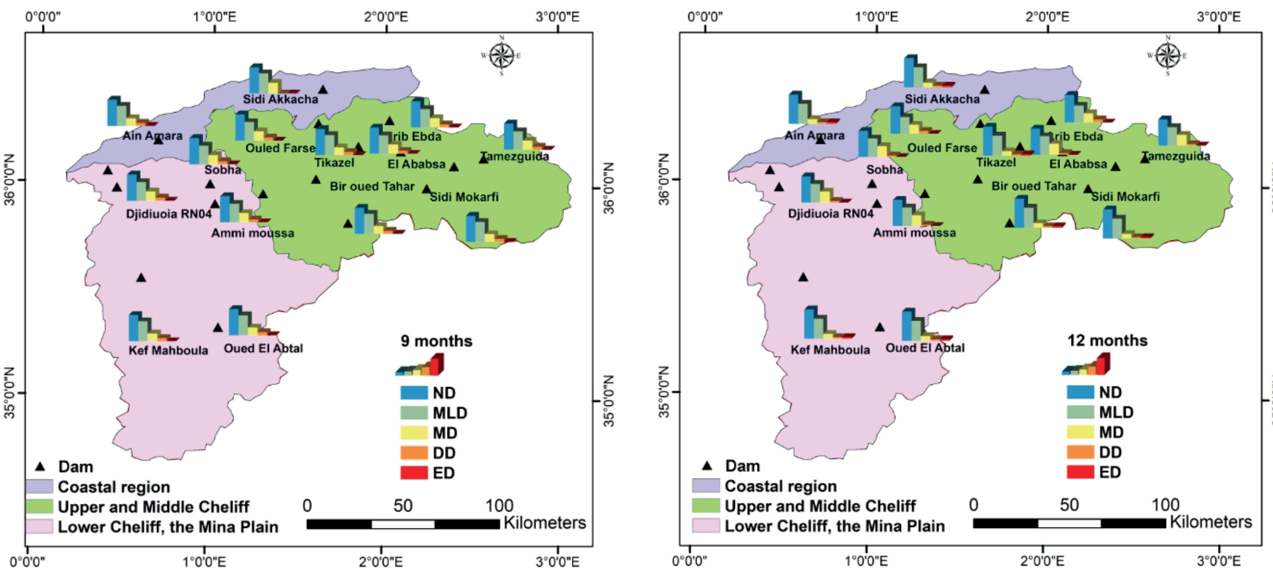

Figure 9. Frequency distribution of the SDI-9 (left) and SDI-12 (right).

First-order Markov chain

In this study, we used the stochastic first-order Markov chain model and the SDI to investigate hydrological drought episodes at various time scales (3, 6, 9, and 12 months) and during a period spanning from 1973 to 2009. To better visualize the variability of hydrological drought, we represented the probabilities of transitions using a histogram. A first-order Markov chain was used to generate probability histograms for three basins (Coastal, Middle and Upper Cheliff, as well as Lower Cheliff and the Mina).

The analysis of these histograms of probability of transition from one dry hydrological year to another dry hydrological year (D-D, Figure 10) over a three-month period (September-October-November) revealed a north-south gradient of 75% to 50%, indicating a strong trend of hydrological drought in the north. In the Middle and Upper Cheliff basins, however, the probability of transition on a 6-month scale (September, October, November, December, January, and February) recorded high values (about 80%). The Lower Cheliff and the Mina basins had the lowest transition probabilities for D-D (40%-45%). In the Middle and Upper Cheliff basins, and in the Coastal basin, the probability of transition from one dry hydrological year to another dry hydrological year (D-D) over 12-month and 9-month periods was fairly similar, rang-

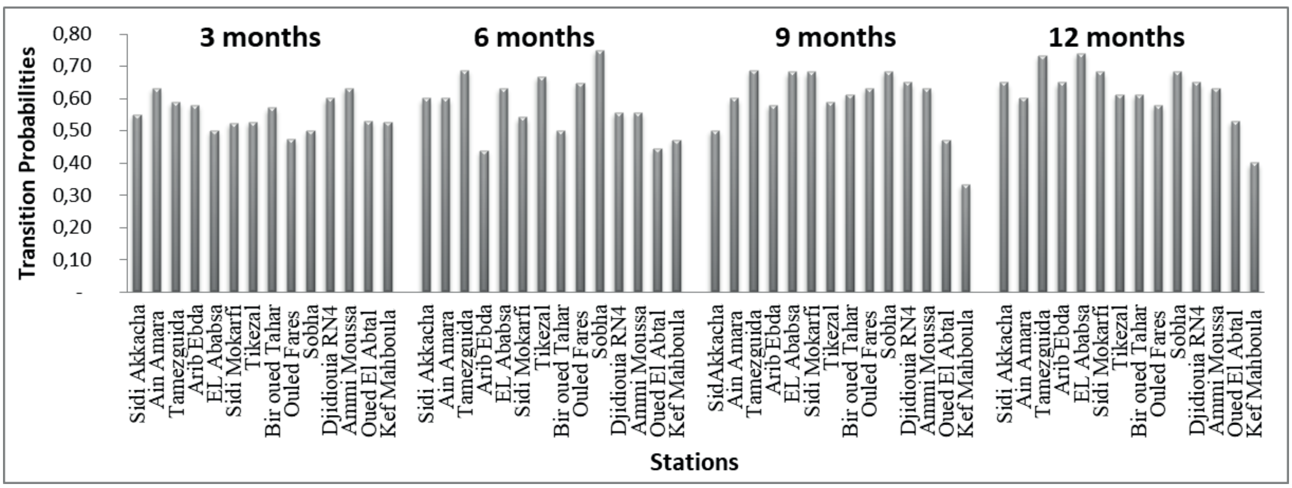

Figure 10. Transition Probabilities (D-D) for the First-Order.

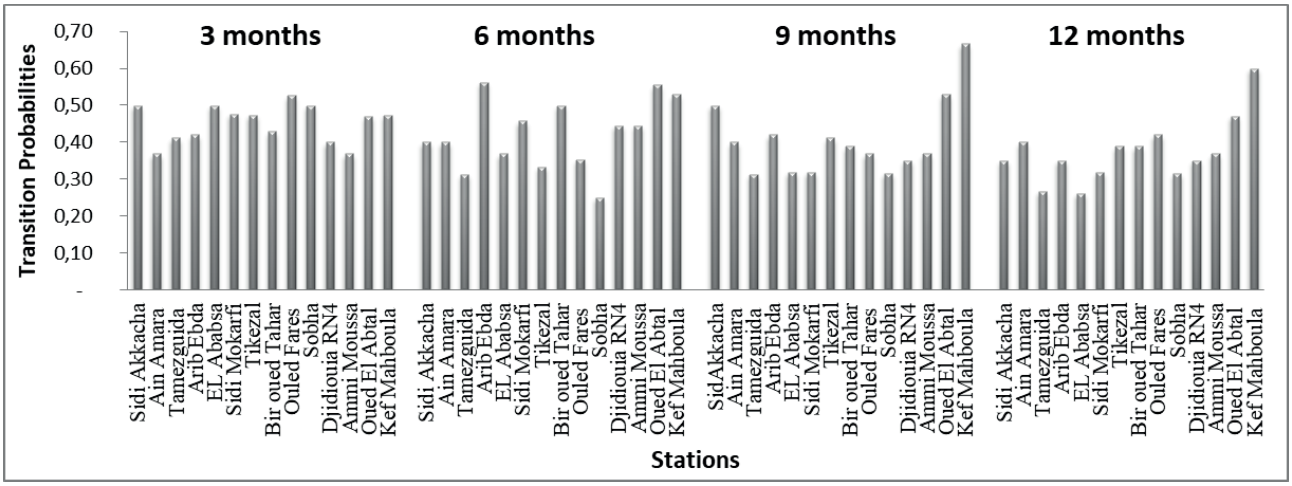

Figure 11. Transition Probabilities (D-W) for the First Order.

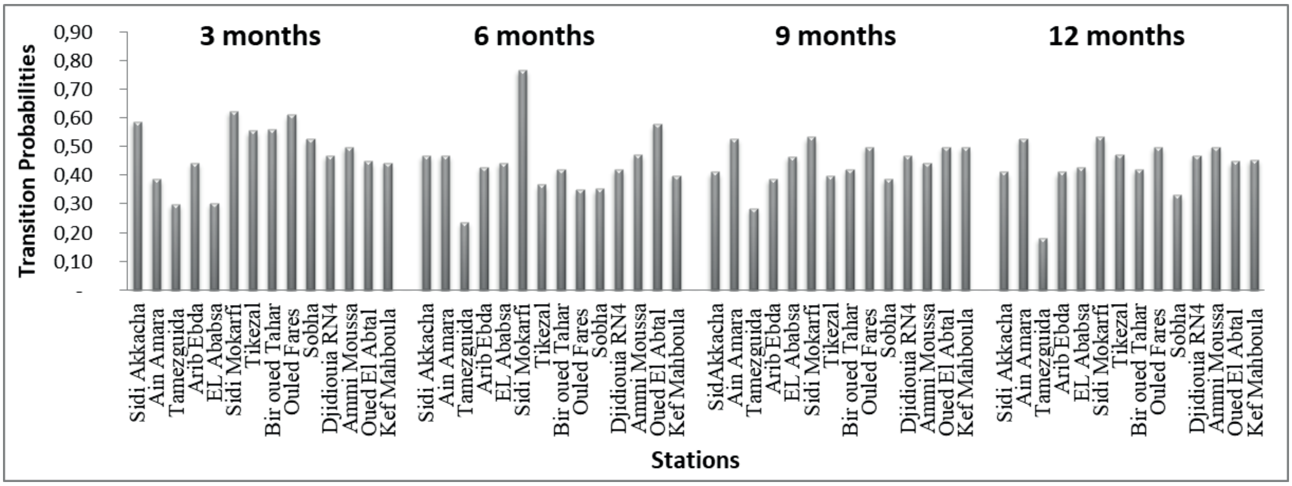

Figure 12. Transition Probabilities (W-D) for the First Order.

ing between 50% and 69%. In the Lower Cheliff and the Mina basins, however, it ranged between 33% and 65%.

For the 3-month scale, the probability of a dry year followed by a wet year (D-W, Fig. 11) revealed a decreasing east-west gradient of 53% (Ouled Fares) to 37% (Ammi Moussa). However, for the same stations, the 6-month transition probability was 31% to 0.56% (Middle and Upper Cheliff), 40% (Coastal), and 44% to 56% (Lower Cheliff and the Mina). The transition probabilities for D-W on a 9-month time scale showed a high probability at the Kef Mahboula station (67%). On the other hand, probabilities of between 31% and 0.41% were found in the Middle and Upper Cheliff basins. In the Coastal basin, the probabilities (D-W) were rather high (> 40%). The probability of transition (D-W) of 14 stations showed a north-south trend of 35% to 60% during a 12-month time scale, with minimum values recorded at the levels of El Ababsa (26%) and Tamesguida (27%).

The transition probability of a wet state followed by a dry state (W-D, Fig. 12) was revealed by an east-west gradient from 63% to 30%.

In the Middle and Upper Cheliff basins, the probabilities (W-D) on a 6-month time scale ranged from 30% to 63%. In the meantime, the remaining stations in these basins ranged from 32% to 58%. It's also worth noting that the study's stations had nearly identical transition probabilities (W-D) for the two scales, 9-month and 12-month (between 18 and 53%).

On a 3-month scale, the probability of transiting through two wet years in a row (W-W, Fig.13) ranged

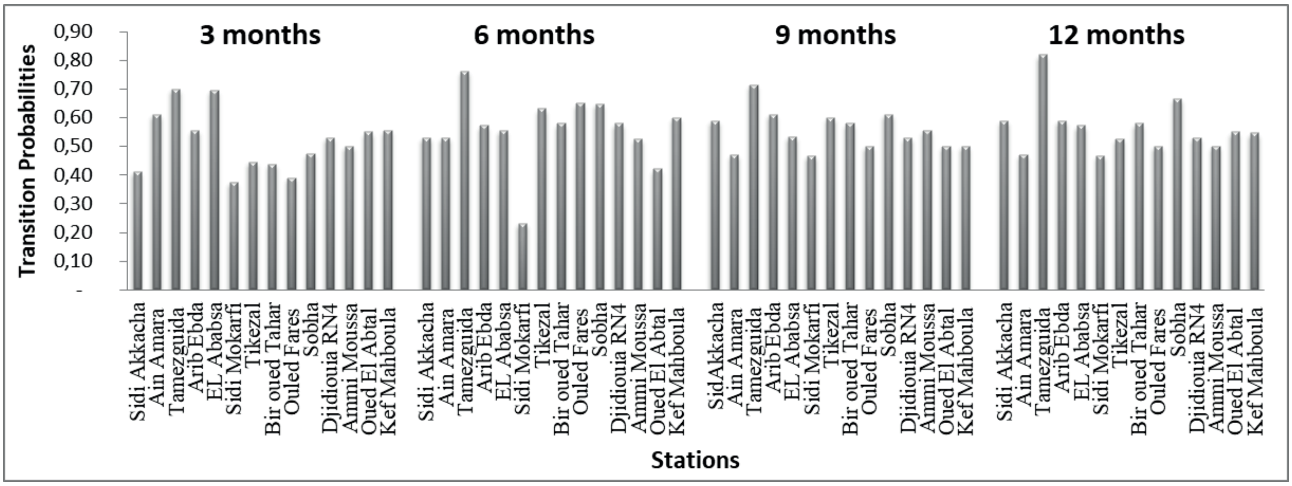

Figure 13. Probability of transition W-W for the first-order.

from 38% to 70%. For example, the two stations Sidi Mokarfi and El Ababsa in the Middle and Upper Cheliff basins were determined by probabilities of 38% (W-W) and 70% (W-W), respectively, and the station Ain Amara in the Coastal basin was determined by a probability of 70% (W-W). The two stations in the Coastal basin recorded the same probability of transition during a 6-month period (53%). In the Middle and Upper Cheliff basins, however, the probability of transition varied between 76% (W-W, Tamesguida) and 23% (W-W, Sidi Mokarfi).

Comparatively, the stations in the Lower Cheliff and the Mina basins recorded probabilities ranging from 40% (W-W, Oued El Abtal) to 60% (the Mina) (W-W, Kef Manboula). In the Lower Cheliff and the Mina basins' and in the Coastal basin's 12-month time scale, probabilities corresponding to 47%-59% were recorded for the two consecutive years (1st order Markov chain, W-W). The stations of the Middle and Upper Cheliff basins, on the other hand, had values ranging from 47% in Sidi Mokarfi to 82% in El Ababsa.

Comparison with previous studies

The balance between resources and needs is an important indicator that guides us in correcting the future of water policy to mitigate the effects of the deficit in all sectors. It is clear that the North African country of Algeria is experiencing a severe resource shortage at a time when demand is growing and the available water supply is shrinking. This is due to a variety of natural and human-caused issues that affect water catchment sites (siltation of dams (3%), or 34 million m3/year in 2000).

Northern Algeria has been exposed to hydrological drought (Nekkache et Megnounif Abdessalem, 2011; Rahmouni et al., 2022). During the different periods 3, 6, 9 and 12 months, the Lower Cheliff and the Mina, Middle and Upper Cheliff, and Coastal Dahra basins were subjected to severe drought with maximum intensity as high maximum values were recorded for example (-2.42) and observed between 7519 and 1995. These results are confirmed by several research works in northern Algeria, for example Meddi et al 2014, showed by a hydrological analysis of drought based on SDI that almost all stations in the Tafna basin (northern Algeria) have suffered from drought during the study period and especially after 1975. Additionally, extreme droughts occurred most frequently after 1975. Bendjemaa et al (2019) showed by the SSFI index that the Bouchegouf station is the most affected by continuous drought conditions in the periods 1987/1988 to 2001/2002 and 2005/2006 to 2009/2010. Nekkache and Megnounif (2011) showed by Standardized Streamflow Index (SSFI) that the two basins of Meffrouche and Béni Bahde (northern Algeria) experienced extreme drought which reached -2.30. Nekkache and Megnounif (2013) showed a deficit of 30% for precipitation after 1970 which caused a drop in flow of more than 60% da in the supply basin of the Meffrouche dam (North-West of Algeria. The driest hydrological years were 1991-1993 and 2005-2006, and that a time scales of 12 months was the most appropriate for developing an effective drought mitigation strategy (Atallah et al., 2022). Brouziyne et al., 2020, the Bouregreg watershed (Marocco) exhibited several dry years with a higher frequency and a significant decrease in annual water inflows were simulated during dry years, ranging from -45.6 %. Tareke and Awoke (2022) showed by SDI index that 1984/85, 1986/87, 2002/03 and 2010/11 were the most severe and extreme drought years in the river basins of Tekeze, Abbay and Baro.

Hydrological drought and Markov chains have been studied by many researchers, e.g. Nalbantis and Tsakiris (2009); Tabari et al.,2015; Yeh et al., 2015 and Rahmouni et al., 2021 ; Hasan et al., 2021. Our results by the SDI drought index and the transition probabilities indicate that the study area is sensitive to hydrological drought. On the other hand, Meddi et al 2009 and Habibi et al 2018 showed that northern Algeria experienced severe drought by SPI index and Markov chains.

CONCLUSION

This study used statistical methods to investigate hydrological drought in three semi-arid basins (the Coastal basin, the Middle and Upper Cheliff basins, and the Lower Cheliff and the Mina basins). The statistical treatment of hydrological data allowed researchers to investigate drought frequency and persistence using a first-order Markov chain for the period of 1973-2009. The study area consisted of 14 hydrometric stations distributed across three basins.

Different time scales (3, 6, 9, and 12 months) were examined to fully understand the hydrological drought. The results obtained from the SDI values in this study showed that the frequency of drought episodes varied significantly in terms of both time and region. Meanwhile, since 1980, most of the stations have experienced increased hydrological drought.

The results obtained by the SDI index at different time scales showed that hydrological drought was dominant over the entire study area. Mild drought, on the other hand, was defined by a frequency of greater than 5% but less than 21%. Moderate drought episodes had a frequency of between 5% and 18%, whereas severe and extreme drought years had a low percentage (about 4% to 1%). Furthermore, the SDI calculation for periods of 3, 6, 9, and 12 months revealed that almost all the stations experienced moderate-to-mild drought throughout the study period.

For the time scales of 6, 9, and 12 months, the transition probability of first-order non-stationary Markov chains showed that two years of drought (D-D) were more likely in the Middle and Upper Cheliff basins (> 60%). On a three-month scale, the transition probabilities (D-D) were greater than 50% in the Coastal basin and in the Lower Cheliff and the Mina basins, and less than 50% in the Middle and Upper Cheliff basins.

This research highlighted the relevance of studying hydrological drought and how it affects water resource management. The organizations and managers of water resources are responsible for monitoring and controlling the indicators of drought. In the meantime, the interventions to consider: optimization of water resource management, improvement of irrigation techniques to reduce losses and maximize the use of water resources and then structural works (dams, etc.)

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