Characterization of Climatic Drought Sequences in the Upper Moulouya Watershed, Morocco

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ABSTRACT

Like most of the countries of the African continent and the MENA, Morocco has experienced alternating wet and dry periods for several decades and is still confronted with the effects of unstable climate change due to the specificities conferred by its geographical position and the diversity of its ecosystems. It is one of the countries most affected by desertification, with an arid and semi-arid climate covering more than 93% of its territory. Indeed, the Upper Moulouya watershed has been exposed to severe droughts several times in recent decades. The spatial and temporal distribution of drought episodes in this watershed is studied over a 91-year period between 1931 and 2022. In order to characterize and evaluate the severity and sustainability of drought in this watershed, four indices were used and applied in this study, as they have advantages in terms of statistical consistency and have the capacity to describe, through different time scales (short, medium and long) the impacts of the climatic drought in question. These are the Standardized Precipitation Index SPI, RDI, RI and DI. The annual rainfall series at the eight meteorological stations of the said watershed show irregularities and very marked spatial and temporal variability with a generally decreasing trend. The SPI calculation results obtained show a heterogeneous distribution of SPI values throughout the watershed area. The analysis of the graphical illustrations of this index allowed to highlight an important fluctuation of the dry and wet periods with a strong dominance and tendency to drought with the order of 51% in the stations of Midelt, and Ansegmir, 52% in the station of Zaida, 59% in the stations of Tabouazant, Barrage (Dam) Enjil and El Aouia, 58% in the station of Louggagh, 47% in the station of Anzar Oufounes. The analysis of the results of the of the drought indices RDI, RI and DI at the level of this watershed also made it possible to highlight the existence of numerous drought sequences alternating with other wet sequences and indicates a dominance of dry years, perfectly remarkable during the period 1976-93. The most important dry episode, in number of successive years, was recorded at the Ansegmir station from 1976-89 and the most important rainy episode was recorded at the Midelt station from 1966-76. The years of the 2015-2022 series show an overall persistent decrease in rainfall, thus allowing the installation of a severe drought episode. The trend in the entire watershed is a decrease in rainfall and the installation of mild, moderate and severe drought episodes of varying length and duration.

Keywords: drought, precipitation, temperature, flow, Upper Moulouya watershed, SPI, RDI, RI, DI, Morocco.

INTRODUCTION

Drought is a dangerous natural phenomenon of insidious character that affects several countries and poses many problems throughout the world due to its immediate and long-lasting repercussions on human-related socio-economic activities and on the proper ecological functioning of ecosystems. It is also characterized by a decrease or misdistribution or even an absence of rainfall in a given area over a period of time and is one of the most important natural hazards that negatively affect natural water resources in human society for generations (Bootsma et al., 1996).

Drought assessment and prediction provide valuable and relevant information for water resource planners and policy makers to cope with the consequences of drought and to subsequently define adaptation or mitigation strategies on human-related socio-economic activities and on the ecological functioning of ecosystems.

To cope with this drought, several indices have been developed and used by meteorologists and climatologists to assess the severity of drought that are related to hydro meteorological variables. Among the most popular drought indices are: the Palmer Index (Palmer, 1965), the Surface Water Supply Index (Shafer and Dezman, 1982), the Standardized Precipitation Index (McKee et al, 1993), Effective Drought Index (Byun and Wilhite, 1999), Flow Drought Index (Nalbantis and Tsakiris, 2009), Standardized Hydrological Index (Sharma and Panu, 2010), Standardized Maximum Evapotranspiration Index (Vicente-Serrano et al., 2010), Regional Drought Area Index (Fleig et al., 2011) and Agricultural Drought Reference Index (Woli & al., 2012). In this study, the Standardized Precipitation Index (SPI), the Rainfall Deficit Index (RDI), the Rainfall Index (RI) and the Drought Index (DI) are the most popular and adopted for the assessment of drought severity in the Upper Moulouya watershed during the period between 1931–2022.

Drought has always been present in the history of Morocco. Some studies on climate change in Morocco indicate that rainfall is much more contrasted with a strong spatiotemporal variability, an increase in temperatures and a remarkable frequency of drought in recent decades (Elbouqdaoui, et al., 2006; Driouech, 2010; Sebbar, 2013).

Indeed, this watershed is characterized globally by an arid, dry mesothermal climate with a marked mountainous tendency, strongly contrasted with a rainfall and hydrological regime dominated by a very strong irregularity in time and space. In such a variable and unstable climatic situation, the present work has set itself the objective of analysing the meteorological drought sequences on an annual scale in the said watershed. The analysis of the results of the calculation of the different selected indices has made it possible to highlight the existence of an alternation and succession of repetitive, prolonged and persistent dry years (dry episodes) and exceptional wet years (wet episodes) and indicate that the last decades of the series examined are generally characterized by a rainfall deficit (accentuated decrease in rainfall) and present a clear tendency towards an increase in the drought sequences.

The analysis of the results relating to the interannual evolution of the Index (SPI) in correlation with the measured flows of the Wadi (River) Ansegmir, has made it possible to highlight the existence of a very significant correlation showing a strong harmony between the annual values of SPI and the measured annual average flows.

STUDY AREA

The Upper Moulouya watershed is a depression with an elongated triangular shape, open towards the NE and following the middle Atlas direction (NE-SW) and covering an area of 4,500 km², 85% of which are plains and 15% mountains. It constitutes the upstream part of the Moulouya watershed. It is bordered to the south by the reliefs of the High Atlas, to the north by the Middle Atlas and is extended by the basin of the Middle Moulouya beyond the Ksabi fault (Fig. 1). The average altitude of the plains is around 1600 m. The maximum altitudes of the Middle Atlas vary between 2000 and 2300 m, while the High Atlas culminates at 3680 m (Jbel Ayachi). The Midelt plain unfolds its steppe (Alfa) within an almost monotonous framework that extends from the foothills of the Jbel Ayachi mountain in the south to the heights dominating the Ansegmir Wadi towards the north.

Towards the North-West, the Middle Atlas range is separated from the High Atlas by the Tizi-n-Tanout o Filal. The region is largely open to the influences of the high plateaus to the East and to the influences of the Middle Atlas and the High Atlas. These two chains form an orographic funnel whose layout evokes the shape of a divergent longitudinal gutter into which cloud masses, and it also constitutes a wind corridor, narrow in its western part and flared in its eastern part.

The climate of this watershed is arid, dry mesothermal, with a marked mountainous tendency. The average annual rainfall is very variable throughout the basin and is closely linked to altitude and exposure. This irregularity is a limiting factor both for the regional socio-economic development due to the decrease of water resources and the accentuation of extreme hydrological phenomena such as floods and droughts.

The annual rainfall modulus oscillates around 290 mm. The number of rainy days per year averages between 40 and 70 depending on the rainfall station. Maximum rainfall is generally recorded
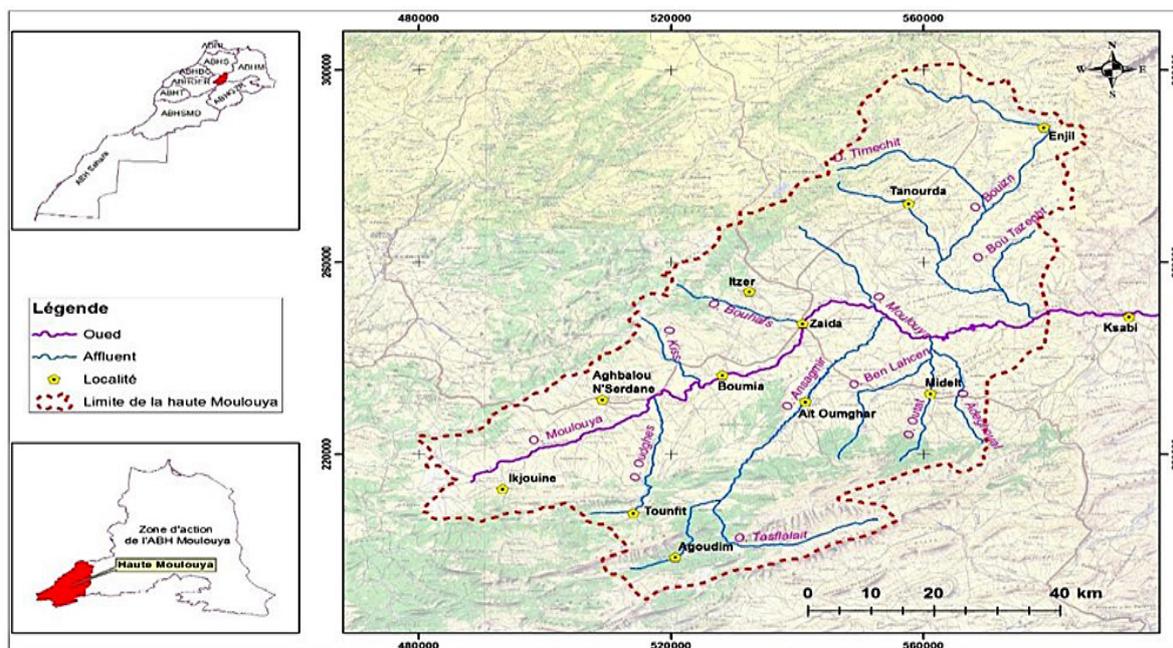
Figure 1. Geographical location of the Upper Moulouya watershed

in April, May and September, with minimums generally observed in June, July and August. The rainfall regime of the Upper Moulouya watershed offers the possibility of rainfall throughout the year and is essentially characterized by two seasons, the first of wet autumn and spring separated by a relatively weak winter season, and the second of dry summer marked by drought.

The presence of snow-covered surfaces in the area is always detected in winter, but with very variable cover. The first snowfalls in October and November are not unusual, but the ground does not remain covered for very long and the melting episodes on these occasions can be relatively short (less than two days). The analysis of the data shows that these early falls or pre-snowfalls are very irregular and very rare in October and relatively more constant in November. As for late snowfalls, spring snowfalls are more frequent, but they show a clear inclination towards the month of March, whereas in April snowfalls occur one year out of two. Moreover, this spring snow cover does not last for more than two days due to the consecutive sunshine.

The most subjective floods are those which are the result of exceptional and very intense showers and generally occur in autumn; they are very violent and devastating and can cause damage (particularly to the ground and banks).

In terms of temperature, this region is generally characterized by often severe, long and cold winters, marked by peaks of negative minimum temperatures. Summers are very hot but bearable because of the dryness of the air. The average annual temperatures vary according to altitude and continental location. The lowest average minimum temperatures are recorded in January and December. On the other hand, the months of July and August have the highest values. The average minimum temperatures range from 0.7°C in January to 16.6°C in July and the average maximum temperatures range from 12°C in December to 32.6°C in July. The monthly averages range from 6.5°C in December to 24.4°C in July. January is therefore on average the coldest month, while July is the warmest.

The dominant winds come from the west in winter and are very violent, dry and cold. In summer, the Chergui, coming from the SE, blow frequently, the winds are swirling and are accompanied by dust. The average wind speed is lowest in October (14 m/s) for all directions, and highest in December and February (28.4 m/s). Nevertheless, gales are not exceptional, sometimes reaching gusts of 187 km/h during extremely violent episodes as was the case in 1973, 1974 and 1987.

As for the hydrological context, the Upper Moulouya watershed covers 4 500 km², 85% of which is plain and 15% mountainous. It is drained by a very dense hydrography, of which the Moulouya Wadi is the main collector of the basin, which has its source at Alemsid in the junction zone of the

two Atlas Mountains. Its course takes a NE bisecting direction between the Middle-Atlasic NNE and High-Atlasic ENE directions and receives along its course a very large number of tributaries of which the rare perennial ones are the Ansegmir Wadi and the Sidi Ayad Wadi. The tributaries on the right bank are all of high atlas origin (Oudrhès Wadi, Ansegmir Wadi and Outat Wadi) and those on the left bank are of medium atlas origin (Kiss Wadi, Aguersif Wadi and Boulajoul Wadi).

The flow regime of the Moulouya Wadi and its main tributaries is very irregular. The low flows of the Moulouya Wadi generally last from June to October, with high water beginning in October. The low water flows of the Wadi Ansegmir are higher than those of the Moulouya, the presence of important springs in the high Atlas basin of the Ansegmir Wadi conditions its regime (ABHM. 2018).

DATA AND METHODS

Climate data

The basic data used in this research are essentially monthly and annual rainfall records spread over a 92-year period between 1931 and 2022 from eight climatic stations covering the entire study area. These data were made available to us by the Moulouya Wadi Basin Agency of Oujda (ABHM) and completed by applying the method of the weighted average with respect to the annual trend of these stations (Anctil F. et al., 2012). The coordinates and climatic characteristics of the stations selected in this study are illustrated in Table 1. The choice of these stations is determined by the availability of climatic data series and was also carried out in such a way as to provide the most homogeneous coverage of the study area.

The eight stations were selected according to criteria of continuity, duration of available information and data quality.

The analysis of the rainfall series of the study area shows that the annual and interannual rainfall variations are very irregular in time and space and indicates that the highest and lowest rainfall amounts are respectively 544.5 mm/year, recorded in 1962/63 and 83.7 mm/year in 1945/46 at Midelt station, 493.3 mm/year, recorded in 1959/60 and 88.5 mm/year in 2020/21 at Ansegmir station, 590. 7 mm/year, recorded in 1975/76 and 114 mm/year in 1992/93 at Zaida station, 678.3 mm/year, recorded in 1995/96 and 190.1 mm/year in 1982/83 at Tabouazant station, 686.6 mm/year, recorded in 1995/96 and 139.7 mm/year in 2021/22 at Louggagh station, 679. 5 mm/year, recorded in 1995/96 and 145 mm/year in 2021/22 at the station of Anzar Oufounes, 581.7 mm/year, recorded in 2008/09 and 115.3 mm/year in 2015/16 at the station of Barrage Enjil and 676.8 mm/year, recorded in 2009/10 and 110.9 mm/year in 1992/93 at the station of El Aouia.

Figure 2 shows that the months of June, July and August generally represent the minimum monthly rainfall in most stations, and are therefore relatively dry. On the other hand, it is in April, May, September and November that the maximum average rainfall is recorded, these being the wettest months of the year.

Methods

To characterize and assess the degree of severity and sustainability of drought in this watershed, four indices were used and applied in this study as they have advantages in terms of statistical consistency, and have the capacity to describe, across different time scales (short, medium and

Table 1. Characteristics of the main stations in the Upper Moulouya watershed

| Station	Coordinates		Atitudes Z (m)	Observation period	Size of the series	Average rainfall (mm)	Standard deviation	Coef. variance (%)
	X (m)	Y (m)						
Midelt	561.800	231.200	1.520	1931-2022	91	210,1	80,4	38%
Ansegmir	545.500	238.600	1.400	1931-2022	91	212,1	69,2	33%
Zaida	541.100	247.000	1.470	1931-2022	91	222,1	74,5	34%
Tabouazant	541.150	217.450	1.640	1976-2022	46	340,5	103,8	30%
Louggagh	530.900	201.000	1.900	1967-2022	55	370,7	137,7	37%
A.Oufounes	522.850	204.000	1.855	1990-2022	32	339,4	119,6	35%
Barrage Enjil	571.000	292.500	1.750	1990-2022	32	291,3	104,6	36%
El Aouia	567.100	294.250	1.790	1990-2022	32	339,1	120,3	35%
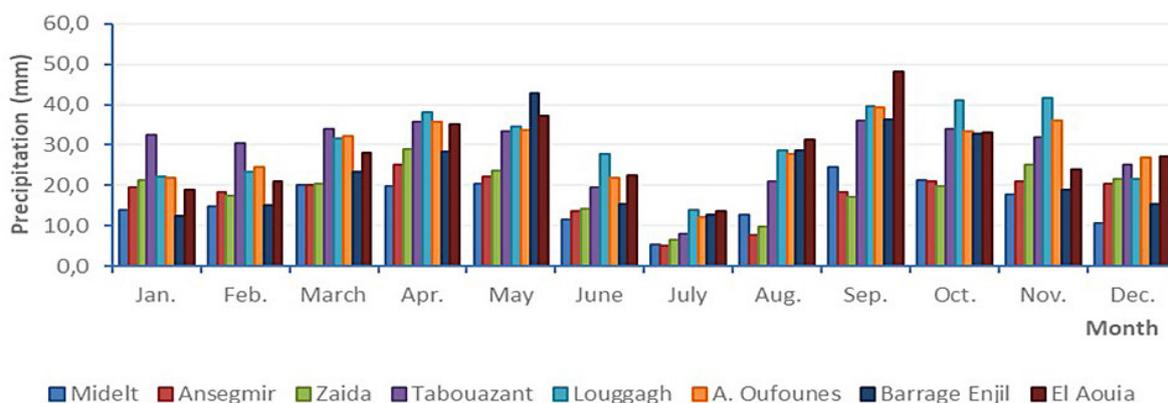
Figure 2. Average monthly precipitation observed at the eight stations of the Upper Moulouya watershed

long term) the impacts of the climatic drought in question. These are the Standardized Precipitation Index (SPI), the Rainfall Deficit Index (RDI) (Bhalme and Mooley, 1979), the Rainfall Index (RI) and the Drought Index (DI).

Standardized precipitation index

The standardized precipitation index (SPI) is an index designed and developed by T.B. McKee, N.J. Doesken and J. Kleist, Colorado State University in 1993 to quantify precipitation deficit at multiple time scales. It is powerful, flexible, very simple and effective in analysing both wet and dry periods or cycles. It was adopted in 2009 by the World Meteorological Organization (WMO) as a global instrument for measuring meteorological droughts, under the terms of the "Lincoln Declaration on Drought Indices" (Jouilil et al., 2013). The necessary parameters required to calculate the SPI are only long-term annual precipitation records spanning at least 20 to 30 years, but preferably 50 to 60 years or more (Guttman, 1994). The SPI is expressed mathematically by the following formula :

$$SPI = (Xi – Xm) / Si \qquad (1)$$

where: Xi – is the cumulative rainfall for year i (mm);

Xm – is the average annual rainfall observed for a given series (mm);

Si – is the standard deviation of the annual rainfall observed for a given series

The intensity of the drought episodes is assessed according to the value of the obtained index. Precipitation is above the median when the SPI values are positive and below the median when the SPI values are negative. It is also

possible to represent humid and arid climates in the same way, as the index is standardized. The classification system adopted and used by McKee et al (1993) is shown in the table of SPI values below (Table 2). It defines the criteria for a drought event on any time scale. A drought occurs when the SPI is consecutively negative and its value reaches an intensity of -1 or less and ends when the index becomes positive. Therefore, for each drought episode a duration, with a beginning and an end, and an intensity for each month in which the episode continues is distinguished.

The fact that the index is normalized allows for the determination of the infrequency of a current drought event (Table 3), as well as the probability of sufficient precipitation to end it (McKee et al., 1993). It also allows the user to confidently compare past and current droughts between different climatic and geographical areas when assessing how often a given drought event occurs.

Rainfall deficit index

The rainfall deficit index (RDI), also known as the deviation from normal, makes it possible to estimate the point variation in rainfall in relation

Table 2. Drought classes according to the SPI (Mckee and al., 1993)

Values of the SPI index	Drought sequences
2.0 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
from -0.99 to 0.99	Near normal
from -1.0 to -1.49	Moderately dry
from -1.5 to -1.99	Very dry
-2 and below	Extremely dry

Table 3. Probability of occurrence (Mckee and al., 1993)

SPI Index	Category	Number of times over 100 years	Frequency
From 0 to -0.99	Mild drought	33	1 time every 3 years
From -1.0 to -1.49	Moderate drought	10	1 every 10 years
From -1.5 to -1.99	Severe drought	5	1 every 20 years
-2 and below	Extreme drought	2	1 time every 50 years

to the normal and to visualize and determine the number of deficit years and their succession. A year is considered wet if this index is positive and dry if it is negative. The accumulation of the indices of successive years makes it possible to identify the main trends, disregarding the slight fluctuations from one year to the next. If the sum of the deviations increases, it is a wet trend, if the sum of the deviations decreases, it is a "dry" trend. The rainfall deficit index (RDI) is calculated from the following formula:

$$RDI\,(\%) = ((Pi - Pm)/Pm) \times 100 \quad (2)$$

where: *RDI* – rainfall deficit index in %,
       Pi – annual rainfall in mm,
       Pm – average rainfall in mm.

If the RDI value is greater than 0, the year is said to be wet or surplus. If the RDI value is less than 0 then the year is said to be dry or in deficit.

Rainfall index

The rainfall index (RI) is defined as the ratio of the rainfall in a year to the annual average rainfall in the series. It is expressed by the following formula:

$$RI = Pi/Pm \quad (3)$$

A year is said to be wet if this ratio is greater than 1 and dry if it is less than 1. According to the principle of this index, a station is considered wet when the sum of the peaks indicating wet years is the most dominant.

Drought index

The drought index (DI) is used to estimate the annual rainfall deficit. This deviation from the average is the difference between the rainfall in a year Pi and the average annual rainfall P of the series. It is expressed by the following formula :

$$DI = Pi - P \quad (4)$$

The index is positive in wet years and negative in dry years.

RESULTS

Trend and variability of annual rainfall in the Upper Moulouya watershed

The Upper Moulouya watershed is characterized by a random distribution of rainfall, essentially due to the relief and the specific features of its geographical position. The annual rainfall series at the eight meteorological stations show irregularities and very marked spatial and temporal variability. To study their trend, we used linear regression, which seems better suited to the study of progressive phenomena such as the effects of climate change. The analysis of the graphs (Figure 3) showed a generally decreasing trend in annual rainfall for all the stations, while highlighting the overall decrease in humidity and the regular installation of a drought, with values of the linear regression slope varying between -0.211 and -6.071.

Characterization of drought in the Upper Moulouya watershed – SPI

At the level of the different stations concerned in the Upper Moulouya watershed, the evolution of the drought severity degrees was analysed using the SPI calculated from several rainfall series of 91, 55, 46 and 32 years, during the period 1931–2022. The obtained SPI calculation results are shown in Tables 4–5 and Figure 4 and show a heterogeneous distribution of SPI values over the whole watershed area. The analysis of the meteorological dryness from the graphical illustrations of this index allowed to highlight an important fluctuation of the dry and wet periods with a strong dominance and tendency to the dryness with the order of 51% in the station of Midelt, 51% in the station of Ansegmir, 52% in the station of Zaida, 59% in the station of Tabouazant, 58% in the station of Louggagh, 47% in the station of Anzar Oufounes, 59% in the station of Barrage Enjil and 59% in the station of El Aouia. The analysis of the results of the calculation of
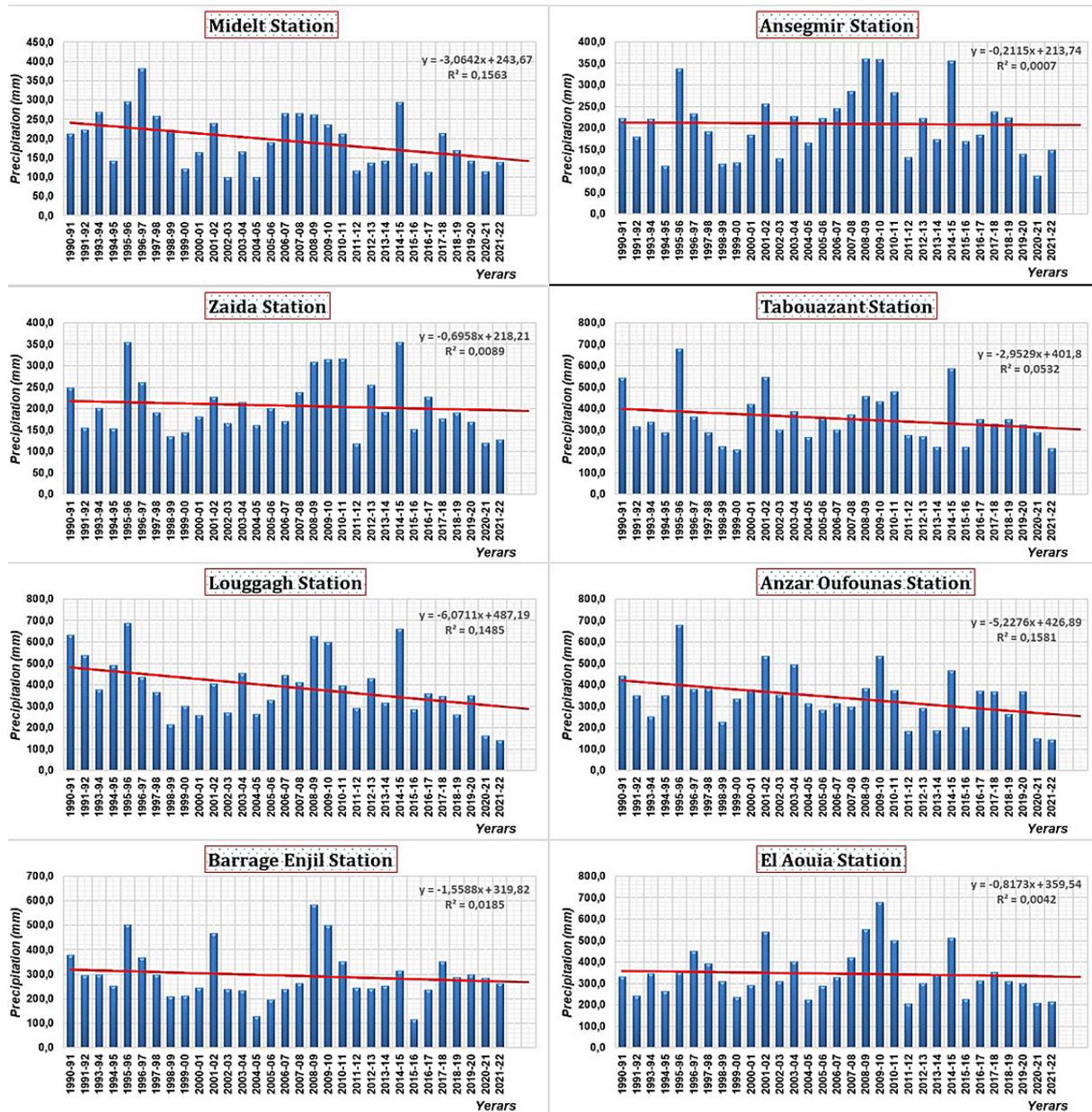
Figure 3. Trend and evolution of annual precipitation at the eight meteorological stations of the Upper Moulouya watershed (1990–2022)

the SPI index at the different stations during the period 1931–2022 showed the existence of an alternation between dry and wet years.

Midelt station

This index indicates the existence of numerous drought sequences and subsequently shows a dominance of perfectly remarkable dry years during the period 1976/77–1992/93. It is also observed that the SPI can reach less than (-1.57), which explains the existence of severe drought years (great drought). The existence of several sequences of wet to extremely wet years is also highlighted, the longest of which is during the period 1966/67–1975/76. In

the period 2015/16–2021/22, however, a drying up of the climatic conditions and the onset of a new drought episode are again noted. The classification of drought severity according to the SPI at this station also indicates very high frequencies for slightly dry sequences (36%) recorded during 33 years, moderate frequencies for moderately dry sequences (12%) observed during 11 years and very low frequencies for severely dry sequences (2%) recorded during 2 years.

Ansegmir Station

In fact, throughout the period analysed, this index highlights the existence of several
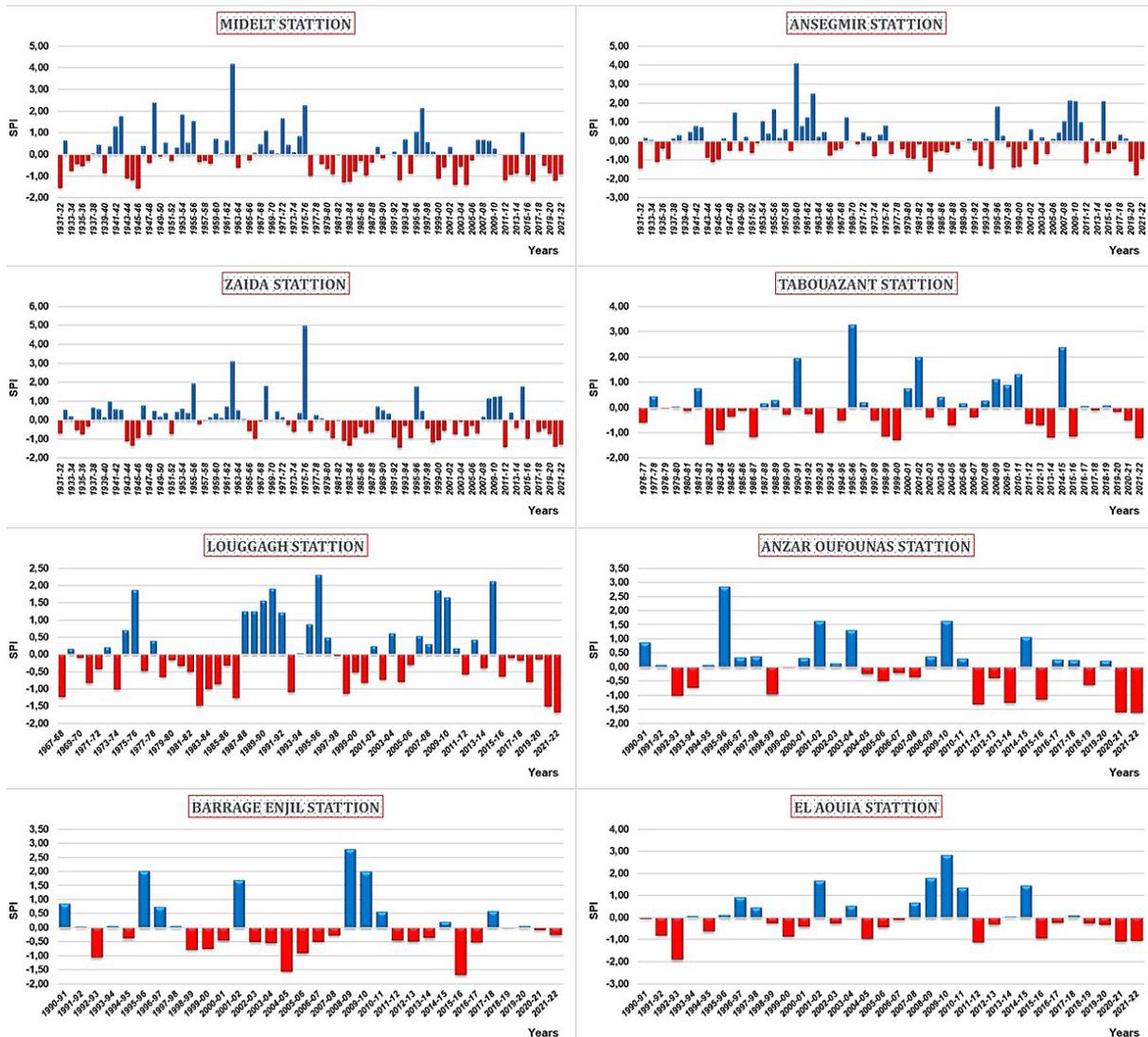
Figure 4. The trend of SPI in the Upper Moulouya watershed (1931–2022)

drought sequences and indicates a dominance of dry years perfectly identified during the period 1976/77–1992/93 and subsequently shows numerous slightly dry sequences recorded during 34 years with very high frequencies of the order of (37%), moderately dry observed during 10 years with modest frequencies of the order of (11%) and severely dry observed during 2 years with very low frequencies of the order of (2%). It is also observed that the SPI can reach a value of less than (-1.79), which explains the existence of years of great drought (severe drought). We also note the existence of several sequences of wet to extremely wet years, the longest of which occurred during the period 2005/06–2010/11. Whereas during the period 2019/20–2021/22, it is noted that these years are deficient and have proved to be much drier to allow the installation of a drought episode again.

Zaida Station

This index highlights the existence of numerous drought sequences and subsequently shows a dominance of perfectly remarkable dry years in the period 1976/77–1987/88. It is also observed that the SPI can reach less than (-1.45), which explains the existence of severe drought years (great drought). The existence of several sequences of wet to extremely wet years is also highlighted. Whereas from 2015/16 to 2021/22, the SPI values become negative again and allow for a new episode of moderate drought. According to this index, the drought classification at this station also indicates very high frequencies on the slightly dry sequences (41%) recorded during 37 years and moderate frequencies on the moderately dry sequences (11%) observed during 10 years.

Tabouazant Station

This index explicitly shows an increasing trend of drought sequences. The most severe drought has been perfectly identified and recorded between 1982 and 1987 with an SPI value of up to (-1.45). In fact, during the 46 years of observations analysed, this index highlights the existence of several drought sequences and subsequently shows numerous slightly dry sequences recorded during 20 years with very high frequencies of the order of (43%), moderately dry sequences observed during 7 years with modest frequencies of the order of (15%). It also clearly shows the existence of several sequences of wet to extremely wet years spread over the periods and years 1977-78, 1979–80, 1981–82, 1987–89, 1990–91, 1995–97, 2000–02, 2003–04, 2005–06, 2007–11, 2014–15, 2016–17, 2018, while during the last period 2019/20–2021/22, it is noted that the values of the SPI become negative (-1.25) to allow the installation of an episode of moderate drought.

Louggagh Station

The SPI index clearly shows an increasing trend of drought sequences, the longest of which was perfectly identified and recorded during the 1976/77–1986/87 period. Indeed, this index highlights the existence of several slightly dry sequences recorded during 23 years with very important frequencies of the order of (42%), moderately dry observed during 7 years with modest frequencies of the order of (13%) and severely dry observed during 4 years with very low frequencies of the order of (2%). It is also observed that the SPI can reach a value of less than (-1.68), which explains the existence of the years of great drought (severe drought). It also clearly shows the existence of several sequences of wet to extremely wet years spread over the periods and years 1968–69, 1972-73, 1974–76, 1977–78, 1987–92, 1993–97, 2001–02, 2003–04, 2007–11, 2012–13 and 2014–15, whereas during the period 2015/16–2021/22, it is noted that these years are deficient and turned out to be much drier to allow the installation of an episode of severe drought again.

Anzar Oufounes Station

This index also indicates the existence of numerous drought sequences spread over the periods between 1992–94, 1998–2000, 2004–08, 2011–14, 2018–22 and clearly shows the existence of several slightly dry sequences recorded

during 9 years with very high frequencies in the order of (28%), moderately dry observed during 4 years with modest frequencies in the order of (13%) and severely dry observed during 2 years with very low frequencies in the order of (6%). It is also observed that the SPI reaches a value of less than (-1.62) in 2021–22, which explains the existence of years of severe drought. It also clearly shows the existence of several sequences of wet to extremely wet years spread over the periods and years 1987–92, 1994–98, 2000–04, 2008–11, 2014–15 and 2017–18, while during the period 2018–2022, it is noted that these deficit years turned out to be much drier to allow the installation of a severe drought episode again.

Barrage Enjil Station

The SPI highlights the existence of several drought sequences observed over the periods between 1998–2001, 2002–2008, 2011–2014 and 2018–2022 and clearly shows that the last years present an increasing trend of drought sequences. Indeed, we observe the existence of several slightly dry sequences recorded during 16 years with very high frequencies in the order of (50%), moderately dry sequences observed during 1 year with modest frequencies in the order of (3%) and severely dry sequences observed during 2 years with very low frequencies in the order of (6%). It is also observed that the SPI reaches a value of less than (-1.68), which explains the existence of the years of great drought.) We also underline the existence of two sequences of wet to extremely wet years, the longest of which are observed during the periods between 1990–92, 1995–98 and 2008–11, whereas during the period 2015–2022, with the exception of the year 2017–18, we notice that these years turned out to be much drier to allow the installation of a severe drought episode again.

El Aouia Station

The SPI highlights the existence of several drought sequences observed over the periods between 1990–93, 1998–2001, 2004–07, 2011–13, 2015–17 and 2018–22 and clearly shows that the latter years show an increasing trend of drought sequences. It can be seen that there are slightly dry sequences recorded for 15 years with very high frequencies of around (47%), moderately dry sequences observed for 3 years with modest frequencies of around (9%) and severely dry sequences recorded for 1 year with very low frequencies of around (3%). It is also observed

Table 4. Frequencies of SPI classes at meteorological stations in the Upper Moulouya watershed (1931–2022)

		Midelt Station						Ansegmir Station			
SPI values	Category	Number of years	Number of times in 100 years	Frequency	Frequency	SPI values	Category	Number of years	Number of times in 100 years	Frequency	Frequency
2.0 and above	Extreme humidity	4	4	23	1 time every 23 years	2.0 and above	Extreme humidity	5	5	18	1 time every 18 years
1.5 to 1.99	Severe humidity	4	4	23	1 time every 23 years	1.5 to 1.99	Severe humidity	2	2	46	1 time every 46 years
1.0 to 1.49	Moderate humidity	4	4	23	1 time every 23 years	1.0 to 1.49	Moderate humidity	5	5	18	1 time every 18 years
From 0 to 0.99	Light moisture	33	36	3	1 time every 3 years	From 0 to 0.99	Light moisture	33	36	3	1 time every 3 years
From 0 to -0.99	Light dryness	33	36	3	1 time every 3 years	Fom 0 to -0.99	Light dryness	34	37	3	1 time every 3 years
From -1.0 to -1.49	Moderate dryness	11	12	8	1 time every 8 years	From -1.0 to -1.49	Moderate dryness	10	11	9	1 time every 9 years
From -1.5 to -1.99	Severe drought	2	2	46	1 time every 46 years	From -1.5 to -1.99	Severe drought	2	2	46	1 time every 46 years
-2 and below	Extreme dryness	0	0	0	No occurrence	-2 and below	Extreme dryness	0	0	0	No occurrence
		Zaida Station						Tabouazant Station			
2.0 and above	Extreme humidity	2	2	46	1 time every 46 years	2.0 and above	Extreme humidity	2	4	23	1 time every 23 years
1.5 to 1.99	Severe humidity	4	4	23	1 time every 23 years	1.5 to 1.99	Severe humidity	2	4	23	1 time every 23 years
1.0 to 1.49	Moderate humidity	3	3	30	1 time every 30 years	1.0 to 1.49	Moderate humidity	2	4	23	1 time every 23 years
From 0 to 0.99	Light moisture	35	38	3	1 time every 3 years	From 0 to 0.99	Light moisture	13	28	4	1 time every 4 years
Fom 0 to -0.99	Light dryness	37	41	2	1 time every 2 years	Fom 0 to -0.99	Light dryness	20	43	2	1 time every 2 years
From -1.0 to -1.49	Moderate dryness	10	11	9	1 time every 9 years	From -1.0 to -1.49	Moderate dryness	7	15	7	1 time every 7 years
From -1.5 to -1.99	Severe drought	0	0	0	No occurrence	From -1.5 to -1.99	Severe drought	0	0	0	No occurrence
-2 and below	Extreme dryness	0	0	0	No occurrence	-2 and below	Extreme dryness	0	0	0	No occurrence
		Louggagh Station						Anzar Oufounas Station			
2.0 and above	Extreme humidity	2	4	28	1 time every 28 years	2.0 and above	Extreme humidity	1	3	32	1 time every 32 years
1.5 to 1.99	Severe humidity	5	9	11	1 time every 11 years	1.5 to 1.99	Severe humidity	2	6	16	1 time every 16 years
1.0 to 1.49	Moderate humidity	3	5	18	1 time every 18 years	1.0 to 1.49	Moderate humidity	2	6	16	1 time every 16 years
From 0 to 0.99	Light moisture	13	24	4	1 time every 4 years	From 0 to 0.99	Light moisture	12	38	3	1 time every 3 years
Fom 0 to -0.99	Light dryness	23	42	2	1 time every 2 years	Fom 0 to -0.99	Light dryness	9	28	4	1 time every 4 years
From -1.0 to -1.49	Moderate dryness	7	13	8	1 time every 8 years	From -1.0 to -1.49	Moderate dryness	4	13	8	1 time every 8 years
From -1.5 to -1.99	Severe drought	2	4	28	1 time every 28 years	From -1.5 to -1.99	Severe drought	2	6	16	1 time every 16 years
-2 and below	Extreme dryness	0	0	0	No occurrence	-2 and below	Extreme dryness	0	0	0	No occurrence
		Enjil Barrage Station						El Aouia Station			
2.0 and above	Extreme humidity	2	6	16	1 time every 16 years	2.0 and above	Extreme humidity	1	3	32	1 time every 32 years
1.5 to 1.99	Severe humidity	2	6	16	1 time every 16 years	1.5 to 1.99	Severe humidity	2	6	16	1 time every 16 years
1.0 to 1.49	Moderate humidity	0	0	0	No occurrence	1.0 to 1.49	Moderate humidity	2	6	16	1 time every 16 years
From 0 to 0.99	Light moisture	9	28	4	1 time every 4 years	From 0 to 0.99	Light moisture	8	25	4	1 time every 4 years
Fom 0 to -0.99	Light dryness	16	50	2	1 time every 2 years	Fom 0 to -0.99	Light dryness	15	47	2	1 time every 2 years
From -1.0 to -1.49	Moderate dryness	1	3	32	1 time every 32 years	From -1.0 to -1.49	Moderate dryness	3	9	11	1 time every 11 years
From -1.5 to -1.99	Severe drought	2	6	16	1 time every 16 years	From -1.5 to -1.99	Severe drought	1	3	32	1 time every 32 years
-2 and below	Extreme dryness	0	0	0	No occurrence	-2 and below	Extreme dryness	0	0	0	No occurrence

Table 5. Frequency of the drought index at the scale of the Upper Moulouya watershed

Stations	Standardized precipitation index								
	Extreme humidity 2.0 and above	Severe humidity from 1.5 to 1.99	Moderate humidity from 1.0 to 1.49	Light moisture from 0 to 0.99	Light dryness from 0 to -0.99	Moderate dryness from -1.0 to -1.49	Severe drought from -1.5 to -1.99	Extreme dryness -2 and below	Drought tendency
Midelt	4%	4%	4%	36%	36%	12%	2%	0%	51%
Ansegmir	5%	2%	5%	36%	37%	11%	2%	0%	51%
Zaida	2%	4%	3%	38%	41%	11%	0%	0%	52%
Tabouazant	4%	4%	4%	28%	43%	15%	0%	0%	59%
Louggagh	4%	9%	5%	24%	42%	13%	4%	0%	58%
A. Oufounes	3%	6%	6%	38%	28%	13%	6%	0%	47%
Barrage Enjil	6%	6%	0%	28%	50%	3%	6%	0%	59%
El Aouia	3%	6%	6%	25%	47%	9%	3%	0%	59%
Moyenne	4%	5%	4%	32%	41%	11%	3%	0%	54%

that the SPI reaches a value of less than (-1.90), which explains the existence of the years of severe drought. We also note the existence of two sequences of wet to extremely wet years, the longest of which are observed during the periods between 1995–98 and 2007–11, whereas during the period 2015–2022, with the exception of the year 2017–18, we note that these deficit years turned out to be much drier to allow the installation of an episode of severe drought again.

In general, on the different stations studied in the Upper Moulouya watershed, light drought records the highest frequencies at all stations (above 28% with a maximum of 50% at the Enjil Dam station). It is followed by the moderate drought whose maximum is observed at the level of the station of Tabouazant (15%). Except for the stations of Zaida and Tabouazante, the severe drought is identified at the level of the other stations, and records very low frequencies whose maximum is observed at the level of the stations of Barrage Enjil and Anzar Oufounes (6%).

Rainfall deficit index

We note that the values of this index present a strong irregularity for the whole of the stations and that the most important deficit noted during all the period of observation is recorded at the level of the station of El Aouia with a value of the order of -67,3%. The analysis of the results of the calculation of this index at the level of the eight rainfall stations of the watershed between 1931–2022 showed that the most important rainfall deficit, in terms of successive years, was recorded at the Ansegmir station from 1976–77 to 1988–89.

Midelt Station

During the entire observation period (1931–2022), the largest rainfall deficit recorded at this station was of the order of -60.2% in 1945–46. This index (RDI) has made it possible to highlight the existence of an alternation and succession of deficit years (dry) and wet years observed respectively during 46 years (50.5%) and 45 years (49.5%) and clearly shows that the last decades of this series present an increasing tendency of drought sequences. The longest and most significant rainfall deficit, in terms of number of successive years, was recorded during the periods between 1978–1988 and 2015–2022. The first phase was spread over a period of ten years with a maximum rate of -48.6%, while the second phase is spread over a period of seven years with a maximum rate of -46.6%. The longest and most significant excess rainfall, in terms of number of successive years, observed during 1931–2022, was recorded during the periods between 1966–1976 (10 years) with a maximum rate of 86.6% and 2006–2011 (5 years) with a maximum rate of 26.5%. The last years of the 2015–2022 series were generally characterized by a marked rainfall deficit with a maximum peak of around -46.6% observed in 2016–17, with the exception of the year 2017–18 which recorded a rainfall excess of around 1.6%.

Ansegmir Station

During the entire observation period (1931–2022), the largest rainfall deficit recorded at this station was of the order of -58.3% in 2020–21. This index (RDI) has made it possible to highlight the existence of an alternation and succession of deficit years (dry) and wet years observed

respectively for 46 years (50.5%) and 45 years (49.5%) and clearly show that the last decades of this series present an increasing trend of drought sequences. The longest and most important rainfall deficit, in terms of number of successive years, was recorded during the periods between 1976–1989 and 1997–2001. The first phase was spread over a period of thirteen years with a maximum rate of -52.1%, while the second phase was spread over a period of four years with a maximum rate of -47.0%. The longest and most significant excess rainfall, in terms of number of successive years, observed during 1931–2022, was recorded during the periods between 1937–1943 (6 years) with a maximum rate of 26.3%, between 1959–1965 (6 years) with a maximum rate of 132.5% and 2005–2011 (6 years) with a maximum rate of 69.8%. The last years of the 2015–2022 series were generally characterized by a marked rainfall deficit with a maximum peak of around -58.3% observed in 2020–21, with the exception of the years 2017–19 which recorded a rainfall excess of around 12.2% and 5.6% respectively.

Zaida Station

During the entire observation period (1931–2022), the largest rainfall deficit recorded at this station was of the order of -46.4% in 1992–93. This index (RDI) shows the existence of an alternation and succession of dry and wet years for 47 years (51.6%) and 44 years (48.4%) respectively, and also clearly shows that the last decades of this series show an increasing trend of drought sequences. The longest and most significant rainfall deficit, in terms of number of successive years, was recorded in the periods between 1979–1988 and 2015–2022. The first phase was spread over a period of nine years with a maximum rate of -44.4%, while the second phase is spread over a period of seven years with a maximum rate of -46.4%. The longest and most significant excess rainfall, in terms of number of successive years, observed during 1931–2022, was recorded during the periods between 1937–1943 (6 years) with a maximum rate of 32.7%, between 1958–1965 (7 years) with a maximum rate of 103.6% and 2007–2011 (4 years) with a maximum rate of 41.6%. The last years of the 2015–2022 series were generally characterized by a marked rainfall deficit with a maximum peak of around -46.4% observed in 2020–21, with the exception of the year 2016–17 which recorded a rainfall excess of around 2.4%.

Tabouazant Station

During the entire observation period (1976-2022), the most significant rainfall deficit recorded at this station was of the order of -44.2% in 1982–83. This index (RDI) has made it possible to highlight the existence of an alternation and succession of dry and wet years observed respectively for 27 years (58.7%) and 19 years (41.3%) and clearly show that the last decades of this series present an increasing tendency of drought sequences. The longest and most significant rainfall deficit, in terms of number of successive years, was recorded during the periods between 1982–1987 and 2015–2022. The first phase was spread over a period of five years with a maximum rate of -44.2%, while the second phase is spread over a period of seven years with a maximum rate of -36.9%. The longest and largest rainfall excess, in terms of number of successive years, observed during 1976–2022, was recorded during the periods from 2007–2011 (4 years) with a maximum rate of 40.2%. The later years of the 2015–2022 series were generally characterized by a marked rainfall deficit with a maximum peak of around -36.9% observed in 2021–22, with the exception of 2016–17 and 2018–19 which recorded excess rainfall of around 2.2% and 3%.

Louggagh Station

During the entire observation period (1967–2022), the largest rainfall deficit recorded at this station is of the order of -62.3% in 2021–22. This index (RDI) has made it possible to highlight the existence of an alternation and succession of dry and wet years observed respectively for 32 years (58.2%) and 23 years (41.8%) and also clearly shows that the last decades of this series present an increasing tendency of drought sequences. The longest and largest rainfall deficit, in terms of number of successive years, was recorded during the periods between 1978–1987 and 2015–2022. The first phase was spread over a period of nine years with a maximum rate of -55.1%, while the second phase is spread over a period of seven years with a maximum rate of -62.3%. The longest and most significant excess rainfall, in terms of number of successive years, observed during 1967–2022, was recorded during the periods between 1987–1992 (5 years) with a maximum rate of 70.6%, between 1993–1997 (4 years) with a maximum rate of 85.2% and 2006–2011 (5 years) with a maximum rate of 68.7%. The last years of
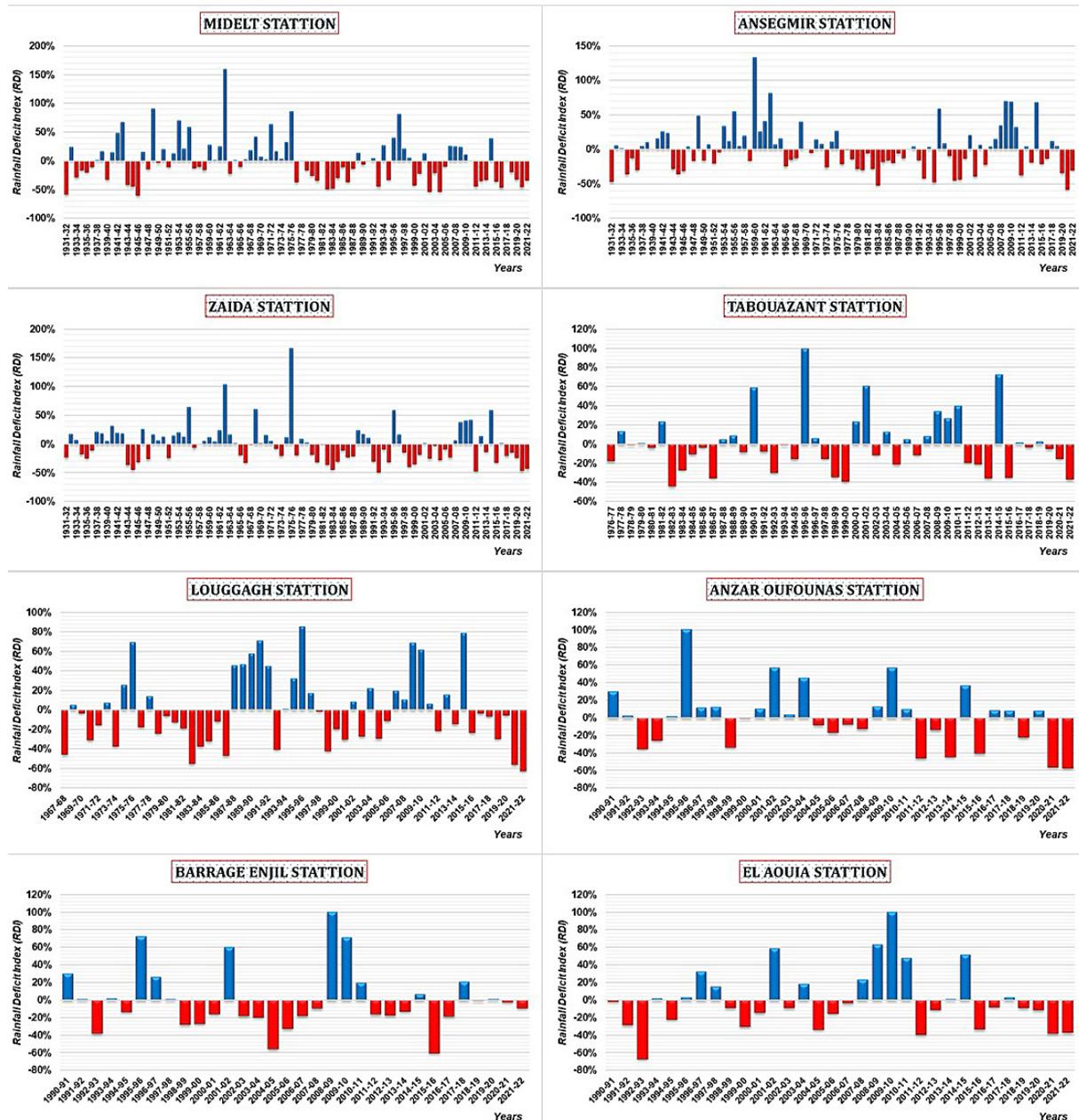
Figure 5, Evolution of the rainfall deficit index of eight rainfall stations in the
Upper Moulouya watershed area over the period 1931–2022

the 2015–2022 series are generally characterized by a marked rainfall deficit with a maximum peak of around -62.3% observed in 2021–22.

Anzar Oufounes Station

During the entire observation period (1990-2022), the largest rainfall deficit recorded at this station is of the order of -57.3% in 2021–22. This index (RDI) has made it possible to highlight the existence of an alternation and succession of dry years (deficit) and wet years observed respectively for 15 years (46.9%) and 17 years (53.1%). The longest and most significant rainfall deficit, in

terms of number of successive years, was recorded during the periods between 2004–2008 and 2011–2014. The first phase was spread over a period of four years with a maximum rate of -16.8%, while the second phase was spread over a period of three years with a maximum rate of -44.7%. The longest and largest rainfall excess, in terms of number of successive years, observed during 1990–2022, was recorded during the periods between 1994–1998 (4 years) with a maximum rate of 100.2% and 2001–2004 (4 years) with a maximum rate of 57.3%. The later years of the 2018–2022 series were generally characterized

by a marked rainfall deficit with a maximum peak of around -57.3% observed in 2021–22, with the exception of 2019–20 which recorded an excess rainfall of around 8.2%.

Barrage Enjil Station

During the entire observation period (1990–2022), the largest rainfall deficit recorded at this station was of the order of -60.4% in 2015–16. This index (RDI) shows the existence of an alternation and succession of dry and wet years for 19 years (59.4%) and 13 years (40.6%) respectively, and also clearly shows that the last decades of this series show an increasing tendency of drought sequences. The largest rainfall deficit, in terms of number of successive years, was recorded during the periods between 2002–2009 and 2015–2017. The first phase was spread over a period of seven years with a maximum rate of -55.9%, while the second phase was spread over a period of two years with a maximum rate of -60.4%. The longest and largest rainfall excess, in terms of number of successive years, observed during 1990-2022, was recorded during the periods between 1995–1998 (3 years) with a maximum rate of 72.2% and 2008–2011 (3 years) with a maximum rate of 99.7%.

El Aouia Station

During the entire observation period (1990–2022), the largest rainfall deficit recorded at this station was of the order of -67.3% in 1992–93. This index (RDI) has made it possible to highlight the existence of an alternation and succession of dry years and wet years observed respectively for 19 years (59.4%) and 13 years (40.6%) and also clearly show that the last years of this series present an increasing tendency of drought sequences. The longest and most significant rainfall deficit, in terms of number of successive years, was recorded in the periods between 1990–1993, 2004–2007 and 2015–2022. The first phase was spread over a period of three years with a maximum rate of -67.3%, the second was spread over a period of three years with a maximum rate of -33.7%, while the third phase was spread over a period of seven years with a maximum rate of -38.3%. The longest and most significant excess rainfall, in terms of number of successive years, observed during 1990–2022, was recorded during the periods between 1995–1998 (3 years) with a maximum rate of 32.8% and 2007–2011 (4 years) with a maximum rate of 99.6%.

The last years of the 2015–2022 series were generally characterized by a marked rainfall deficit with a maximum peak of around -38.3% observed in 2020–21, with the exception of the year 2017–18 which recorded a rainfall excess of around 3.7%.

Rainfall index

Figure 6 shows the evolution of the rainfall index for all the stations studied in the watershed. This index has made it possible to highlight the existence of an alternation and succession of dry and wet years and subsequently to visualize and determine the number of deficit years and their succession. We note that the values of this index show a strong irregularity for all the stations and that the most important deficit noted during the whole observation period (1931–2022) is recorded at the level of the station of El Aouia with a lowest value of the RI which is of the order of 0.33. The analysis of the results of the calculation of this index at the level of the eight rainfall stations made it possible to highlight that the most important dry episode, in number of successive years, was recorded at the station of Ansegmir from 1976–77 until 1988–89 (13 years) and the most important rainy episode was recorded at the station of Midelt from 1966–67 until 1975–76 (10 years). The analysis of the graph relating to the evolution of this index made it possible to highlight that the drought episodes, common to all the stations, are recorded during the periods of 1934–37, 1943–46, 1956–59, 1965v68, 1976–88, 1991–95, 1997–2001, 2002–06, 2011v14 and 2015–22 and are regularly repeated after intervals of 1 to 10 years with an intensity ranging from light to moderate. Wet years become less and less frequent from 1977 to 2022, with a maximum of 2.66 recorded at Zaida station during 1975–76. The years of the 2011–2022 series are generally characterized by a rainfall deficit, the general trend in the entire Upper Moulouya watershed being a decrease in rainfall.

Drought index

The drought index is used to better estimate the annual rainfall deficit of the study area series. The distribution of surplus and deficit rainfall years is plotted for each station in the Upper Moulouya watershed (Figure 7).
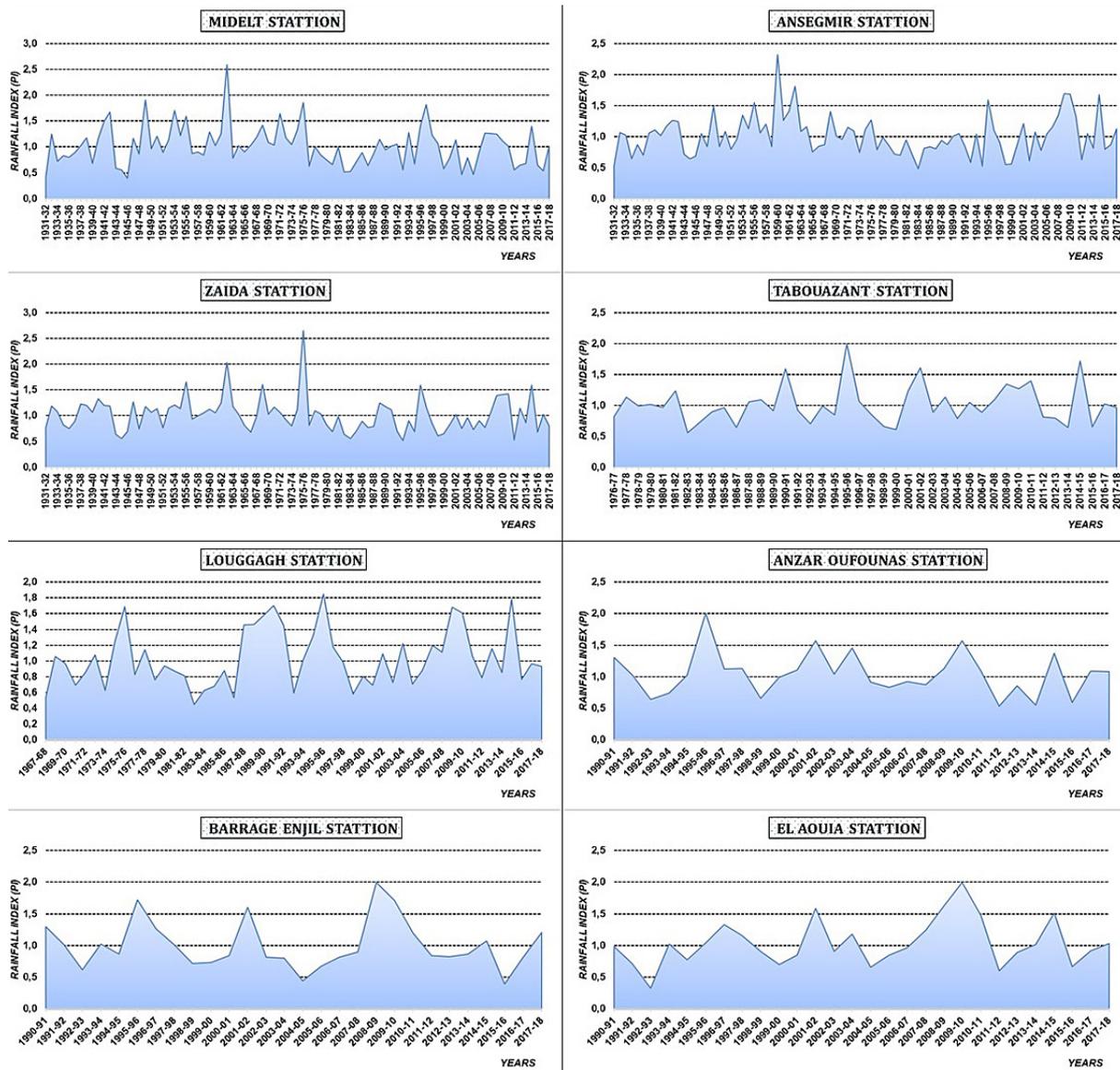
Figure 6. Evolution of the rainfall index of eight rainfall stations in the
Upper Moulouya watershed during the period 1931–2022

The analysis of this graph for the eight rainfall stations studied during the period 1931–2022 revealed the existence of alternating and successive dry and wet years. We note in particular that the values of this index present a strong irregularity for the whole of the stations and that the most important deficit noted during all the period of observation is recorded at the level of the station of El Aouia with a weakest value of the SI which is of the order of -228,20 mm. The analysis of the results of the calculation of this index also confirmed that the most important dry episode, in number of successive years, was recorded at the station of Ansegmir from 1976-77 until 1988-89 (13 years) and the most important rainy episode was recorded at

the station of Midelt from 1966-67 until 1975-76 (10 years). The analysis of the graph relating to the evolution of this index also made it possible to highlight that the drought episodes, common to all the stations, are recorded during the periods of 1934-37, 1943-46, 1956-59, 1965-68, 1976-88, 1991-95, 1997-2001, 2002-06, 2011-14 and 2015-22 and are regularly repeated after intervals of 1 to 10 years. Wet years become less and less frequent from 1977 to 2022, with a maximum of 368.59 recorded at Zaida station during 1975-76. The years in the 2011-2022 series show a persistent decrease in rainfall overall and are generally deficit years, with the general trend across the watershed being a decrease in rainfall.
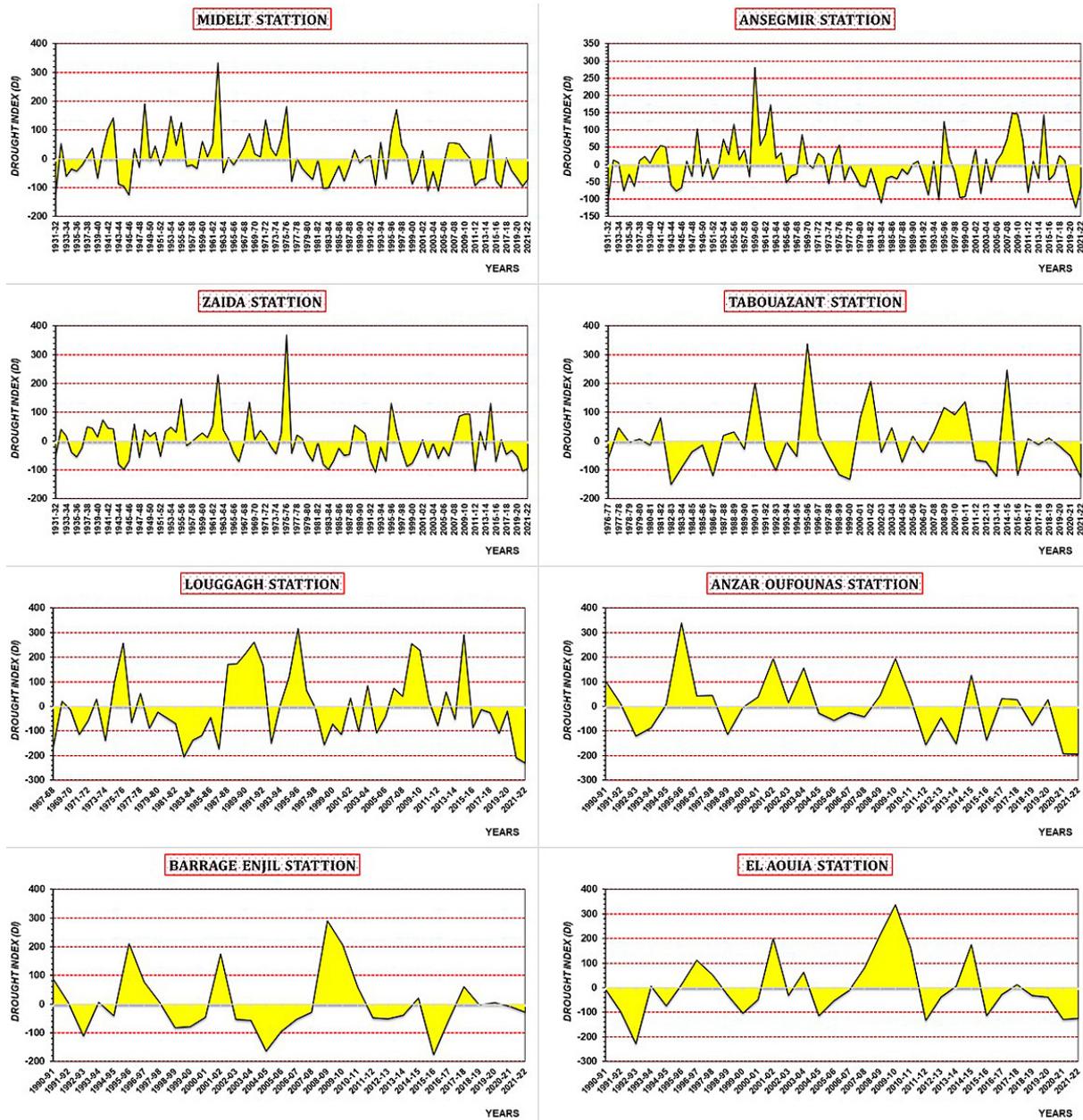
Figure 7. Evolution of the drought index of eight rainfall stations in the
Upper Moulouya watershed during the period 1931–2022

Correlation between the SPI recorded at the Ansegmir station and the annual flow of the Wadi Ansegmir (1970–2015)

The present study has also made it possible to highlight the correlation of the main fluctuations in the rainfall regime (precipitation) and hydrometric regime (average annual flows of the Ansegmir Wadi) at the Ansegmir station during the period 1970/2015. The analysis of the graphical illustrations (Figure 8) relating to the annual evolution of the Standardized Precipitation Index (SPI) and the flows measured at this station, has made it possible to highlight, on the one hand the existence of a very significant correlation which confirms and shows a strong harmony between the annual values of the SPI and the average annual flows measured, with flows decreasing during the years when the SPI values decrease, and on the other hand, the persistence of surface runoff, despite the succession and severity of dry years (deficit years) in the region. The graph also shows a dominance of the dry years, which are clearly identified during the period 1976/77–1994/95 with low flows, and subsequently shows numerous slightly dry
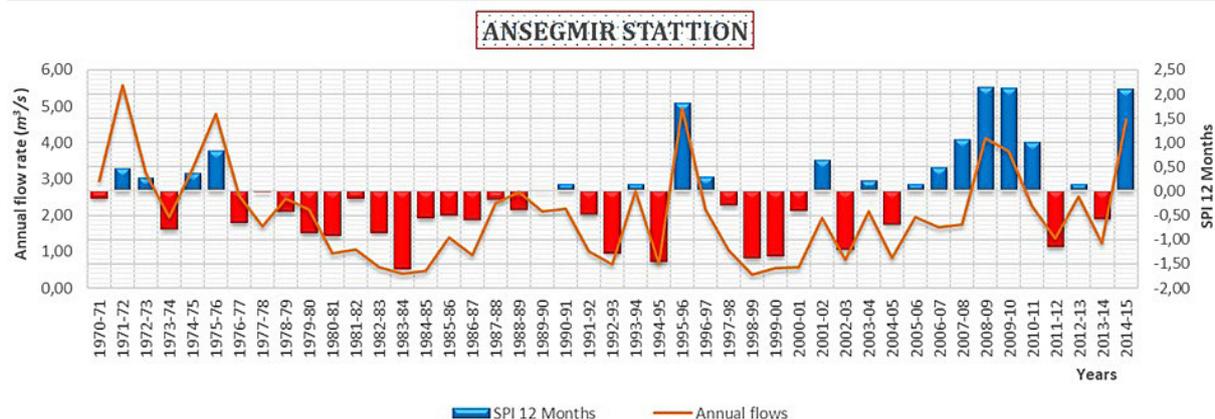
177

Figure 8. Correlation between the SPI and the annual discharge measured
at the Ansegmir rainfall station during the period 1970–2015

sequences that are more persistent and more extensive than the wet sequences.

Thus, it can be concluded that the flow measurements carried out at the Ansegmir station, constitute a means of detection and monitoring of drought and can be used as an indicator to predict the evolutionary trend of climate change in the area.

CONCLUSIONS

In this paper, an analysis of rainfall variability was conducted in the Upper Moulouya watershed for the period 1931–2022. Four meteorological drought indices (SPI, RDI, RI and DI) were used to assess the intensity, duration and frequency of drought using annual rainfall data from eight stations located in the said watershed, despite the difficulties mainly related to data acquisition in the present study.

The analyses of the results of the calculation of the different drought indices common to all the stations allowed to highlight the existence of an alternation and succession of dry years (dry episode) and wet years (wet episode) and indicate that the last decades of this series, are generally characterized by a rainfall deficit (persistent decrease of rainfall) and present a clear tendency to the increase of the drought sequences.

These indices have made it possible to confirm and conclude that the general trend in the entire Upper Moulouya watershed is a decrease in rainfall, while allowing the installation of episodes of light, moderate and severe drought more or less long lasting in the case of wet episodes that become exceptional, which has been affirmed by previous studies conducted at the level of the

Ansegmir Wadi watershed that have also revealed the same conclusions as this study.

In such a variable and unstable climatic context and in order to prevent possible increases in the occurrence of drought impacts in the coming years and implement measures to better respond to drought and limit its impacts, this work constitutes a drought detection and monitoring and early warning system.

It would also be interesting if the analysis of rainfall variability in this region could form the substance of a future study that would complement this one to see how the drying trend in this watershed is likely to evolve over this century in response to unpredictable climate change.

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