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Long-term seasonal characterization and evolution of extreme drought and flooding variability in northwest Algeria

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Abstract. A three decade-long study on the variability of drought in relation to the contribution of rainfall was conducted at the Wadi Mekerra watershed, located in northwest Algeria, covering the period from 1973 to 2005. The runoff and rainfall data were analyzed using the Mann-Kendall test, the double mass curve method and the *SPI* index. A rupture of the studied series appeared during the 1980s. The rainfall and runoff trends and contributions were in general, sharply reduced. The region experienced extreme drought between 1981 and1989, and between 1993 and 2001, rainfall contributions were greater than 60%. This increase, which was recorded in August, September and October for all the parameters studied, shows the importance of the superficial runoff component when combined with decreased infiltration. These climatic conditions reduce the natural recharging of groundwater, and cause an increased susceptibility to soil erosion, reduced agricultural production and an increased risk of floods.

Keywords: runoff, trend, contribution, drought

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1. Introduction

In recent years, the occurrence of prolonged, severe drought and extreme flooding has increased, affecting many regions around the world. This has led to significant social, economic and environmental losses (Zhang et al. 2017; Selek et al. 2018; Warwade et al. 2018). In recent decades, the Mediterranean region has experienced intense and severe drought (WMO 2009; Medejerab, Henia 2011; Nassopoulos 2012; Kablouti 2014; Nouaceur, Laignel 2014). Variability in rainfall from a deficit to excess has resulted in an increase in floods affecting this region (Michiels et al. 1992; Meddi et al. 2010; Coscarelli, Caloiero 2012). Recently, northwest Algeria experienced a drought characterized as severe by its magnitude (Medejerab, Henia 2011) and spatial extent (Meddi, Toumi 2013). Since the 1980s, this region has recorded many occurrences of short-term precipitation alternating with long dry periods that lead to deadly floods (Abdelhalim 2012; Baouab, Cherif 2014).

The objectives of this study were: (1) to analyze runoff and rainfall parameters with their contribution to monthly time steps, in order to detect trends and years when there was a loss of homogeneity using the Kendall test and the double mass curve method; (2) to determine dry periods using the *SPI* index, taking into account the monthly contribution of rainfall inputs; and (3), to assess the relationship between drought and flood and to detect monthly lags between rainfall and runoff.

2. Data and area of study

2.1. Area of study

The watershed of Wadi Mekerra is located in western Algeria between the latitudes 0° and –1° and longitudes 34°50' and 35°50' (Fig. 1). It is bounded on the north by the mountain range of Tassala, on the south by the Ras El Ma highlands, on the east by the Telagh plateau and the Saïda Mountains, and on the west by the Tlemcen Mountains. The main stream, Wadi Mekerra, originates in the high steppe valleys at an altitude of 1,250 m. It drains an elongated area of approximately 3,000 km^2 and flows from south to north with a slope of 5.5%.

Following the 1994 flood that affected the study area, the authorities decided to set up large-scale hydraulic developments that were supposed to protect the Sidi Bell Abbes city in the medium term (Nadir 2009). Key objectives of the development included:

- The development of the upstream watershed by the construction of banquettes in areas with steep slopes (Bachi 2011).
- The creation of spraying areas on two of the main tributaries of Wadi Mekerra, namely Wadi Mouzen, with a spreading area of 2 million m^3 of capacity, and Wadi Mellah, with a capacity of 2.4 million m^3 (Nadir 2009).
- The creation of a water diversion structure from upstream of Sidi Bel Abbes that allows the evacuation of a maximum runoff of 150 m^3/s (Nadir 2009; Bachi 2011).

2.2. Data

Rainfall and runoff data were provided by the National Hydraulic Resources Agency (ANRH). Twenty-four rainfall stations could have been used in this study, but the quality of the results may have been compromised. Quality control relied on the significant criteria of continuity and homogeneity over a long and common period, allowing for the investigation of the spatial and temporal evolution of precipitation. This, fifteen rainfall stations covering the common period from September 1973 to August 2005 were maintained in this study, with 12 stations located at the watershed of Wadi Mekerra and 3 outside (Fig. 1, Table 1). The remaining stations exhibited gaps in the data or were too low for statistical purposes.

The rainfall data (mm) used in the study was the (P_{month}) monthly rainfall and (P_{day} *max*) annual maximum daily rainfall. The runoff data ($m^3 s^{-1}$) was made up of the maximum annual daily runoff (Q_{day} *max*) and the monthly runoff (Q_{month}).

From a geomorphological point of view, this basin can be subdivided into three parts:

- Upper Mekerra (drained part 01): Extends from the south of Ras El Ma to Sidi Ali Benyoub. This drained part of the basin is analyzed from the monthly data of the rainfall station No 1 and the runoff station No 01-01 (Fig. 1).
- Middle Mekerra (drained part 02): Between Sidi Ali Benyoub and Sidi Bel Abbes. This drained part of the basin is analyzed from the monthly data of the rainfall stations No 1, 2 and 15, and the runoff station N. 02-01 (Fig. 1).
- Lower Mekerra (drained part 03): Corresponds to all the part of the basin located downstream of the city of Sidi Bel Abbes. This drained part of the basin is analyzed from the monthly data of all the rainfall stations and the runoff station No 3 (Fig. 1) (Nadir 2009; Bachi 2011).

3. Methods

Fluctuations in rainfall and discharge were analyzed daily, monthly and annually, using the mean value of the P_{day}, P_{day} *max* and P_{month} on the separate parts of the catchment area defined above in Section 2.2. The analysis of the rainfall-runoff data and the determination of the trends was performed using the XLStat software at a 95% confidence level. The calculation of the tau parameter, τ, of Kendall (Mann 1945; Kendall 1975) was used to detect possible changes in trends (Chen et al. 2007; Shadmani et al. 2012; Tramblay et al. 2013; Yanon, Ndiaye 2013; Zeleňáková et al. 2013; Faye 2014; Benhamrouche et al. 2015; Sohoulande Djebou 2015). In particular, the Mann-Kendall test was used to detect trends in monthly rainfall-runoff variables for the different stations. In addition, the monthly contributions of rainfall and runoff were estimated respectively by the ratios P_{day} *max*/P_{month} and Q_{day} *max*/Q_{month}.

Table 1. Rainfall and runoff stations (Z: altitude; D.mer: distance to the sea)

No	Type	Name of Station	Z [m]	D.mer [km]
1	Rainfall	Ras El Ma	1,097	128
2		El Hacaiba	950	113
3		Hassi Zahana	630	77
4		Sidi Ali Boussidi	610	67
5		Tessala	580	52
6		SBA	485	61
7		Tabia	620	83
8		Hassi Dahou	650	76
9		M Ben Brahim	590	70
10		Ain Trid	530	47
11		Sidi Lahcen	501	62
12		Telagh	877	104
13		Ain Frass	424	68
14		Sfissef	545	77
15		Sidi Ali Benyoub	635	85
01-01	Runoff	El Hacaiba	950	113
02-01		Sidi Ali Benyoub	635	85
03-01		SBA	485	61

3.1. Stationarity of the series

The stationarity of the series was studied using the double mass curve method, which is simple, visual and practical. It is widely used in studies of long-term changes in hydrometeorological data (Mu et al. 2010). This method was used to analyze the maximum daily rainfall series (P_{day} *max*) and maximum daily water runoff (Q_{day} *max*).

3.2. Variability and series trends

In order to study the variability of precipitation (P_{month}) and monthly runoff (Q_{month}), box plots was introduced for a schematic representation of the distribution of these two variables where extremes and quartiles diagrams were constructed and processed.

3.3. Occurrence and magnitude of dry and wet sequences

Deficit and excess rainfall are assessed with the *SPI* index (WMO 2012) at 3 months (*SPI*-3), 9 months (*SPI*-9),

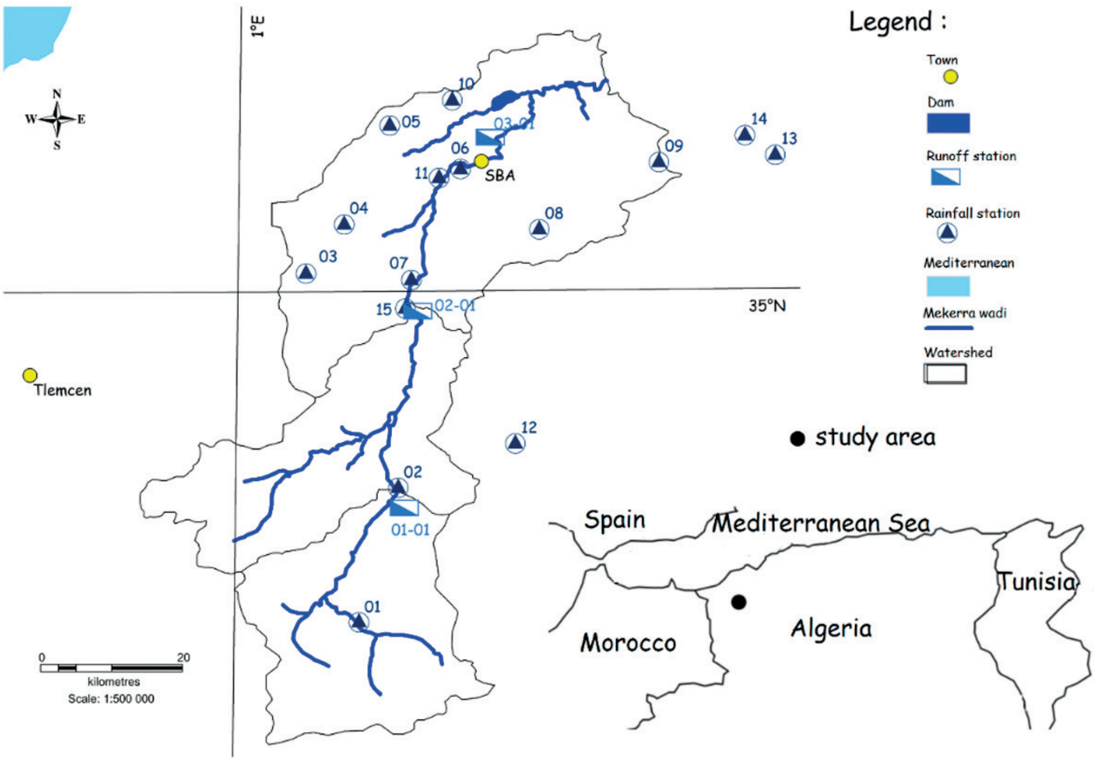

Fig. 1. Rainfall and runoff stations in the study area

Table 2. Classification of sequences by *SPI* index (WMO 2012)

2,0 and more	EW	Extremely wet
1,5 to 1,99	VW	Very wet
From 1,0 to 1,49	MW	Moderately wet
From –0,99 to 0,99	CN	Close to normal
From – 1,0 to –1,49	MD	Moderately dry
From –1,5 to –1,99	VD	Very dry
–2 and less	ED	Extremely dry

Table 3. Time intervals over the study period (1973-2005)

Period	Start Date		End Date	
P 1	September	1973	August	1977
P 2	September	1977	August	1981
P 3	September	1981	August	1985
P 4	September	1985	August	1989
P 5	September	1989	August	1993
P 6	September	1993	August	1997
P 7	September	1997	August	2001
P 8	September	2001	August	2005

12 months (*SPI*-12) and 24 months (*SPI*-24). *SPI* values range from extreme drought to extreme wet (Table 2).

After defining the EW, VD, VD and ED sequences, the contribution of rainfall inputs was introduced to assess whether rains were concentrated or spread out during each period.

To analyze the results of *SPI* for the 32-year study, we distributed the data into eight 4-year intervals (Table 3). The choice of the interval length was determined according to the following: allowing for a reasonable number of characteristic values, making it possible to attenuate the strong inter-annual irregularity of the *SPI* indices while maintaining the overall temporal trend; distributing as evenly as possible, the high flooding events (observed during the years 1986, 1990, 1994, 1995, 1997, 2000, 2002 and 2003) across the selected intervals.

4. Results and discussion

4.1. Stationarity of series

The analysis of P_{day} *max* and Q_{day} *max* by the double mass curve method is presented in Figure 2. The analysis of the stationarity between P_{day} *max* and Q_{day} *max* by the double mass curve method showed a loss of homogeneity during the year 1986. After this date, the slope of the adjustment line increased significantly. In agreement with other published reports (Meddi et al. 2009; Talia et al. 2011), there were many years of rainfall deficit during the 1980s and 1990s. An increase in rainfall-runoff extremes was recorded at the three drained parts of the watershed; 27% for the first, 148% for the second and 800% for the third drained part of the basin. In addition, accumulations of P_{day} *max* and Q_{day} *max* at the three drained portions, 01, 02 and 03, were observed as 750, 1,200 and 1,950 mm, respectively, for the maximum daily

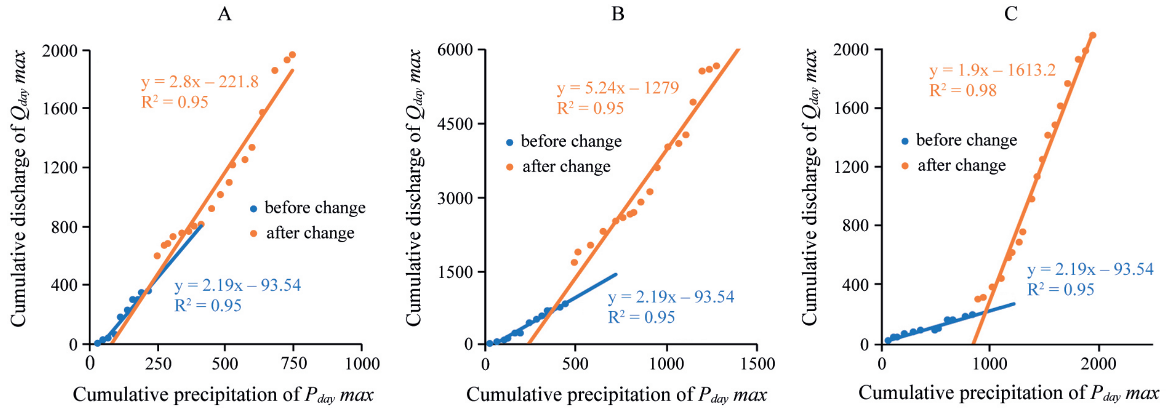

Fig. 2. Double mass curve of P_{day} *max* and Q_{day} *max* during 1973-2005 at Wadi Mekerra (A: drained part 01, B: drained part 02, C: drained part 03)

rainfall, and 1,900, 5,600 and 2,000 m^3/s, for maximum daily runoff.

Extreme values of rainfall demonstrated an increasing trend since the first part drained at the outlet, while the extreme values of runoff increased from the first to the second drained parts. On the other hand, cumulative Q_{day} *max* decreased significantly in drained part 03. This decrease can be attributed to the protective installations constructed in order to minimize the flooding risks of the Sidi Bel Abess city. Indeed, discharges that reach the threshold of 150 m^3/s are controlled by redirecting the water to diversion structures. However, before the rupture date, the threshold was exceeded only once in 1979, with a peak discharge of 197 m^3/s. Whereas after 1986, 12 events occurred with a peak discharge greatly exceeding the threshold, with 4 peaks exceeding 500 m^3/s, and a maximum of 808 m^3/s. These events caused 8 major flooding actions with considerable damage to the villages upstream of the Sidi Bel Abess city (Abdelhalim 2012): October 1986: 1 dead and 200 homeless; April 1990: 2 dead and 130 homeless; September 1994: 1 dead and 22 homeless; September 1997: 1 dead; December 1997: 1 dead and 5 homeless; July 2000: 100 homeless and significant damage in rural areas during 1995, 2002 and 2003. As a result of the diversion structures, more than 60% of the drained water did not reach the gaging station controlling part 3.

4.2. Variability and trends of series

4.2.1. Drained part No 01

Monthly precipitation varied from 0 to 110 mm (Fig. 3A). The lowest values (3 mm on average) were recorded in the month of July. During the months of June and August, however, the average recorded values were 10 mm, while we found average monthly values of 20 mm during the other months. In spite of that, a big difference between Q3 and Q4 was noticed, meaning that there were several extreme values. The areas experiencing flooding during the months of August, September and October (Fig. 3B) had very high runoff values between 141-290 m^3/s, while values for the other months were <150 m^3/s.

The analysis depicted in Figure 3C showed two periods: the first from November to July, during which there was a considerable decline in runoff and precipitation; the second period encompassed the months of August, September and October, where there was a marked increase in the parameters studied.

4.2.2. Drained part No 02

Monthly precipitation values ranged from 0 to 155 mm (Fig. 4A). The three months of summer June, July and August recorded the lowest values with an average of 7 mm, while during the other months of the year the average value was 25 mm. There were large differences between Q3 and Q4 during the months of February, March and September.

Floods occurred during the months of August, September and October (Fig. 4B) with very high runoff values between 403 and 808 m^3/s. During the other months, the maximum runoff varied between 0 and 300 m^3/s. The runoff contribution decreased considerably during all the months of the year except for October and November, when there was a remarkable increase in precipitation and runoff (Fig. 4C).

4.2.3. Drained part No 03

For the third part, the monthly precipitation values varied between 0 and 137 mm (Fig. 5A). During the months of June to September, the average minimum value was 10 mm, while the other months had an average of 30 mm. A large difference between Q3 and Q4 rainfall was observed during the months of March, April, November and December. Floods occurred during the months of August, September, October and November (Fig. 5B) with very high values between 142 and 215 m^3/s. The other months have values <140 m^3/s. The trend of rainfall, runoff and their contribution (Fig. 5C) generally decreased throughout the year with the exception of September, October and November. The month of September was characterized by a sharp rise in rainfall and corresponding contribution of runoff. The two months of October and November were marked by an increase in both rain and runoff; however, the overall trend of the runoff was declining.

When comparing the three parts of the watershed, the intra-annual rainfall distribution was similar. The rainy season occurred from September to May and declined in summer season (June, July and August). The extreme events may occur at any time of the year. However, the annual runoff was mainly done during the fall season with the occurrence of the strongest extreme events. At the upstream watershed, part 1, eight months of the year shown an increase trend of the monthly rainfall. Similar behavior has been observed for six months when regarding the ratio trend of $P_{day}\ max/P_{month}$. For all months of the year, the ratio trend remains lower than the monthly rainfall trend. The highest increases are close for both tendencies and recorded during the month of August. The monthly runoff trends were declining except for the months of the fall season with the highest trend observed in August. Taking into account the rainfall recorded downstream, parts 2 and 3, the spatial average rainfall trend has changed considerably. During the spring season, the monthly precipitation trends, positive in Part 1, have declined and become negative in the Parts 2 and 3 of watershed. Further, the positive rainfall trend observed during the month of December, Part 1, was shifted to January in parts 2 and 3 of the watershed. Similarly, for runoff measured, the positive trend recorded during the fall season, in the gaging station no 1, decreased significantly at gaging stations no 2 and no 3. Globally, the increase of the ratio trend of $Q_{day}\ max/Q_{month}$ in comparison with the runoff trend, attests that runoff are more and more concentrated in time.

After the rupture date, the decrease in annual rainfall was significant, as confirmed by the analysis of the previous Kendall tau results. Trends detected for our study area are consistent with other studies of the Mediterranean region, particularly in North Africa (Brunetti et al. 2004; Costa, Soares 2009; Reiser, Kutiel 2009; Meddi et al. 2010; Caloiero et al. 2011).

The Kendall test for the P_{month}, Q_{month} series, with their contribution from northwest Algeria, demonstrated a change in the trend of the parameters studied. An increase in runoff was seen during August, September and October, outside the winter season where the rainfall-runoff elements are usually most important. During the remaining months, a decrease in rainfall contribution was recorded with a very strong drop in the runoff.

4.3. Occurrence and magnitude of dry and wet sequences

The temporal evolution of *SPI* (at 3, 9, 12 and 24 months) in 4-year periods is presented in Figure 6. Based on the *SPI*-3, *SPI*-9 and *SPI*-12 results, drought affected the study area for the periods of P3 (1981-1985) and P7 (1997-2001). In contrast, the wet sequences occurred during the periods P1 (1973-1977) and P6 (1993-1997), with precipitation contributions averaging at 35%. A high average rainfall contribution of approximately 66% was observed for the periods of P3 (1981-1985) and P7 (1997-2001). *SPI*-24 demonstrated a rainfall contribution of 45% during P1, while for the other dry sequence periods, very high contributions were recorded (greater than 60%). Since 1981, the ED and VD sequences for SPI-24 have maintained rainfall contributions between 30 and 60%. In contrast, the EW and VW sequences were observed during the period P1 (1973-1977), indicating that rainfall decreased to a contribution of less than 40%.

During the study period, a sharp rise in rainfall-runoff parameters was recorded for the three months of August, September and October. At the same time, very large floods affected our study area. In addition, from 1981, a severe drought affected this region, generating several phenomena as follows. Soil degradation and erosion measured over 12 years ranged from 4,217 to 124,384 t/km^2 per year at the Sidi Bel Abbes station, with an average of 44,048 t/km^2 per year (Yamani K et al. 2014). This corresponds to an annual average concentration of approximately 4.52 g/L. Secondly, a drop in agricultural production was observed, with only 7,150 ha irrigated out of 30,000 ha of irrigable potential land, due to a lack of water resources (Slimani, Aidoud 2004). Thirdly, the risk of floods that severely damage property increased, as well as the loss of agriculture and industry (Abdelhalim 2012). It should also be noted that this region has also experienced human casualties. The flood of SBA (04/10/86) left 1 dead and 200 injured, while the flood of Moulay Slissen (17/08/97) claimed 1 dead and 34 injured (Abdelhalim 2012).

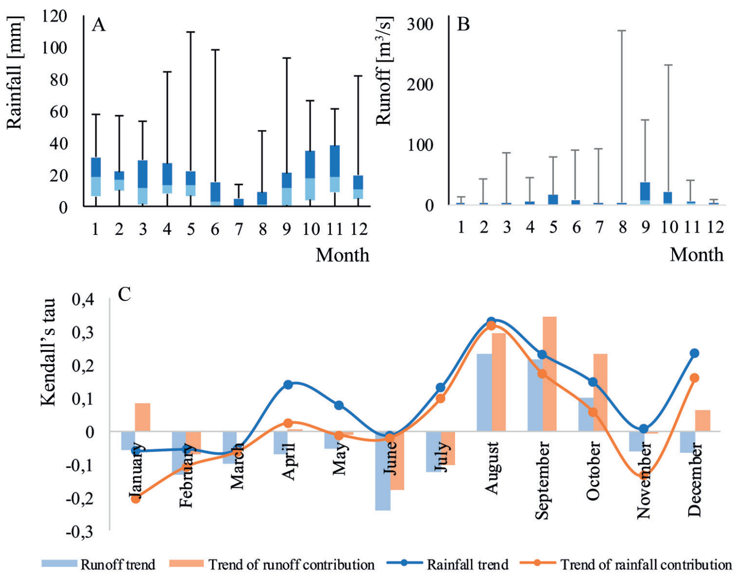

Fig. 3. Monthly rainfall (A), runoff (B) and Kendall's tau (C) in the drained part 01 of Wadi Mekkera

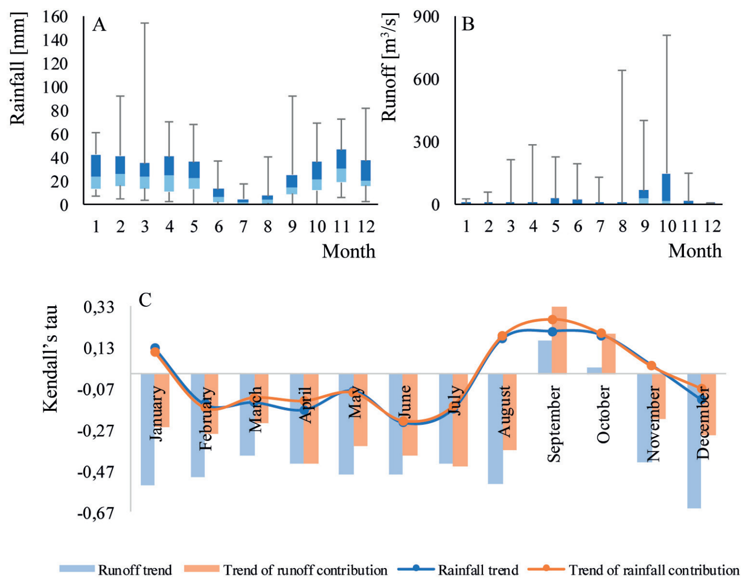

Fig. 4. Monthly rainfall (A), runoff (B) and Kendall's tau (C) in the drained part 02 of Wadi Mekkera

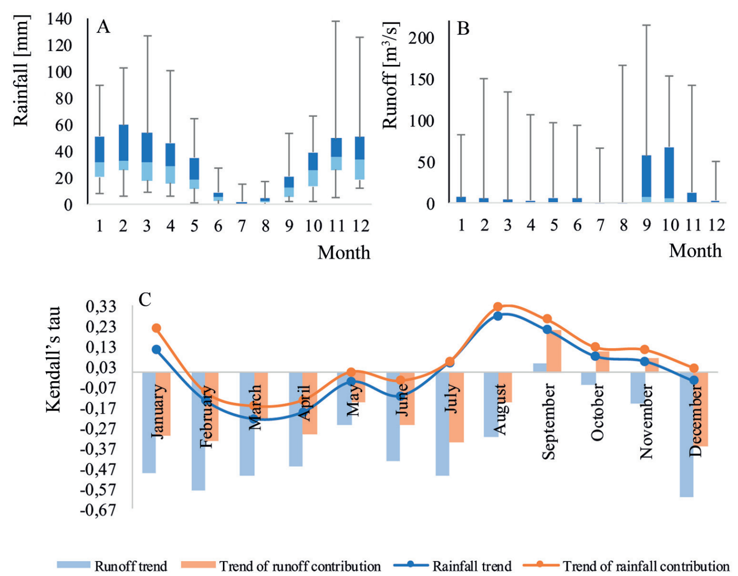

Fig. 5. Monthly rainfall (A), runoff (B) and Kendall's tau (C) in the drained part 03 of Wadi Mekkera

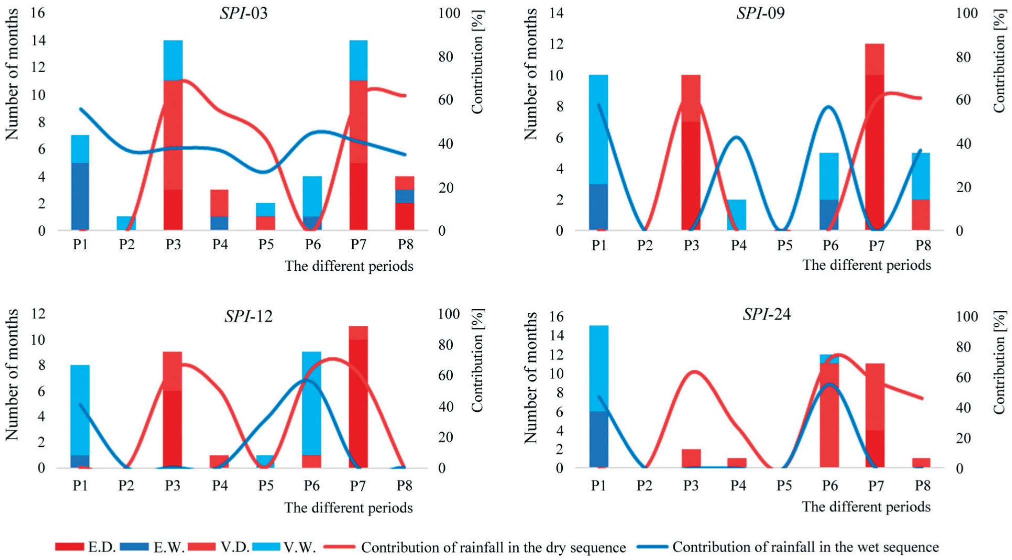

Fig. 6. Number of months and rainfall contribution in a given humidity class (Table 1) in the 4-year periods

5. Conclusions

The time series analysis and the statistical tests indicated a loss of homogeneity during the year of 1986. Following this, the slope of the adjustment line increased significantly. Compared to the second drained section, there was an observed decrease in cumulative Q_{day} *max*. Despite protective work, devastating floods still affected our study area. During the study period, the Mekerra watershed experienced a decline in rainfall and discharge. However, increases in the studied parameters were recorded during August, September and October, with a strong variability in the runoff series. This indicates that several extreme values were present. In general, there were two distinct periods. The first extended from November to July, during which there was a considerable reduction in runoff and precipitation. The second period encompassed the months of August, September and October, when there was a sharp rise in all parameters. Analysis of *SPI* results from the study area showed that the region experienced both Extreme Drought (ED) and Very Dry (VD) sequences. The latter was recorded since 1981, with a rainfall contribution of between 30 and 60%. In contrast, EW and VW sequences were observed in the P1 period (1973-1977), indicating that rainfall contributions dropped to less than 40%.

During the dry season, there was a sharp increase in rainfall-runoff parameters, with very large floods affecting our study area. Because of this, the soil will eventually become saturated, such that any increase in the volume of rain will result in an equivalent increase in the volume of water discharged by the river at its outlet. Under these conditions, any amount of rain that falls will contribute to flooding, soil degradation and erosion. Seasonal rainy periods that occur during the fall generate significant runoff, usually causing flooding. The study area was found to have two distinct seasonal periods with different rainfall-runoff patterns. The first was from November to July and was characterized by precipitation, with a small runoff contribution, while the second, from August to October, manifested intense rainfall accompanied by a strong contribution from runoff.

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