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CLIMATE CHANGE AND TRANSBOUNDARY WATER MANAGEMENT IN THE TUNISIAN MELLEGUE CATCHMENT

Klimatförändring och gränsöverskridande vattenhantering i Mellegue avrinningsområde, Tunisien

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Abstract

Human activities and climate change affect hydrological and sedimentological characteristics within catchments. For arid and semiarid areas this induces direct negative economic and environmental consequences on society. In fact, stability in the rainfall regime and less siltation trapped in reservoirs mean more water for irrigation, water supply, and better flood control. This is especially important in the Tunisian semiarid region where water needs are close to potential water resources and siltation is reducing the reservoir capacity rapidly. Wadi Mellegue was chosen in order to study trends of water resources availability. Linear regression modelling and Mann-Kendall tests were performed for trend analysis. The study dealt with rainfall, discharge, and sediment patterns in the catchment area during a 44-year period. The results display a common decline in rainfall depth at different time scales. However, a positive trend related to discharge and siltation process was found. An increase in vulnerability to the new climate conditions is described. Consequently, water resources and agricultural landscape management for the Mellegue catchment should be revised in order to ensure a sustainable up- and downstream catchment development.

Key words – Discharge, rainfall, semiarid, siltation, trend analysis, Tunisia

Sammanfattning

Mänskliga aktiviteter och klimatförändringar påverkar avrinningsområdens hydrologi och sedimenttransport. Inom arida och semiarida klimatområden, är denna påverkan ofta negativ för ekonomisk utveckling och miljö. Större variation av nederbörd kan innebära mindre mängder vatten för bevattning, dricksvatten, sämre kontroll av översvämningar och större upplagring av sediment i reservoarer. Detta är speciellt viktigt i Tunisiska semiarida områden där verkligt utnyttjande av vattenresurser ligger nära de potentiella och där reservoarkapaciteten snabbt minskar. Den icke-perenna floden Mellegue studerades för att undersöka trender i vattenresurstillgänglighet. Linjär regression och Mann-Kendalltester användes för att bestämma dessa. Studien undersökte nederbörd, avrinning och sedimentering i avrinningsområdet under en 44-års period. Resultaten visade att nederbörden är vikande för de flesta tidsskalor. Avrinning och sedimentering visar en ökande trend. I sin tur indikerar detta en ökande sårbarhet i det nya klimatet. Eftersom Mellegue avrinningsområde är viktigt för både Algeriet och Tunisien är det viktigt att en hållbar vattenhantering tar hänsyn till detta i planeringen.

Introduction

Climate change as well as weather and climate variability are potentially connected to large economic losses (Katayama 1993; Wisner et al. 2003). Unlike the developed countries, developing countries suffer from severe vulnerability in the future global warming conditions (Tag-Eldeen and Nilsson 1978; Sachs 1999; Mirza 2003; UNDP 2003). These conditions will constitute a hardship within a number of key sectors, including water resources, soil erosion, floods, and crop production (Wilhelmi et al. 2002; Kundzewicz et al. 2004; Zhang et al. 2005; Chaplot, 2007). The vulnerability of many developing countries is very high due to draining of their natural resources throughout history and their present development strategies that create a vicious cycle of poverty and environmental degradation (e.g., Wisner et al. 2003). Consequently, evaluation of the potential effects of climate change and human activities at the country scale and main hydrological systems are crucial to set adaptation strategies (e.g., Wisner et al. 2003; USCCSP 2008 Jebari et al. 2015). Still few studies have analyzed hydrological systems in semiarid areas (e.g., Hodgkins et al. 2005; Verkerk et al. 2017).

Now, human activities and climate change are compelling facts (e.g., IPCC 2007; Liu 2010). MENA (Middle East and North Africa) region has been identified as one of the most vulnerable areas in terms of shortage and adaptability to future climate conditions. Moreover, fragmented approach related to shared water resources management has often led to landscape degradation, hydrological hazards, and conflict situations (Earle et al. 2010). Hence, it is important to establish links between hydrological trends and water resources availability using relevant statistical techniques within this region.

Tunisia is one of the MENA countries within the Mediterranean Basin that has been classified among areas most seriously affected by a future climate change (Moss et al. 2001; Giannakopoulos et al. 2005). The country displays significant irregular rainfall regimes, water scarcity, rapid reservoir siltation, and agricultural landscape degradation (GOPA & GTZ 2005; Ennabli 2007; MARH; Jebari et al. 2010). In order to mitigate these problems, adaptive strategies need to be introduced, in particular water harvesting structures, flood protection, water storage systems, and silting trap structures (Jebari et al. 2016).

As a consequence of the above, there is a great need to develop methodologies for trend analysis in areas with large hydrological and sedimentological variability. Obviously, the change in rainfall characteristics has great influence on rural development progress in terms of water and soil resources availability (Cudennec 2007). Hence, the objective of this paper was to detect persistent temporal changes that are particularly useful for water and soil resource management. The utilized data in this paper are from the transboundary Mellegue catchment that discharges into one of the oldest reservoirs in Tunisia. For this reason the catchment conditions are closely monitored. Precipitation, discharge, and sediment load observations were analysed for this purpose. The obtained results are meant to strengthen knowledge related to climate change vulnerabilities in the semiarid areas, help engineers to revise hydraulic infrastructure design, and finally to implement adaptation measures within the future climate conditions.

Material and Methods

Studied area

The climate in semiarid Tunisia is characterized by mild, rainy winters and hot, dry summers with large year to year variations. The rainy season begins in September and ends in May (Rodier 1981). Transition seasons (spring and autumn) are characterized by convective

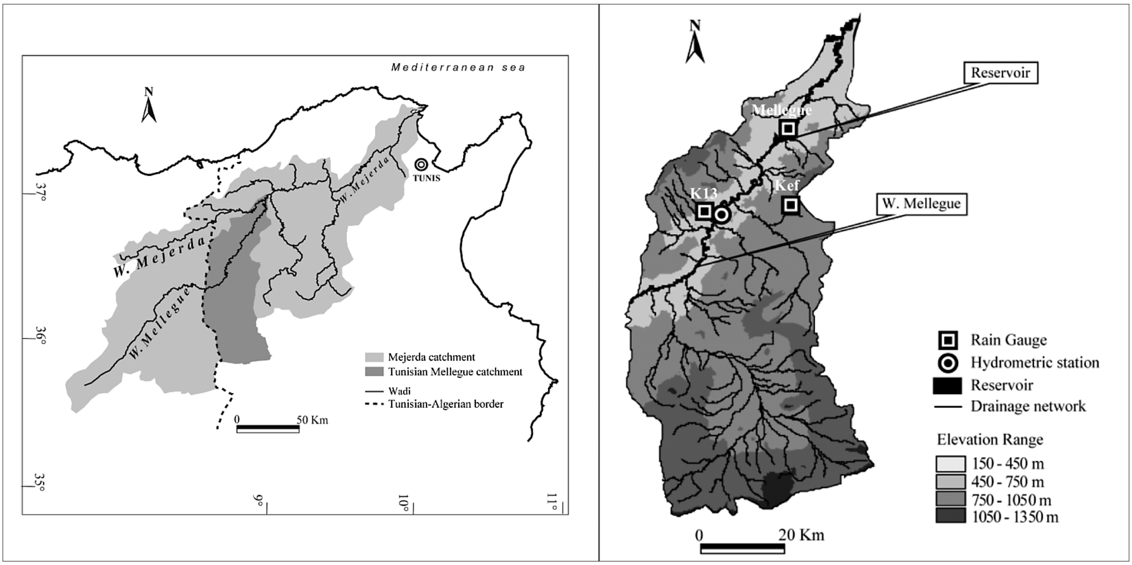

Figure 1. *Study area and observation network.*

rain (e.g., Dhonneur 1985). The yearly average precipitation of Mellegue catchment is about 420 mm and the number of rainy days ranges from 20 to 70.

The Mellegue catchment is located 180 km from Tunis in the north-western part of the country (Figure 1). It is the most important affluent of the main permanent river in Tunisia, the Mejerda. Mellegue watershed covers 10300 km^2 of which two thirds are in Algeria (6095 km^2). The south border of the transboundary Mellegue catchment coincides with the Dorsal Mountain range. The average altitude is about 800 m and the uncovered bedrock, made up of marls and calcareous–marls represents 80 % of the catchment. This land is particularly vulnerable to erosion especially in the upstream parts of the catchment where the slopes reach 20 %. This situation leads to hierarchical gully erosion (Ben Mamou 1998). The land cover corresponds to 30 % of cereal crops, 27 % of forests, and finally 43 % of bare soil.

The average hydrological regime of the Mellegue catchment is mainly rain-fed. It is characterized by high flows in the cold season and low flows in the hot one. The lowest flow is about 200 l/s and the average solid transport is about 40 g/l. However, during extreme floods, the sediment concentration may reach 140 g/l. The wadi originates in the high plateaus at 1408 m altitude and flows in the Mejerda River at 22 km downstream of the Nebeur reservoir. This reservoir was built in 1954 close to the Tunisian-Algerian border. It collects more than 300 Mm^3 out of which an average volume of 150 Mm^3 are annually renewable. The annual runoff volume from the upstream part located in Algeria is about 100 Mm^3. The dam ensures a regular downstream flow of the river, protection of the mid-valley of Mejerda, irrigation of several thousands of hectares, and production of power. Large floods induce rapid siltation despite the fact that it was originally designed for a lifetime exceeding 100 years (Gottis and Strohl 1952).

Data

Monthly hydrological data are crucial for water resources management and agricultural productivity (Hodgkins *et al.* 2005). However, we used annual, seasonal, monthly, and daily precipitation at Kef, Mellegue, and K13 stations (Table 1). These time series extend from 1960 to 2004. The K13 is also a runoff station operating since 1923. It is situated 25 km upstream of the Nebeur reservoir and gives main observations needed for the dam management. The current study focused on 44 years mentioned above related to discharge, water level, and suspended sediments. In general, suspended sediments display a strong yearly variation. They are highly correlated with exceptional rainfall conditions that are reported by the Tunisian Water Resources Department, e.g., during the exceptional years 1955–56, 1958–59, 1963–64, 1969–70, 1973–74, 1989–90, 1995–96, and 1999–2000. These events were the main cause of the Nebeur reservoir siltation (Abdelhedi 2001).

Table 1. *Descriptive characteristics of the three experimental rainfall stations (1960–2004).*

Rainfall Gauge	Kef	Mellegue	K 13
Longitude (degrees)	8° 42’58”	8° 30’08”	8° 30’ 02”
Latitude (degrees)	36° 07’33”	36° 10’52”	36° 07’ 15”
Altitude (m)	620	325	324
No. rainy days (day/year)	79	71	54
Max. (mm/day)	103.4	105.0	82.0
Max. (mm/month)	261	248.5	163.6
Mean (mm/year)	488.1	448.9	319.3
Min. (mm/year)	240.8	223.9	106.8
Max. (mm/year)	818.0	795.6	517.0
Std. dev. (mm/year)	126.5	124.6	84.8
Coef. Var. (%)	25	27	26

Siltation measurements were made using bathymetric observations of water depths along pre-defined transects (Claude & Chartier 1977; Claude et al. 1977; Jemmali 2000). Thousands of points defined by three Cartesian coordinates (x, y, and z) were measured. The change in reservoir volume was deduced from the difference from one observation time to another. Dredged volumes allowed the assessment of theoretical solid volumes caught in the reservoir (Jemmali 2000). The general situation, drainage area, and monitoring stations are presented in Figure 1. The reliability of the data has previously been analysed by the DG/RE (Department of Water Resources) and DG/EGTH (Department of Study and Construction of Big Hydraulic Infrastructure). Missing data correspond to about 3 %. The siltation conditions and general life span of the Nebeur reservoir are comparable to many dams located in semiarid Tunisia (Abdelhedi 2001; Ben Mamou 1998; Jebari et al. 2010). The analyzed period was compared to long-term rainfall conditions (Figure 2).

Methods

In the current study, two methods were used to find actual trends and fluctuations in hydrological and sedimentological time series namely, simple linear regression and Mann-Kendall test. The annual time series of siltation and dredging were analyzed using the same methods in order to reveal human impact on the studied area and to display the efficiency of the current management strategies related to the hydraulic infrastructures and the natural resources in general.

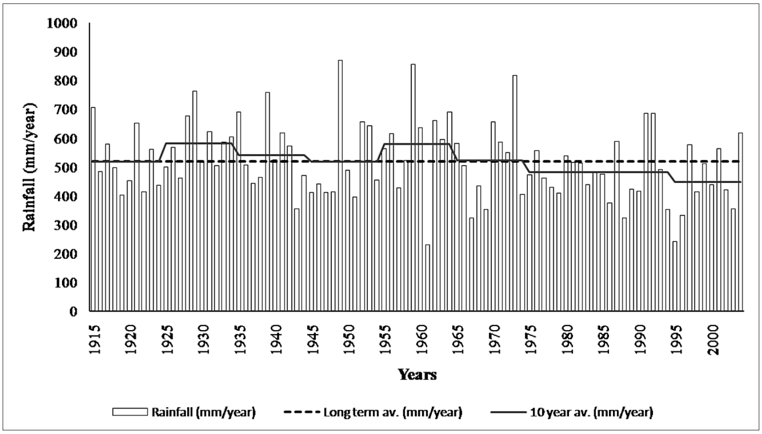

Figure 2. *The Kef annual rainfall during 1915–2004. Source: Tunisian Water Resources Department.*

Homogeneity tests

Homogeneity testing is a crucial tool to overcome uncertainty problems in climate trend studies (e.g., Easterling et al. 1995). To reveal breaks within the studied rainfall time series, a comparison using the "double mass curve" as a qualitative way was first performed (Kholer 1949). The results of the procedure displayed an almost straight line for the different stations and indicate that no errors are at hand regarding main properties of the data (Figure 3). As a second step, a normal homogeneity test developed by (Alexandersson 1986; Hanssen-Bauer 1994).

Linear regression

This method consists of two steps, fitting a linear simple regression equation with the time t as independent variable and the hydrological variable, Y as dependent variable, and testing the statistical significance of the slope of the regression equation (Wang et al. 2001; Zang et al. 2004). The linear regression method accounts for the seasonality and autocorrelation in time. In this context, if the residuals are autocorrelated in time, the efficiency of least-squares parameter estimates is affected and the standard error estimates are biased. Consequently, the Durbin-Watson D-statistic test can be used to ensure the absence of first order autocorrelation in residuals (ICES 2001). Only ordered and equally spaced time series data should be used with no missing values for this methodology.

Mann-Kendall test of trend

The Mann-Kendall method is a non-parametric test (Kendall 1975; Libiseller et al. 2005). The Mann-Kendall test can assess the significance of nonlinear trends in hydro-meteorological and environmental time series as well as on a spatio-temporal scale (Zhang et al. 2004; Becker et al. 2006; Jónsdóttir, 2006). The Mann-Kendall test does not require the data to be normally distributed, but it is applied to de-correlated data (Khaliq et al. 2006; Jónsdóttir et al. 2008). Finally, the Mann-Kendall method is reported to be less influenced by the presence of outliers in the data and that it can be used even if the sample is not large (Lanzante 1996).

In this study, the different time series were analyzed using the Mann-Kendall trend test. We intended to assess the randomness of a sample of a variable X (McCuen 2006). The null hypothesis was that the values x_i are independent and identically distributed random variables. When this assumption is rejected, an increasing or a decreasing monotonic trend exists in the time series. The Kendall statistic test S is described as (Da Silva 2004; De Jongh 2006):

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \text{sign}\,(x_i - x_j)$$

where x is the data at times i and j, n is the length of the data set, and sign represents the absolute value.

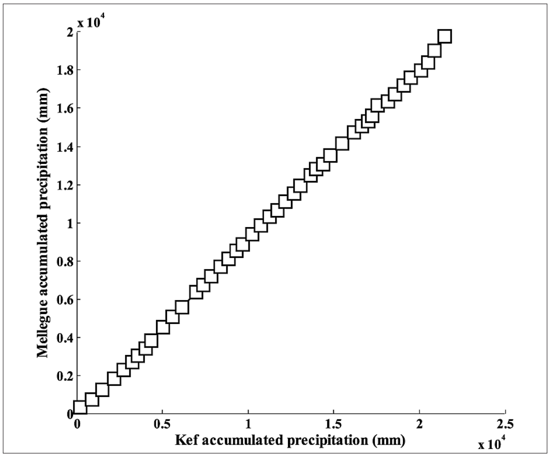

Figure 3. *Double mass curve for Kef and Mellegue annual rainfall.*

For large sample size n, the statistic S is approximately normally distributed with zero mean and variance defined as follows:

$$\mathrm{Var}\,(S) = \frac{n(n-1)\,(2n+5)}{18}$$

The standardized test statistic is given by:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{V}} & \text{if } S < 0 \end{cases}$$

where Z is the value of a standard normal deviation and V is the variance of S. In this work, Z indicates either decreasing or increasing trend at $p = 0.3$ significance level. The p-value is obtained for each analyzed time series from normal probability tables.

Based on the above, the significant trend within the current manuscript is chosen related to high probability value (p) (Hopkins 2002). This is relevant for comparison, shift detection, and magnitude trend indication (e.g., Saporta 1990; Pal et al. 2011).

The binomial and uniform distribution of Mann-Kendall statistics induce trends mainly related to local effects rather than the general changes (Nasria & Modarres 2009). However, considering the stochastic hydrological reasoning and the spatial correlation between stations, results from regional trend are better defined than at the individual station level (Douglas & Chelsea 2011). Consequently, as far as the current work is concerned, a special emphasis was given to both local and regional scales. Findings related to Kendall's S computed at each station were then averaged for a regional value. When stations display positive and negative trends, comments on slopes were given to emphasize the main relevant magnitude in time.

Hydrological trend and test of significance

Opposite to experimental data and idealized distribution, it is not usual to find significance for natural processes and hydrological trends (e.g., Saporta 1990; Hopkins 2002). This is related to specific characteristics of the time series which present a high variability and effects of local changes and regional global climatic conditions. Significance within water resources studies is usually identified as weak (e.g., Hulme 1996; Kripalani et al. 2003; Sakiss et al. 2004; Gong et al. 2004; Basistha et al. 2009; Rose 2009; Kliment & Matoušková 2009; Douglas and Chelsea 2011) .

Significance and non-significant results are for instance dependent on the analyzed serial correlation and the sample size (Cunderlik & Ouarda 2009; Kwarteng et al. 2009; Pal & Al-Tabbaa 2011). In fact, a positive autocorrelation can overestimate the probability of a trend, while there may be actually none. A negative autocorrelation may underestimate the probability and does not enable to detect the trend. Moreover, it is important to be aware that, the used Mann-Kendall (M-K) test is nothing but a rank-based procedure. Consequently, the more successive sign values that are either positive or negative, the more likely the M-K test will produce a significant Z-value or trend (Novotny & Stefan 2007; Nasria & Modarres 2009; Cunderlik & Ouarda 2009; Subash et al. 2011).

According to Snedecor & Cochran (1989) the misuse of significance tests has discouraged work that would have been fruitful. While given non-significant result researchers must still decide, about the meaning and the application of their findings. Cohn & Lins (2005) mentioned that statistical significance that do not account for long-term persistence is likely to be meaningless. Moreover, Yue & Hashino (2003) argued that some trends may be statistically non-significant but might still be of practical interest. Finally, Radziejewski & Kundzewicz (2004) added that even if a climate change component is present, it does not need to be detected by statistical tests at a satisfactory significance level.

Water resources management and its corresponding infrastructure design are based on return period intervals of the hydrological variables. The theoretical return period is related to the probability that the event will exceed in any one year. As far as soil loss is concerned, return period interval that characterizes the rainfall events in describing the landscape degradation and reservoir siltation ranges from one to hundreds of years (e.g., Jebari et al. 2008; 2010). Thus, e.g., a 2-year exceptional rainfall has 50 % chance of being exceeded in any one year. Actually, the estimated return periods in this field are computed from a set of observed data which are different from the theoretical series in an idealized distribution. Consequently, natural and hydrological contexts allow dealing with higher probability values.

Results and Discussion

Trends in rainfall depth

The annual rainfall displays some peaks early in the period. However, large fluctuations characterize the whole studied period. Results indicate that during 1960–2004, there was a negative trend for the three

Table 2. *Regional rainfall trend analysis results. The Z value of the standard normal deviation which indicates the increasing and the decreasing trend at p significant level about 30 %. The slope of the regression line is presented. The autocorrelation in the time series and in the residuals are displayed.*

Rainfall data	Z	P value	Slope	Trend	Autocorr. Coeff.	Residual Autocorr.
Annual data (mm)	0.78	0.28	4.22	–	0.13	1.72
Nb. Rainy day (days/year)	2.02	0.04	0.36	+	0.38	1.57
Seasonal data (mm)						
Autumn	1.9	0.05	1.23	+	0.11	2.36
Winter	0.55	0.33	0.52	–	0.25	1.78
Spring	1.11	0.21	3.36	–	0.28	1.89
Summer	1.19	0.19	0.65	–		
Monthly data (mm)						
September	1.7	0.08	0.59	+	0.24	2.44
October	0.58	0.31	1.3	–	0.26	2.06
November	1.86	0.06	0.63	+	0.16	1.76
December	0.68	0.29	0.20	+	0.03	1.69
January	1.18	0.17	0.07	–	0.15	2.15
February	1.12	0.19	0.75	–	0.22	2.47
Marsh	2.73	0.008	0.78	–	–0.27	1.76
April	0.49	0.32	0.37	–	0.13	1.99
May	0.31	0.34	0.13	+	0.13	1.98
June	0.6	0.3	0.05	–	0.18	2.2
July	1.69	0.08	0.03	–	0.15	2.27
August	0.47	0.32	0.13	–	0.13	2.01
Exceptional rainfall charact.						
Max. Monthly (mm)	0.44	0.33	0.45	+	0.21	1.9
Max. Daily (mm)	1.65	0.08	0.15	–	–0.37	1.84
Nb. Rainy days > 12 mm	2.61	0.015	0.03	–	–0.25	1.87
Nb. Rainy days < 12 mm	4.08	0.0001	1.04	+	0.22	1.8
Nb. Rainy days > 7 mm	0.69	0.31	0.69	–	0.14	1.74
Nb. Rainy days < 7 mm	3.81	0.0002	0.82	+	0.25	1.63

studied rainfall stations (Table 2). The slope of the regression line is clearly shown for the Kef station and it reaches –6.1 mm/year. However, for the Mellegue and the K13 stations, the slopes of the regression lines are –4.3 and –2.4 mm/year, respectively (Fig. 4).

The seasonal trend estimation reveals a positive trend for the autumn and a negative trend for spring and summer. The winter season displays different trends for Kef and Mellegue on one hand and K13 on the other. Actually, the autumn season presents positive trends for the

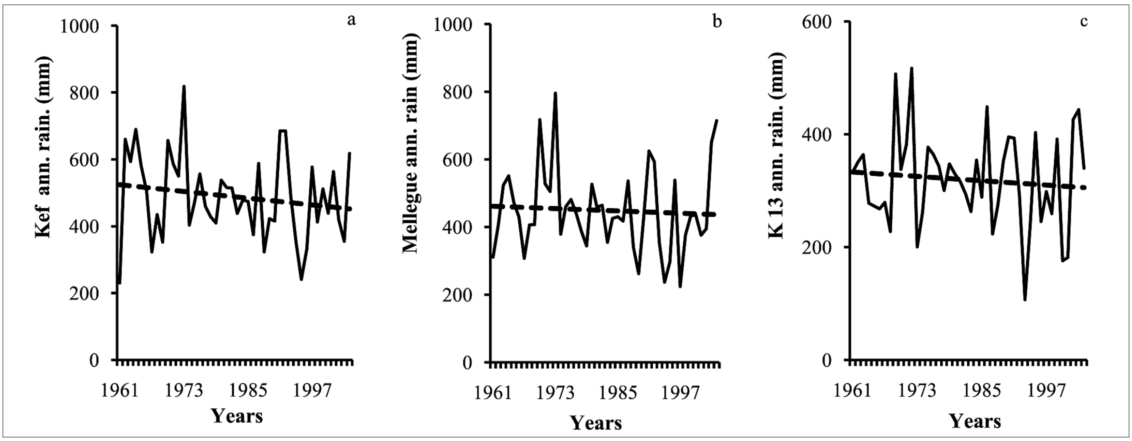

Figure 4. *Annual rainfall trend. (a) Kef station. (b) Mellegue station. (c) K 13 station.*

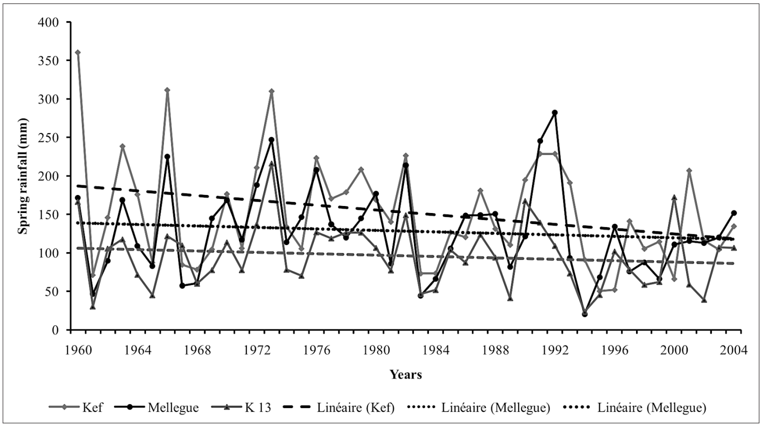

Figure 5. *Spring rainfall trends for the three studied rainfall stations.*

Kef and K13 data with slope of 1.6 and 1.2 mm/year. However, the Mellegue time series presents a trend with a regression line slope of 1.1 mm/year. During the winter season, a negative trend characterize the Kef and the Mellegue data according to respectively –0.4 and –0.8 mm/year. Meanwhile, K13 shows a positive trend with a regression line presenting a slope of 0.3 mm/year. All the negative trends observed in the spring season display slopes which are –8.7, –0.9, and –0.4 (mm/year) for the Kef, Mellegue, and K13 time series, respectively (Figure 5). Summer which is also characterized by negative trends shows linear regression slopes of –0.7 (mm/year) on average. Primarily, the dominant seasonal trends are mostly negative (Table 2). A decline in seasonal rainfall is quite obvious. This seems to be well illustrated by the spring slope of the Kef time series considered to be a rainy station (Figure 5). The decreasing trends observed in summer season are derived by the negative magnitude in time of the corresponding months. This drier context will obviously affect the natural vegetation cover in particular and the ecological fragile semiarid context of the catchment. It is interesting to note that revealed trends display the large variability that characterizes the used data series. In fact, the latter are affected by local changes and regional global climatic conditions as mentioned by Touchan et al. (2008).

When the trend analysis focused on the different months of each season, results revealed main months responsible for the dominant negative or positive characteristics. For example if we consider September and November in the autumn season, we find positive trends. However, October is characterized by a negative trend (Figure 6). A comparison between these opposite trends in terms of slope values was performed for all data series. It displays that the negative trend (–1.30 mm/year) is more important than the positive one (0.66 mm/year). Finally, the autumn positive trend may not reflect the most important increase of the rainfall variable.

On a monthly basis, January, February, March, April, June, July, and August display the only negative trends for all data series. For example, February which is characterized by 11 % of annual rainfall depth displays an average slope of –0.8 mm/year. Rainy months like, October, February, March, and April all display nega-

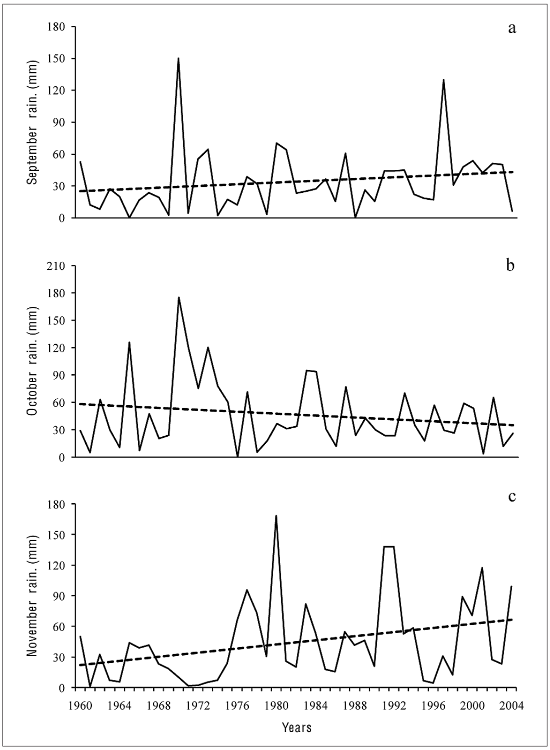

Figure 6. *Autumn month trends at the Kef station.*

tive trends for all the studied time series with slopes ranging from –0.1 to –1.2 mm/year. However, these months constitute 210 mm/year (42 %) for the Kef area, 192 mm/year (42%) at Mellegue and 131mm/year (41 %) for the K13 station.

In terms of maximum monthly rainfall, a negative trend is observed for the Kef station with a slope of –0.64 (mm/year). And, Mellegue and K13 stations display positive trends with 0.63 and 0.28 (mm/year) slope values and with similarly trends for daily maximum rainfall (Table 2). The trends observed at Kef station downstream the catchment are different from the Mellegue and K13 which are located in the upper parts within the same watershed. Downstream rainy areas seem to be more affected by negative trends. The Kef and Mellegue stations have a similar trend behavior as the drier K13 station rainfall characteristics (Figure 5).

Number of rainy days trend

On the annual time scale, Kef, Mellegue, and K13 display positive trends. For the seasonal scale, both positive and negative trends are shown. The linear regression lines are mostly characterized by low slopes. Autumn displays positive trends for the three studied rainfall stations. This is more pronounced when moving from the wettest to dryer stations. In fact, Kef, Mellegue, and K13 show respectively 0.21, 0.14, and 0.028 slope values related to the yearly rainy days. This decrease simultaneously and gradually affects winter, spring, and summer seasons. The linear regression slopes are characterized by continuously lower values.

Small slopes are also shown for the number of days related to 12 mm. Negative significant trend is observed for Kef and Mellegue data. Meanwhile, a positive trend is displayed for K13 (Table 2). As far as the number of rainy days greater than 12 and 7 mm are concerned, opposite trends are revealed. In fact, negative trends characterized the different time series for the daily rainfall larger than 12 mm. However, positive trends are displayed for daily rainfall larger than 7 mm. When the number of daily rainfall is less than 12 and 7 mm, only positive trends show up (Table 2). The related observed slopes at Kef and Mellegue are about 1.2 and 0.7 yearly rainfall days (Figure 7).

The main result above for daily rainfall appears to be that larger rainfall amounts above 12 mm are declining while smaller daily amounts corresponding to 7–12 mm appear to be increasing. At the same time a slight increase in the number of rainy days is related to less depth. This could be interpreted as a transition towards a more arid climatic condition. This latter finding is in accordance with the decrease in orographic storms which was mentioned by Sarkar et al. (2004) and Rosenfeld et al.

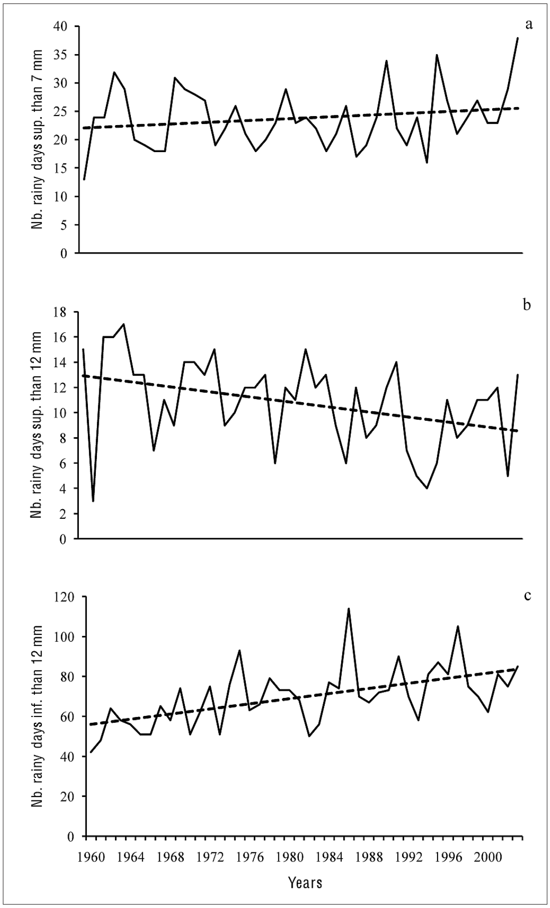

Figure 7. *Kef station. (a) Positive non significant trend of rainy days larger than 7 mm. (b) Negative significant trend of rainy days larger than 12 mm. (c) Positive significant trend for rainy days less than 12 mm.*

(2007). This fact is due to anthropogenic aerosol which creates clouds of smaller water droplets that are less likely to fall.

Decreasing trends which are characterizing the depth and the number of exceptional rainy days are consistent with most published water resources literature (e.g., Qian & Lin 2005; Schmidli & Frei 2005; IPCC 2007; Basistha et al. 2009; Douglas et al. 2011; Pal & Al-Tabbaa 2011). The reduction in precipitation is often related to the atmospheric circulation changes, the replacement of natural vegetation by croplands, spreading upstream of irrigated areas, the deforestation and the soil moisture where evaporation is high (e.g., Pielke et al. 1999; Koster et al. 2004; Gupta et al. 2005; Ramankutty et al. 2006; Ray et al. 2006; Baines 2006; Ramesh & Goswami 2007). All the above aspects which are related

Table 3. *Hydrological and sedimentological trend analysis.*

Variables	Z	P value	Slope	Trend & Significance	Autocorr. Coeff.	Residual Autocorr.
Max. discharge (m^3/s)	2.13	0.04	23.38	+	0.3	2.29
Low water vol. (Mm^3)	0.94	0.25	0.46	+	–0.13	1.55
Max. water depth (m)	0.29	0.37	0.46	+	–0.13	1.53
Flash flood vol. (Mm^3)	0.77	0.29	0.11	–	0.01	2.32
Sediment load vol. (Mtons)	1.55	0.09	0.03	+	–0.05	2.34
Dam siltation vol. (Mm^3)	2.5	0.02	0.008	+	0.03	2.05
Silt dredging vol. (Mm^3)	0.06	0.35	0.005	–	0.14	2.26

to human activities are valid for the Mellegue catchment. Their impacts are well covered through the above illustrated trends.

Discharge, siltation, and water management

The maximum discharge monitored at K13 displays a positive trend with 23.4 $m^3/s/year$. The low-water discharge is also increasing but much more modestly. On the opposite, the maximum water level and the flash flood volumes display small negative trends (Table 3). As far as the sediment loads are concerned, a positive trend is observed. Its linear regression trend is 0.025 Mt/year. Almost the same value is at hand for the siltation trend characterizing the Nebeur dam. The sedimentation process is continuously occurring despite dredging actions performed by the managers. The dredging time series shows a small negative trend (Table 3). All these hydrological and sedimentological trends allow us to better estimate the upstream environmental impact (Figure 8).

Positive trends related to the discharge as well as the siltation reservoir process might be linked to the socio-economic development projects which took place on both sides of the Tunisian-Algerian border. Increasing population pressure of the farming environment, and the political context during the last 50 years are partly responsible for these trends. The late 1960's and the 70's were characterized by the building of hydraulic infrastructure which was performed without paying sufficient attention to the proper management of upper catchment areas. All these projects have induced changes in hydrological and sedimentological response at the watershed level. Consequently, floods are increasingly occurring downstream with gradually lessening discharge (Lebdi et al. 2006; Zahar et al. 2008).

The upward trend of the low water discharge can be explained by the soil characteristics that are not well developed and often shallow. In fact, the high potential evaporation rate caused formation of calcareous crusts at

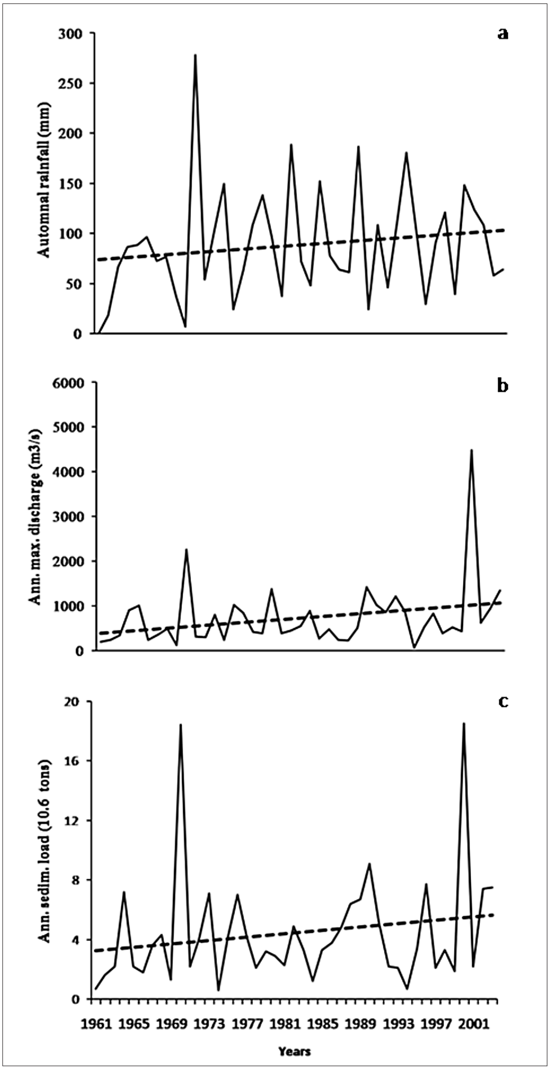

Figure 8. *K 13 station. (a) Positive significant trend related to autumn rainfall. (b) Positive significant maximum discharge. (c) Non significant sediment load trend.*

about 50 cm depth. The latter prevents water from seeping downwards and obstructs efficient drainage. Given wet antecedent conditions, the soil reaches quickly the saturated situation, becomes less able to store water and hence transmit more direct runoff to the wadi explaining the above trend.

The positive trend of sediment load reveals somehow active land degradation. The catchment shows a young geological relief and the rate of erosion prevents soils from reaching maturity. The soil cover degradation that characterizes the studied area has led to much soil erosion leaving a thinner and more uneven soil cover that often exposes the underlying rock surface. This is partly responsible for the serious soil loss problems at Mellegue catchment. The silting speed of the reservoir can also be explained by the stored water management during the different hydrological years (floods or droughts). In fact, dredging does not seem prevent the Nebeur dam from being seriously silted.

As far as the downward trend related to the flash floods and maximum water depth are concerned, explanation can be mostly related to the decrease of the orographic precipitations that characterizes the studied area. In fact, such trend can also be induced by the negative trend of daily exceptional rainfall larger than 12 mm.

Related factors to trends, human activities, and climate change

Explanation of the hydrological trends can be based on the impacts of human activities and climate change. The growing pressure on catchment resources is also putting pressure on the natural hydrological cycle (e.g., He & Jiao 1998; Brown et al. 2005; Hao et al. 2007; Hejazi & Markus 2009; Kliment & Matoušková 2009; Liu et al. 2010; Juahira et al., 2010). Even though a decrease in rainfall was observed since the mid 60's (e.g., Basistha et al. 2009; Subash et al. 2011) the hydrological variable changing point started to be identified in the beginning of the 70's and 80's (e.g., Kliment & Matoušková 2009; Yang et al. 2009; Liu et al. 2010). Obviously, the human influence is crucial on catchment scale in terms of landscape degradation that affects the hydrological regime (e.g., Jebari 2009; Jebari et al. 2010). If we only consider the last hundred years, continuous changes were undertaken by the introduction of new crop cover, deforestation, urbanization, river network modification, and dam buildings, embankment. Therefore relating anthropogenic influence to global climate change are receiving an increasing attention worldwide (e.g., Robinson et al. 2003; Zheng et al. 2007; Chaves et al. 2008; Juckem et al. 2008; Huo et al. 2008; Zhang et al. 2008). This information is required in many emerging practical rural engineering tasks needed for adaptation to the future climate conditions. We can mention especially the tasks of water resource planning, reservoir maintenance, shortage, flood management, and hydro-agricultural infrastructure design (Yang et al. 2009; Subash et al. 2011; Jebari et al. 2015; Verkerk et al. 2017).

Conclusion and Discussion

Generally, time series for annual, seasonal, and monthly rainfall depth as well as the number of rainy days per year show a decreasing trend. Moreover, we notice that the daily rainfall depth is decreasing from 12 towards 7 mm depth. During the studied 44-year period, the four rainiest months giving more than 40 % of the annual precipitation volume have lost about 35 mm.

The trend analysis related to the monthly data is more revealing than the seasonal and annual time series. It displays the periods with water deficit that is crucial for the water storage strategies. Consequently, the use of monthly data better displays the observed trend. The annual and seasonal time series might bias the trend due to irregular monthly variations.

The station locations and the atmospheric circulation patterns of the region seem to be crucial for the trend's behavior. In fact, the Kef station which has higher average precipitation displays a stronger negative trend. This station is followed by the Mellegue station (downstream situation) and then the K13 (upper stream situation) with smallest trend. This is noticeable for the rainfall depth as well as the number of rainy days. As far as the extreme rainfall characteristics are concerned, opposite tendencies are noticeable.

The Kef and Mellegue stations are affected by a drying process. It is mainly characterized by an even contribution over the different seasons in terms of rainfall depth and number of rainy days. The rainiest months during winter are moving towards early spring with a decrease in rainfall amounts. The dominant rainy season during late spring appears to be changing gradually for all stations. A decline in rainfall depth is noticeable all over the studied data. This will probably mean less stored water in the soil and in reservoirs. However, smaller amounts of rainfall do not seem to reduce the solid transport process since reservoir siltation has a positive trend. Consequently, considering the increasing tendency of the maximum discharge, the siltation may become a real threat leading to decrease in dam storage. Finally, for Mellegue catchment, the water resources management should be revised in order to ensure its sustainability for the future climate conditions. This concerns the Tunisian as well as the Algerian parts which should promote an integrated development plan with a better collaboration to synchronize human activities and choices related to the hydrological and sedimentological regimes. For this, it is necessary to use a holistic approach and look at both up- and downstream conditions.

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