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Evaluating annual and seasonal patterns of suspended sediment loads in a semi-arid watershed, central Algeria

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Abstract: Soil loss is a major problem for watersheds management in semi-arid environments. The objective of the present study is to analyze the annual and seasonal patterns of suspended loads and quantify the specific sediment yields in a semi-arid environment of the Mazafran Watershed in central Algeria. The obtained information of water discharge and suspended sediment load, recorded during 19 years, was confronted with precipitation data in order to establish the relationships between the forcing agents and erosive processes. The specific sediment yield was estimated by assessing rating curve data under two types of identified responses. The obtained results allowed confirming the seasonality on suspended sediment transport in the studied basin, which accounts for 56% of the total suspended sediment load estimated in winter. The mean annual suspended sediment is estimated at 17.52 $Mg \cdot ha^{-1} \cdot y^{-1}$. The results highlighted that the type 2 event dominates the production of sediment in the study area in comparison with type 1 event. The analysis of the variability of rainfall erosivity index showed that there is a strong correlation between the annual precipitation and modified Fournier index (*MFI*), and a weak correlation with the monthly precipitation concentration index (*PCI*). Moreover, the spatial distribution of the modified Fournier index at the basin scale showed the highest precipitation aggressiveness in the Southern part of the study region for both type of events, whereas the precipitation aggressiveness low to moderate in the remaining part of the study region.

Keywords: erosivity, seasonality, sediment yield, semi-arid environments, suspended sediment dynamics

INTRODUCTION

Understanding soil loss and the associated erosion processes is quite difficult because the processes of identifying and measuring natural and anthropogenic operations are highly complex [Touaibia *et al.* 1999]. Suspended sediment transport in watersheds is a fairly important topic in the field of hydrology [Tachi *et al.* 2016]. Furthermore, the amount of sediment loads within the river flow has a crucial impact on water quality, reservoir siltation and ecosystem vulnerability, etc. However, today these processes, and their downstream effects, pushed researchers to deepen their understanding of soil erosion mechanisms and transport processes and their interactions in order to explain their causes and consequences [Balla *et al.* 2017].

In the Maghreb countries, siltation and solid transport represent a major concern as they cause a lot of damage, such as the degradation of agricultural soils and water quality, which induce large financial losses for these countries [Meddi *et al.* 1998]. Numerous researchers have worked on the quantification of sediments transported in rivers and streams as well as on the relationships existing between hydro-meteorological drivers in Maghreb environments [Achite, Ouillon 2007; Bouchelkia *et al.* 2014; Bouanani 2004; Bourouba 1996; 1998; Bouzeria *et al.* 2017; Cherif *et al.* 2009; Demmak 1982; El Mahi *et al.* 2012; Ghenim *et al.* 2007; Ghenim, Megnounif 2013; Meddi 1992; 1999; Meddi *et al.* 1998; Selmi, Khanchoul 2016; Tixeront 1960; Yles, Bouanani 2012]. In 114 dams currently operated throughout the Algerian territory, about 32 mln m^3 of water are lost annually as a result of siltation [Mekerta *et al.* 2008].

The Northern part of Algeria is characterized by watersheds that are seriously affected by erosion [Bourouba 2002]. Soil loss and erosion processes are widely encountered in the environment in general, and in semi-arid or temperate regions in particular, which highlights Algeria's vulnerability to erosion [Bouchelkia 2009]. With an annual average of specific sediment yield (*SSY*) between 20 and 40 Mg·ha^{-1}, Algeria is ranked as the country that has the most erodible soil in the world [Demmak 1982].

Furthermore, Algeria is characterized by climatic aggressiveness, which leads to an increase in precipitation intensity and to higher frequency of extreme events, engendering more frequent large-scale flood events. Obviously, these flood events affect the large-scale patterns of erosion and sediment transport within river catchments [Coulthard *et al.* 2012]. It is widely admitted that erosion, runoff and infiltration are mainly due to intense rainfall [Elagib 2011], land-use, and vegetation cover [Nunes *et al.* 2013; Xu *et al.* 2019]. It is well known that rain erosion is the most common and important type of erosion [Lal 1990; Mazour, Rosse 2002; Ryumugabe, Berding 1992]. Aggressive rainfall causes rainstorms and severe water events that cause severe erosion processes such as gullying, rilling or rain-drop impacts [de Luis *et al.* 2010a; Diodato *et al.* 2011; Helioui, Hajri 2015; Modeste *et al.* 2016].

The modified Fournier index (*MFI*) and the precipitation concentration index (*PCI*) may be employed in assessing the aggressiveness of rainfall in the erosion phenomenon [Abd Elbasit *et al.* 2013; Khali, Issa 2016; Khorsandi *et al.* 2012; Lujan, Gabriels 2005; Mello *et al.* 2013]. Also, this would also give a better representation of the aggressiveness of rainfall in the watersheds of Algeria [Bessaklia *et al.* 2018; Meddi 2015; Meddi *et al.* 2014; 2016]. Other researchers such as Taguas *et al.* [2013] and Rutebuka *et al.* [2020] were also interested in developing a relationship between rainfall and the *MFI*, on one hand, and between rainfall and *PCI* on the other.

The quantification of suspended sediments and the available water discharge is essential before the construction of hydraulic structures for the efficient management of water resources [Frigui 1996]. In addition, sediment transport processes and their downstream effects can be understood through the quantification of suspended sediment concentration (*SSC*) and water discharge (*Q*) and their relationship. This relationship, or rating curves, could be used to assess sediment yield and the effects of seasonality on erosive responses, as have previously been reported in Mediterranean environments [Crawford 1991; De Girolamo *et al.* 2015; Farguell, Sala 2006; Ferguson 1987; Millares *et al.* 2020; Selmi, Khanchoul 2016; Warrick 2015].

MATERIAL AND METHODS

STUDY AREA

This study is focused on the central part of Algeria (Fig. 1). This region covers an area of 2056 km^2, with a perimeter of 394.17 km. It is situated between 1° and 1°20' East and 36° and 36°30' North. The coastal basin under study is located 40 km of the capital Algiers. It is part of a series of dunes that form the border between the Wilayas (Provinces) of Algiers and Tipaza. This watershed is limited to the North by Bouzareah, to the East by the watershed of Wadi El Harrach, to the South by the Isser basin and to the West by Wadi Chiffa.

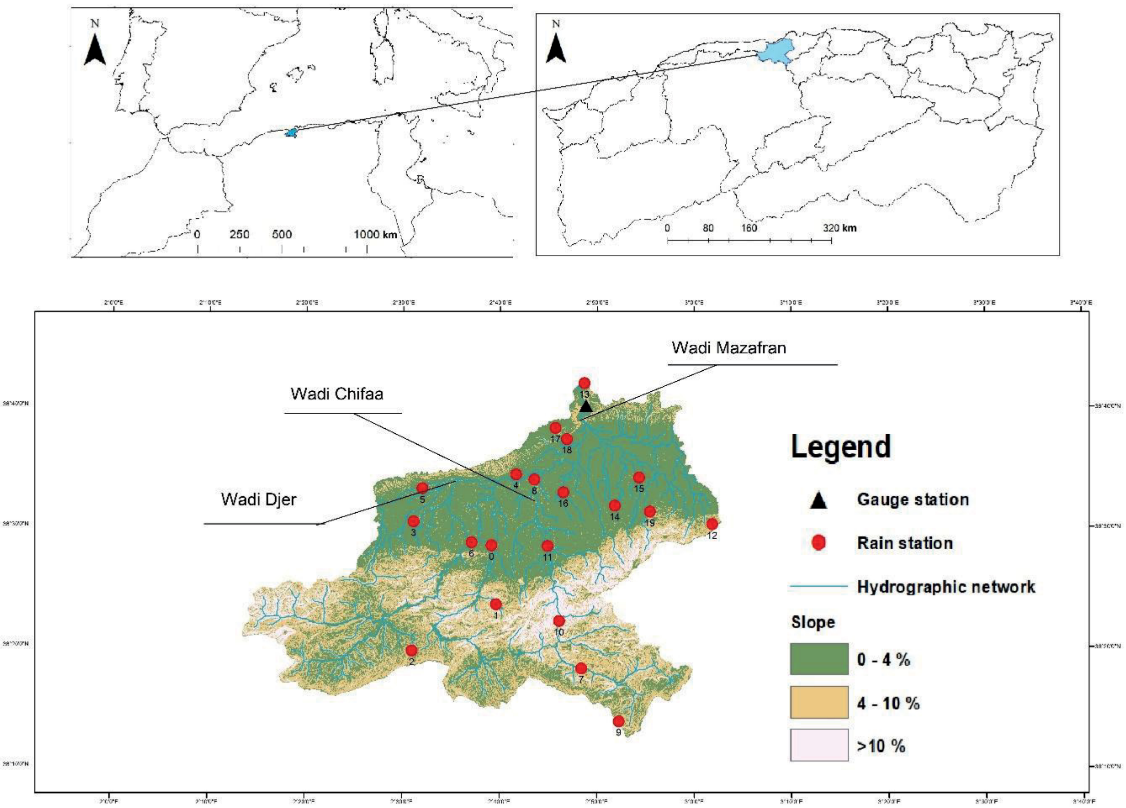

Fig. 1. Hydrographic network for the Mazafran watershed; source: own elaboration

The main types of soils encountered in the Mazafran watershed are alluvial soils and calcareous soils. The Wadi Mazafran has a temperate climate that is characterized by dry summers and winters in the wettest season [MEDDI *et al.* 2016; MESSAOUD 1987] with an interannual temperature of 18°C (Fig. 2a). The topography of the region shows strong contrasts in temperatures, with some implications of the spatio-temporal distribution of rainfall [MEDDI *et al.* 2014], with the wettest periods monthly in November (75 mm) and December (84 mm). It is worth noting that MEDDI *et al.* [2016] estimated that the basin receives between 300 and 800 mm of rain per year; with an interannual average of 517 mm for the period extending from 1976 to 1994. The topography of the basin is characterized by moderate to steep slope, except for the plains and creeks of the main watercourses. The extreme altitudes of the watershed are between 6 m and 1 628 m and the average slope of the main river is 6.2%. Also, 60% of the basin area has slopes with gradients less than 10% (Fig. 1). The described region is characterized by very active erosion processes. Some previous studies reported that the erosion rates in watersheds in central of Algeria are between 1.36 and 32.56 $Mg\cdot ha^{-1}\cdot y^{-1}$ [ACHITE, OUILLON 2007; BOUROUBA 1996; 1998].

AVAILABLE DATA

In this study, the analysis of annual and seasonal patterns of suspended loads and the quantification of the specific sediment yield in the case of Mazafran Basin (Central Algeria) were carried out. For this, the available data of water discharge and suspended sediments, recorded during 19 years at the outlet of the watershed, were used. Moreover, the seasonal rating curves were analyzed and the relationships between rainfall and erosion processes were evaluated.

The data used in the present study include daily discharge and suspended sediment concentration measurements that had previously been carried out by the National Agency for Hydraulic Resources (Fr. Agence Nationale des Ressources Hydrauliques – ANRH) Alger. The Wadi Mazafran is controlled by the hydrometric station "Fer à Cheval" (S13) at the outlet of the Mazafran basin (Fig. 1). The sampling method consisted of obtaining daily water samples, with time steps of 15 min, during floods. Sediment samples were taken at time steps of up to 30 min [GHENIM, MEGNOUNIF 2013]. The depth of water recorded was transformed to flow using a regularly updated calibration curve; this was done for the purpose of analyzing the samples in the laboratory in order to determine the solid concentrations. Figures 2c and 2d give the values obtained during the study period.

The suspended sediment concentration (Fig. 2c, d) was later estimated using the filtration method by weighing the sample after drying in an oven at 105°C for a period of 30 min. The sampling was validated by multiplying the number obtained during floods or variable discharge [GHENIM *et al.* 2007]. The data used relate to the period extending over a period of 19 years, i.e. from 1976 to 1994. These data are presented as a series of pairs of water discharge ($m^3\cdot s^{-1}$) and sediment concentration ($g\cdot dm^{-3}$). On the other hand, 20 meteorological stations distributed over the studied watershed (Fig. 1), were selected to assess the influence of rainfall on soil loss and erosion processes, and to

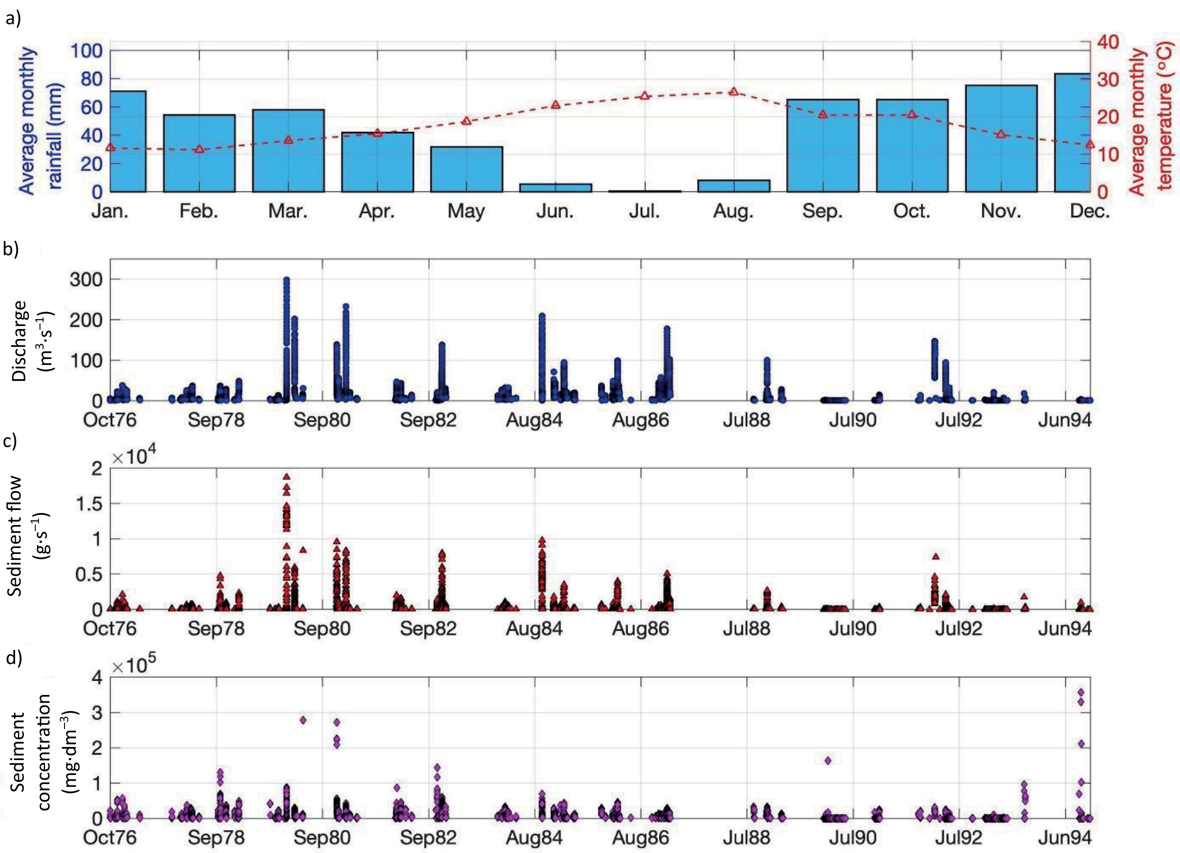

Fig. 2. Available data for the studied watershed: a) ombrothermic diagram at 21 meteorological stations, b) water discharge measurements at the gauge station, c) sediment water discharge measured at the gauge station, d) concentration at the gauge station; source: own elaboration

differentiate between dry and wet periods. The rainfall and temperature data used were provided by the National Meteorological Office (Fr. Office National de la Météorologie – ONM) for the same period of 19 years, from 1976 to 1994.

METHODS

Due to the quality of the available data and highlighting the relationship between concentration and water discharge, the analysis based on the complete annual periodicity gave weak results that are not useful for understanding the relationship. This is why this distinguishing particular types of years. Also, it appears that the first and second types exhibit different behavior. Besides, several conclusions can be drawn between seasons (dry and wet) and the seasons.

Figure 3 gives a schematic presentation of the methodology followed in this work. As can be observed, the methods are organized according to two types of years. This is done for the purpose of assessing the impact the hydrologic characteristics of each type of years on the specific sediment yield. Moreover, the sediment contribution, based on the rating curves, is estimated at the event scale from seasonal and annual periods. The event-scale approach includes the selection of rainfall events for dry and wet periods. The approaches followed are detailed in the following sections. The data available for SSC (g·dm^{-3}), sediment flow Q_s (kg·s^{-1}) and water discharge (m^3·s^{-1}) are analyzed, considering the frequency, periods with and without data, standard deviation and average, minimum, maximum and of measurements [MILLARES *et al.* 2020]. According to the historical records, the periods of wet and dry seasons were determined based on the ombrothermic diagram. The continuous approach of *SSY* assessment was based on the synthesis of rating curves for each period. The annual and seasonal *SSY* estimates were also done from differences observed on the rating curves. The *SSY* was obtained for each year and each season for the entire study period, and lately compared with previously completed estimates. Furthermore, the relationship between *SSY* and water discharges (m^3·s^{-1}) was also analyzed. Besides, the available precipitation data for all 20 measuring stations was analyzed. The average monthly precipitation concentration index (*PCI*), the modified Fournier index (*MFI*), and the modified Fournier index (*MFI* Meddi) were calculated, in order to validate the statistical relationship between each indicator and the average annual precipitation. Finally, the spatial distribution of rainfall erosivity, the *MFI*, and the *MFI* Meddi were performed for the purpose of checking the specific spatial pattern in the spatial distribution of each type.

SUSPENDED SEDIMENT CONTRIBUTIONS

The sediment rating curves were analyzed. The relationship considered was studied in the power form $SSC = \alpha Q^{\beta}$, where the parameters *a* and *b* are regression coefficients which are related to river basin characteristics, such as the topographic relief and runoff [SYVITSKI *et al.* 2000]. The coefficient of determination R^2 and the correlation coefficient ρ are used to validate each adjustment and the statistical relationship between *SSC* and *Q*.

The annual and seasonal water contribution and sediment yield were calculated from [GHENIM *et al.* 2007].

$$A_S = \sum_{j=0}^{N} \frac{(Q_{j+1}C_{j+1})(Q_jC_j)}{2}(t_{j+1} - t_j) \tag{1}$$

where: A_s is the seasonal or annual sediment suspended load (Mg·y^{-1}), C_j is the measured suspended sediment concentrations (kg·m^{-3}), Q is the water discharge (m^3·s^{-1}), t_{j+1}, t_j is the time step between two consecutives measured.

Finally, the specific sediment yield *SSY* (Mg·h^{-1}·y^{-1}) was calculated by dividing the annual sediment yield *Ys* (Mg·y^{-1}) considering the area of the watershed *A* (km²).

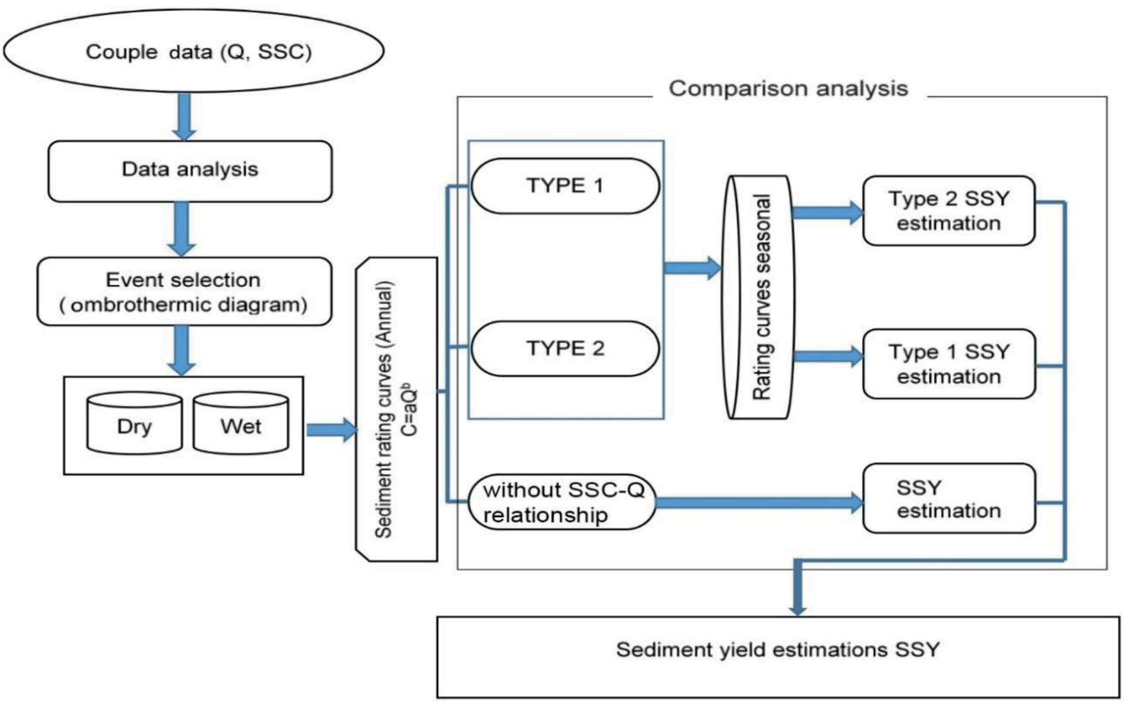

Fig. 3. Methodological flowchart proposed in this study; source: own elaboration

THE RAINFALL EROSIVITY INDICES

Besides, several precipitation indexes were estimated in order to assess their relationship with the suspended sediment transport.

The Fournier index elaborated by FOURNIER [1960] has previously been assessed by several researchers (MEDDI [1992], ODURO-AFRIYE [1996], FERRO *et al.* [1999], MEDDI [2013] and MEDDI *et al.* [2016]). The Fournier index is calculated with the relationship:

$$FI = {P_m}^2/P \tag{2}$$

where: P_{m} represents the precipitation for the wettest month of the year (mm), P is the annual precipitation (mm).

Range of values have been previously assessed between 1 and >100 for different *SSY* rates, as presented in Table 1. ARNOLDUS [1980] developed the modified Fournier index (*MFI*) from the Fournier index (*FI*), which is based on the year-round precipitation (P_i), The modified Fournier index can be expressed as:

$$MFI = \frac{\sum_{i=1}^{12} P_i^2}{P} \tag{3}$$

where: P_i is the average monthly precipitation (mm).

Table 1. Fournier index classes

Class	*SSY* (Mg·ha^{-1} y^{-1})	Fournier index interval	Erosion risk
1	<5	<20	very slow
2	5–12	21–40	slow
3	12–50	41–60	moderate
4	50–100	61–80	severe
5	100–200	81–100	very severe
6	>200	>100	extremely serious

Explanation: *SSY* = specific sediment yield.
Source: ODURO-AFRIYA [1996].

MEDDI *et al.* [2013] stated that the *MFI* explains much of the specific rainfall erosivity and degradation. Moreover, another equation, which allows calculating the index based on the annual precipitation and watershed longitude, is expressed as [MEDDI *et al.* 2014]:

$$MFI \text{ Meddi} = 0.43 \cdot P^{0.94} X^{-0.9}$$

where: P is the annual precipitation (mm) and X the longitude of the watershed (km).

MEDDI *et al.* [2014] used 117 rainfall stations to study and calculate the *MFI* in terms of the annual rainfall. Table 2 shows the range of values of *MFI*. The precipitation concentration index (*PCI*), as proposed by OLIVER [1980], expresses the seasonal and annual variability of precipitation in percent (Tab. 3) [OLIVER 1980]. This index has the advantage of evaluating and comparing the rainfall concentrations between different rainfall stations. The precipitation concentration index is expressed as follows:

$$PCI = \frac{\sum_{i=1}^{12} P_i}{\left(\sum_{i=1}^{12} P_i\right)} \tag{5}$$

Table 2. Modified Fournier index (*MFI*) classes

Class	*MFI* interval	Erosion risk
1	<60	very slow
2	60–90	slow
3	90–120	moderate
4	120–160	high
5	>160	very high

Source: CEC [1992].

Table 3. Conceptual scale to evaluate the PCI index

Class	PCI	Concept
1	0.8–10	uniform
2	11–15	seasonal moderate
3	16–20	seasonal
4	21–50	seasonal and strong
5	51–100	irregular

Source: OLIVER [1980].

RESULTS

ANALYSIS OF SEDIMENT RATING CURVES

All the data were first analyzed to estimate the quality and number of samples recorded. Table 4 shows the record of days in which measurements are done with and without data. A significant number of gaps are observed due to several factors. The most important one is attributed to the absence of events or failed campaign [MILLARES *et al.* 2020]. The events statistical parameters (Tab. 5) confirm the annual variation of the hydrological mode of Wadi Mazafran.

The regression of all separate measurements reduced the correlation coefficient when applied to the 1993 *Q*–*SSC* couples. Because of the low correlation coefficient, different periods of rating curves were analyzed separately, into two groups of years (Tab. 4). A differential annual behavior is observed for each series of years; type I: 1976, 1977, 1979, 1984, and 1991; type II: 1978, 1981, 1985, 1986, 1987, and 1989.

Furthermore, an attempt was made by dividing the data according to different type: winter, spring, summer, autumn, dry and wet season data. The data were divided in order to study seasonal impacts. This allows explaining the effect of seasons on solid transport [YLES, BOUANANI 2012].

Figure 4 allows conducting the analysis of the rating curves through.

Furthermore, Figures 4a, 4b show the values of regression analysis of the relationship between the sediment concentration (*SSC*) and the instantaneous water discharge (*Q*), from samples for each type of years through the identification of periods and seasons.

Table 4. Statistical values of the measured variables (water discharge *Q*, specific sediment yield *SSC*) for the period 1976–1994

Type of data	Period	Measured variable	Analyzed period (days)	Periods without data (days)	Periods with data (days)	Mean	Standard deviation	Min.	Max.
All data	all periods	Q ($m^3 \cdot s^{-1}$)	6649	4656	1993	36.18	47.31	0	298
		SSC ($mg \cdot dm^{-3}$)	6649	4656	1993	16751	36347	0	356000
Type 1	1976	Q ($m^3 \cdot s^{-1}$)	365	307	58	8.76	10.25	0.34	37.04
		SSC ($mg \cdot dm^{-3}$)	365	307	58	16263.39	20468.59	290	56570
	1977	Q ($m^3 \cdot s^{-1}$)	365	334	31	9.12	8.78	0.60	29.20
		SSC ($mg \cdot dm^{-3}$)	365	334	31	5627.74	8345.98	420	35500
	1979	Q ($m^3 \cdot s^{-1}$)	365	267	98	9.76	11.78	0.28	48.20
		SSC ($mg \cdot dm^{-3}$)	365	267	98	11916.84	12019.25	270	48120
	1984	Q ($m^3 \cdot s^{-1}$)	365	179	186	60.89	57.70	0.50	209
		SSC ($mg \cdot dm^{-3}$)	365	179	186	19249.62	15859.18	80	68640
	1991	Q ($m^3 \cdot s^{-1}$)	365	346	19	3.65	5.04	0.01	14.40
		SSC ($mg \cdot dm^{-3}$)	365	346	19	8936.84	9189.44	0	24700
Type 2	1978	Q ($m^3 \cdot s^{-1}$)	365	189	176	11.14	9.45	0.11	36.30
		SSC ($mg \cdot dm^{-3}$)	365	189	176	14802.90	19728.07	270	129960
	1981	Q ($m^3 \cdot s^{-1}$)	365	255	110	77.15	70.30	2.66	232.40
		SSC ($mg \cdot dm^{-3}$)	365	255	110	15824.09	12491.57	80	42230
	1985	Q ($m^3 \cdot s^{-1}$)	365	191	174	27.73	23.72	0.32	94
		SSC ($mg \cdot dm^{-3}$)	365	191	174	10306.38	10413.07	280	42600
	1986	Q ($m^3 \cdot s^{-1}$)	365	160	205	28.06	23.49	0.35	98.80
		SSC ($mg \cdot dm^{-3}$)	365	160	205	8636.90	10145.54	0	45090
	1987	Q ($m^3 \cdot s^{-1}$)	365	219	146	51.96	41.31	2.02	177
		SSC ($mg \cdot dm^{-3}$)	365	219	146	8414.38	8515.70	40	28560
	1989	Q ($m^3 \cdot s^{-1}$)	365	347	18	10.26	9.43	0.85	27.88
		SSC ($mg \cdot dm^{-3}$)	365	347	18	4462.78	4619.26	40	13040

Source: own study.

Table 5. Solid contributions in Wadi Mazafran basin (1976–1996)

Parameter	Annual	Season			Period	
		autumn	winter	spring	wet	dry
Water discharge ($m^3 \cdot s^{-1}$)	17.11	30.71	41.43	28.85	38.33	28.88
Suspended sediment concentrations ($g \cdot dm^{-3}$)	16.37	23.50	15.03	9.25	13.99	19.76
Suspended solid flow ($kg \cdot s^{-1}$)	251.16	721.71	622.56	266.98	536.33	570.77
Solid annual contribution (10^6 $Mg \cdot y^{-1}$)	4.02	1.88	5.94	1.20	7.18	1.84
Specific sediment yield ($Mg \cdot ha^{-1} \cdot y^{-1}$)	17.5214	9.1448	28.8824	5.8267	34.9112	8.9362

Source: own study.

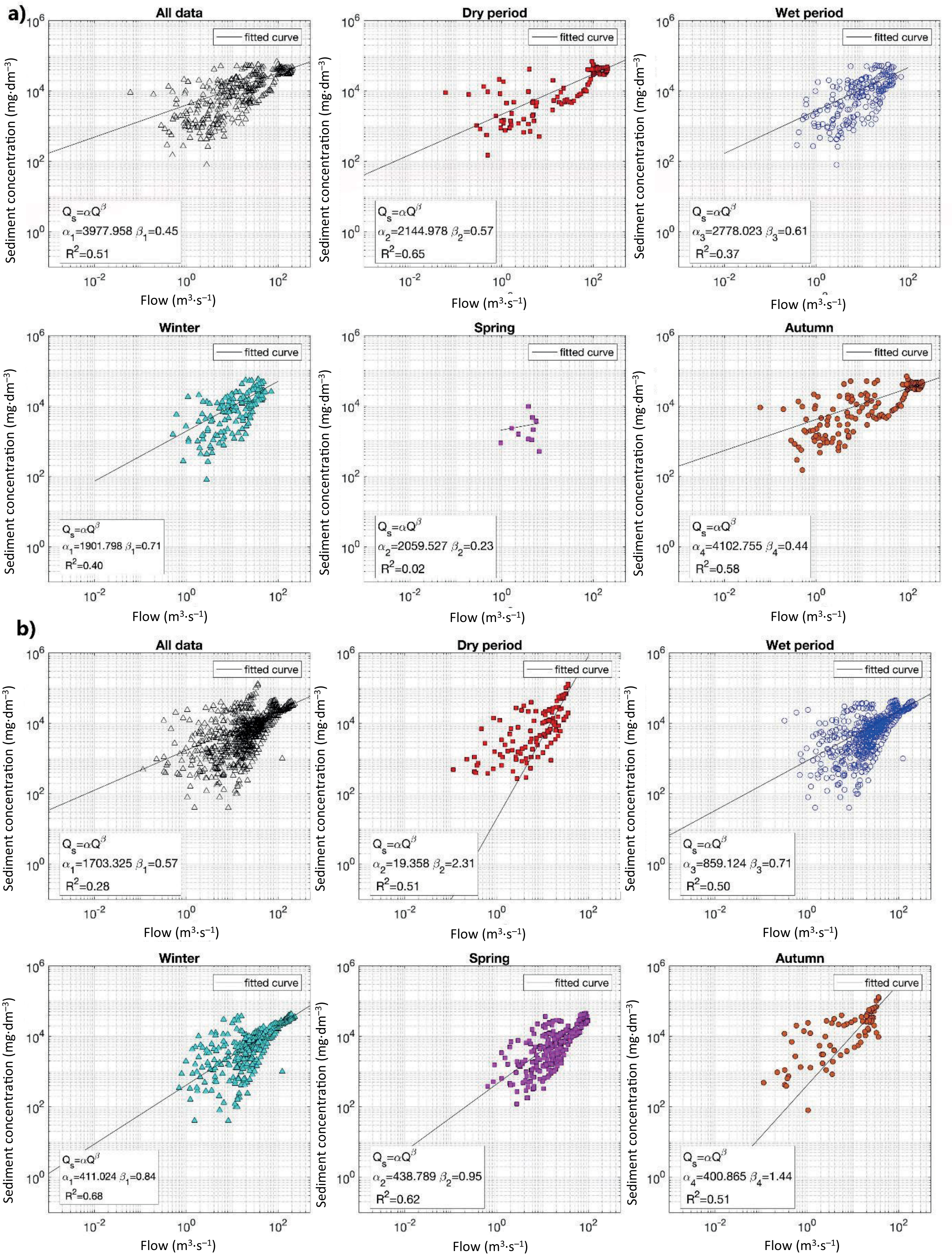

Fig. 4. Sediment rating curves developed on instantaneous water discharges and instantaneous sediment discharges according to different scales: a) type 1, b) type 2; the adjustment based on the $SSC = \alpha Q^{\beta}$ relationship, with fitted parameters and the coefficient of determination; source: own study

This regression analysis for each type has not provided a fairly strong correlation coefficient (type 1: R^2 = 0.51; type 2: R^2 = 0.28) and the *C*–*Q* data show a distribution mainly at highest values (Fig. 4a, b).

SPECIFIC SEDIMENT YIELD ESTIMATIONS (*SSY*)

The rating curves allowed determining the average sediment yield rate in Wadi Mazafran, which made it possible the estimation of the contribution of the sediment loads transported by Wadi Mazafran and the evaluation of the *SSY*. The total estimated *SSY* in Wadi Mazafran for annual and seasonal periods for each type are given in Figure 5, and details are reported in Table 5. Table 6 summarizes the annual distribution of sediment yields during the period from 1976 to 1994; the results obtained are shown in Figure 6.

The temporal relationship of *SSY* for each type of event is identified in this investigation. It is seen how type 2 events dominate the sediment yield in the study area as compared to type 1 events (Fig. 6).

For example, during the hydrologic year 1987/1988, the stream flow, sediment concentration and sediment load were much higher than average the annual suspended sediment load 17.52 Mg·ha^{-1}·y^{-1}. Indeed, during that year, 9.53·10^6 Mg of suspended sediments were transported in the Wadi Mazafran (Tab. 6). This was mainly due to the intensity of rainstorms that exceeded 100 mm·d^{-1} in late November, producing high concentrations of bare soil which was drier than average [KHANCHOUL, JANSSON 2008]. The mean annual water discharge during the study period was 17.11 m^3·s^{-1}. This was too much lesser degree for type 2, where the annual suspended sediment load did not exceed 14 Mg·ha^{-1}·y^{-1}. This was recorded in 1976, where the average solid annual

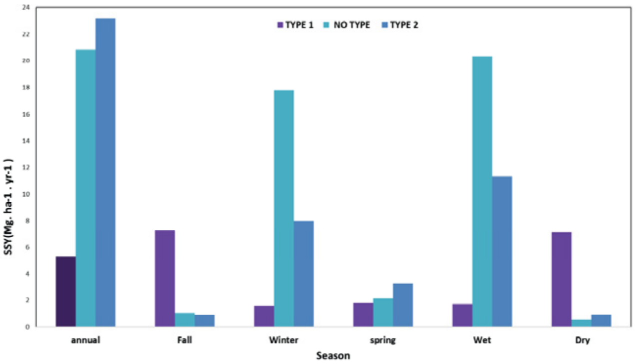

Fig. 5. Specific sediment yield (*SSY*) at different time scales, for each type of years; source: own study

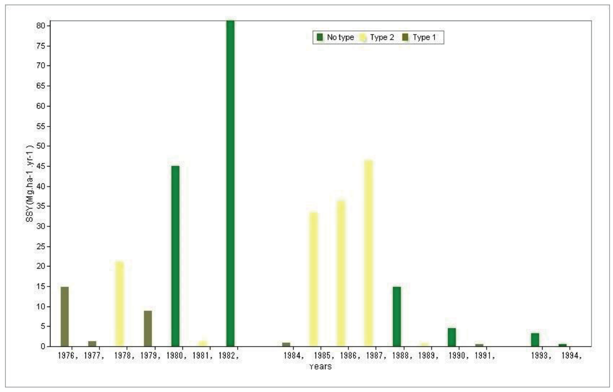

Fig. 6. Annual specific sediment yield (*SSY*) of Wadi Mazafran basin by differencing the type of identified periods; source: own study

Table 6. Annual distribution of suspended solids input (Mg·y^{-1}) and specific sediment yield (Mg·ha^{-1}·y^{-1}) in Wadi Mazafran watershed (1976–1996)

Period	Year	Water discharge (m^3·s^{-1})	Suspended sediment concentration (g·dm^{-3})	Suspended solid flow (kg·s^{-1})	Solid annual contribution (10^6 Mg·y^{-1})	Specific sediment yield (Mg·ha^{-1}·y^{-1})
Type 1	1976	9.25	10.49	97.05	3.06	14.87
	1977	9.12	5.63	51.31	0.26	1.25
	1979	9.83	11.91	117.07	1.82	8.87
	1984	1.77	3.28	5.81	0.18	0.89
	1991	8.94	6.55	58.52	0.11	0.55
Type 2	1978	11.14	14.80	164.95	4.35	21.16
	1981	1.88	4.27	8.03	0.25	1.23
	1985	28.86	10.31	297.48	6.89	33.50
	1986	34.26	8.62	295.21	7.47	36.32
	1987	86.44	8.38	724.72	9.53	46.34
	1989	2.32	4.46	10.34	0.13	0.65
Discarded	1980	9.25	31.72	293.50	9.26	45.02
	1982	37.29	21.30	794.25	16.71	81.28
	1988	37.87	15.43	584.15	3.03	14.75
	1990	2.37	12.51	29.64	0.93	4.54
	1993	1.86	11.46	21.34	0.67	3.27
	1994	2.72	48.34	131.39	0.10	0.47

Source: own study.

contributionload 3.06 Mg·y^{-1} of suspended sediments were transported was much lower than the overall average (Tab. 6). However, the periods in which no correlation of curve ratings were identified showed very large variability (from 0.5 to 81.5 Mg·ha^{-1}·y^{-1}). Considering the *SSY* results (Tab. 5) for each type separately, it is seen that type 2 events dominate the production of sediments in the study area, with an average suspended sediment yield equal to 23.20 Mg·ha^{-1}·y^{-1}, as compared to type 1 events for which the average suspended sediment yield is equal to 5.29 Mg·ha^{-1}. These figures confirm that the most watersheds in the coastal areas of Algeria contain fairly large amounts of sediments, with more than 10 Mg·ha^{-1}·y^{-1} [DEMMAK 1982].

Figure 7 clearly illustrates the results of comparison between the total sediment loads and runoff processes (average yearly discharge) for each type of events. As can be observed from that figure, the production of sediment from type 2 is strongly correlated with the average yearly discharge (R^2 = 0.91). However, this relationship is less significant for type 1 event. As indicated earlier in this Figure 7, winter is the most contributing season in sediment loading (Fig. 4a, Tab. 5). This is mainly attributed to monsoon rains [KHANCHOUL *et al.* 2006]. For example, in 1986, a volume of about 2.17 mln m^3 of water and around 6.89 Mg of sediment were transported. The highest water contribution was recorded in February with a volume of 1.14 mln m^3. This very strong relationship of type 2 event with the runoff processes proves that seasonal rains and prolonged or consecutive precipitation events in the winter period are responsible for the surface runoff and consequently soil erosion [WINTERAEKEN, SPAAN 2010].

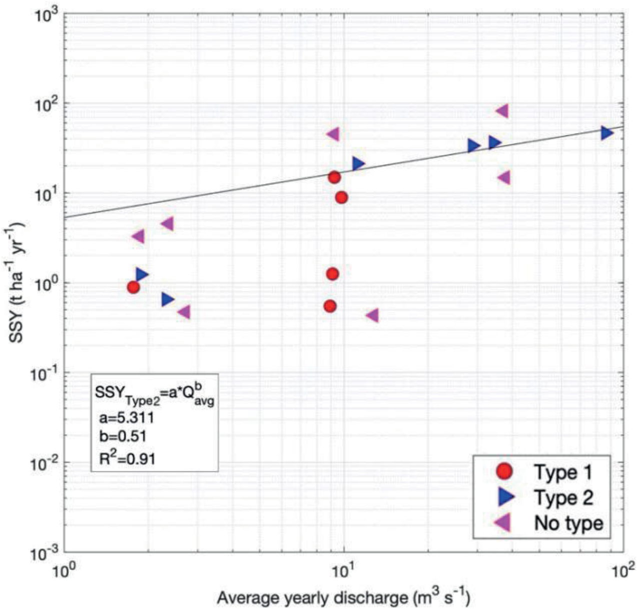

Fig. 7. Relationship between the estimated contribution of sediment load (*SSY*) for each type and the average yearly discharge; source: own study

RAINFALL AND SEDIMENT YIELD INTERACTIONS

The average annual precipitation values for the study area varied between 285.8 and 898.7 mm. To highlight the annual changes more clearly, Table 7 summarizes the average monthly precipitation concentration index (*PCI*), modified Fournier index (*MFI*), modified Fournier index of Meddi (*MFI* Meddi), the sediment load and the annual rainfall values for the study period.

Table 7. Year-to-year variations in annual precipitation (P_{ann}), specific degradation (Mg·ha^{-1}·y^{-1}), modified Fournier index (*MFI*), modified Fournier index by Meddi (*MFI* Meddi) and precipitation concentration index (*PCI*); period 1976–1994

Period	Year	*SSY* (Mg·ha^{-1}··y^{-1})	Annual precipitation (mm)	*MFI*	*MFI* Meddi	*PCI* (%)
Type 1	1976	14.87	417.3	74.22	85.08	14.74
	1977	1.25	441.3	71.68	62.95	19.61
	1979	8.87	558.6	105.87	131.62	13.21
	1984	0.89	563.9	143.31	137.58	15.66
	1991	0.55	628.2	110.95	93.23	14.87
Type 2	1978	21.16	772.15	55.20	62.76	15.15
	1981	1.23	250.43	81.19	84.89	16.16
	1985	33.50	474.64	62.67	70.05	17.06
	1986	36.32	610.9	113.28	103.27	15.30
	1987	46.34	429.1	40.99	56.72	18.30
	1989	0.65	233.2	47.11	59.41	17.19
Discarded	1980	45.02	763.25	105.25	96.36	18.31
	1982	81.28	527.43	175.93	128.29	22.56
	1988	14.75	578.9	84.28	82.97	12.53
	1990	4.54	707.3	66.92	76.52	13.70
	1992	0.43	341.6	63.70	75.18	19.98
	1993	3.27	262.7	63.82	64.98	14.43
	1994	0.47	450.2	81.67	102.66	16.88

Source: own study.

The modified Fournier index values obtained vary between 56.72 and 137.58. According to the index classification proposed in the CEC [1992], the rainfall in the region of study has moderate to high erosivity. These high values may be explained by the significant rainfall occurrence during a very short period of the hydrological year [GHENIM, MEGNOUNIF 2013].

According to the *PCI* classification, it was found that the study area has a moderate seasonal rainfall with a minimum of 12.53% and a maximum of 22.56%. The highest values were seen in 1982 and the lowest values were observed in 1988. These results are consistent with those reported in northern Algeria by MEDDI *et al.* [2014].

In order to study the variable characteristics of the precipitation indices, we detailed the linear relationships between the indicators (*PCI*, *MFI*) and the annual precipitation for each type of data in the extreme central part of Algeria, during the period from 1976 to 1994. Figure 8a shows the relationship between the *MFI* and the annual accumulated precipitation. As can be seen, there is a strong linear relationship. Indeed, a positive correlation is observed in both cases types (R^2 = 0.91, R^2 = 0.66) and, Figure 8b shows the relationship between the *PCI* and the annual accumulated precipitation. As can be seen, there is a very weak linear relationship (R^2 = 0.22, R^2 = 0.11). Indeed, the opposite correlation is observed in both cases types.

The values of the annual precipitation over the period extending from 1970 to 1994 for each type of events are summarized in Table 7. These results highlight a spatial variability for type 1 ranging on average from 367 to 952 mm, with an average spatial variability of 643.68 mm. For periods identified as type 2, the variability ranges on average from 368 mm to 842 mm, with an average spatial variability of 533 mm. The Northern

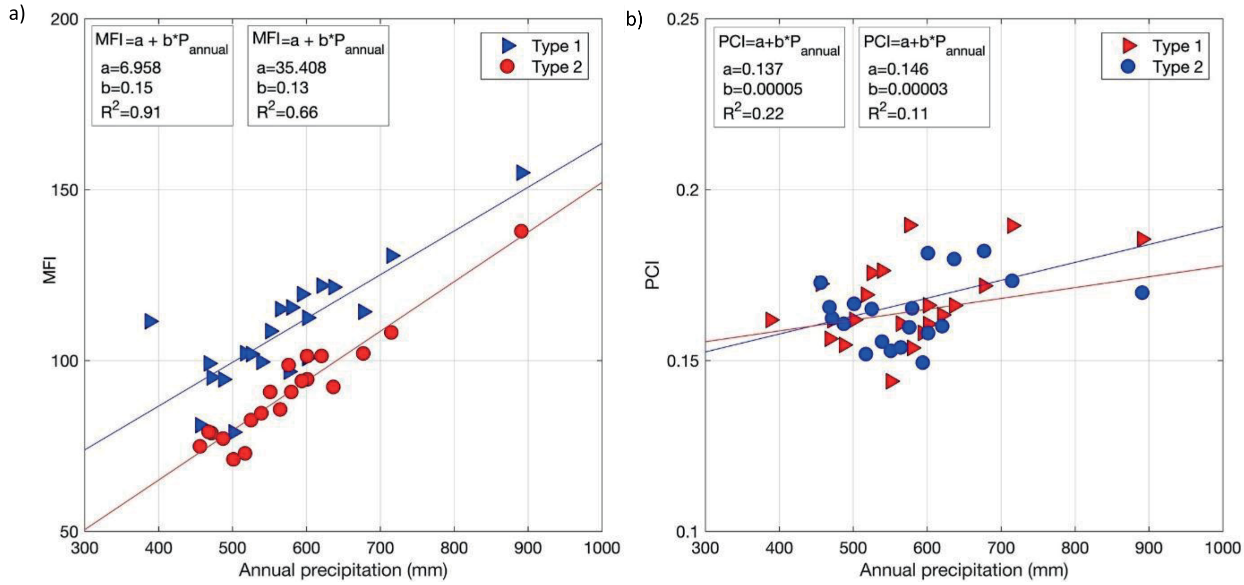

Fig. 8. Relationship between: a) the modified Fournier index (*MFI*) and average annual precipitation (*P*) in 21 rainfall gauge stations, b) the monthly precipitation concentration index (*PCI*) and the average annual precipitation (*P*) in 21 rainfall gauge stations; the adjustment based on the $SSC = \alpha Q\beta$ relationship, with fitted parameters and the coefficient of determination; source: own study

region recorded higher annual precipitation at the station of El Hamdania (S10) (953 mm) and (843 mm) for type 1, type 2 respectively. However, the low annual precipitation values were recorded for type 1 at Sidi Rached Helloula (S4) (368 mm) and for type 2 at Attaba Cave (S6) (369 mm). The values obtained over the whole catchment varied for type 1 from 0.14 to 0.19. The highest values was recorded at the station of El Hamdania (S10) (0.19). However, for type 2 it was from 0.15 to 0.18, with the highest values found at the station of Soumaa (S19) (0.18). In addition, the lowest values were observed for type 1 at the station of the Ouzera (S9) (0.14), however, for type 2 this value was 0.15 was at Fer Cheval (Tab. 8).

Table 8. The variation values of the precipitation concentration index (*PCI*), rainfall (*P*), the modified Fournier index (*MFI*), the modified Fournier index of Meddi (*MFI* Meddi), 20 rain gauge stations across central of Algeria (period 1976–1994)

Station			Values for type 1				Values for type 2			
No.	name	code	*P* (mm)	*MFI*	*PCI* (%)	*IMF*	*P* (mm)	*MFI*	*PCI* (%)	*MFI* Meddi
13	Fer Cheval	21201	613.12	101.21	0.17	102.09	427.74	66.74	0.15	72.85
0	Pont de Bouroumi	21005	565.30	91.09	0.16	95.03	463.83	76.44	0.16	78.76
1	Rouabah	21012	676.94	112.22	0.16	112.52	562.56	91.58	0.16	94.49
2	Ain Dem	21013	590.40	92.70	0.16	99.16	464.58	77.96	0.17	79.10
3	Ameur El Ain	21020	601.96	103.58	0.17	100.72	605.67	114.11	0.18	101.28
4	Attatba Cave	21022	670.32	107.96	0.16	111.46	368.64	73.74	0.16	79.61
5	Sidi Rached Helloula	21024	367.65	86.63	0.15	94.47	453.98	73.03	0.16	77.19
6	El Afroun Dne 44	21026	480.48	81.38	0.17	81.06	439.53	77.64	0.17	74.88
7	Prise de Medea	21102	796.52	144.73	0.19	130.68	651.22	115.57	0.17	108.22
8	Rn4 Chiffa	21105	610.79	106.94	0.18	101.88	488.16	83.08	0.17	82.59
9	Ouzera	21112	653.84	93.69	0.14	108.62	540.87	83.93	0.15	90.81
10	El Hamdania	21115	952.92	176.77	0.19	154.93	842.78	146.02	0.17	137.85
11	Chiffa	21117	697.26	107.03	0.15	115.52	540.28	90.29	0.17	90.81
12	Mouzaia Sp	21132	465.62	75.78	0.16	79.04	415.52	68.73	0.17	71.09
14	Beni Mered	21208	739.64	120.59	0.16	121.91	608.30	98.92	0.16	101.32
15	Boufarik Pepiniere	21209	724.40	115.65	0.16	119.44	562.07	85.49	0.15	94.03
16	Wadi El Alleug	21210	597.26	104.66	0.18	99.60	500.85	79.62	0.16	84.56
17	Kolea	21211	694.66	111.94	0.16	115.04	508.90	79.59	0.15	85.71
18	Kolea Secteur	21233	593.94	116.87	0.19	96.76	604.07	96.78	0.16	98.64
19	Soumaa	21234	691.16	117.74	0.17	114.24	613.60	110.40	0.18	102.09

Source: own study.

To establish the map representing the spatial variability of the precipitation aggressiveness (*MFI*, *MFI* Meddi), 20 rainfall stations were considered. The results are illustrated in Table 8. The rainfall erosivity trend measured by the modified Fournier index (*MFI*) and the modified Fournier index of Meddi (*MFI* Meddi) is illustrated in Figure 9. As observed, the area under study is strongly characterized by the values of the modified Fournier index for this region.

DISCUSSION

ANALYSIS OF SEDIMENT RATING CURVES

The results of the adjustment models for seasons and events showed correlation coefficients ranging from 0.02 to 0.68 (Fig. 4a, b). Depending on the types of years, the correlation coefficient is much larger for the seasons of type 2, i.e. autumn, winter, and spring, dry and wet season for which this coefficient is equal to 0.51, 0.68, 0.62, 0.51, and 0.50, respectively. For type 1, the correlation coefficient for the seasons of autumn, winter, spring, dry and wet season is equal to 0.58, 0.40, 0.02, 0.65 and 0.37, respectively. These results are confirmed by the seasonal influence and irregularity in the types of years on the phenomenon. For type 1, the highest concentration values are usually observed from 1976 to 1984. Moreover, large variations in consecutive years can also be noticed. The highest values of water discharge are observed in 1984. As can be observed in the years of type 1, the average water discharge is 18.44 $m^3 \cdot s^{-1}$ and the concentration of suspended sediments is 12.4 $g \cdot dm^{-3}$.

In the years of type 2, there is a downward trend in the concentration values, with an average value of 11.041 $g \cdot dm^{-3}$. In addition, significant differences were found in the flow between the years, with a peak recorded in the year 1981, with an average values of 34.38 $m^3 \cdot s^{-1}$.

SEDIMENT YIELD ESTIMATIONS

In general, the study of seasonal distribution of sediment load indicates that the greatest flux of suspended solids in the study area throughout the considered period is generally recorded in winter. The results in Table 7 indicate that 5,938,790 Mg of sediments were transported during the winter season, which represents 56% of the total sediment load, with a maximum *SSY* value of 28.88 $Mg \cdot ha^{-1} \cdot y^{-1}$. This is higher than the estimated annual average of 17.52 $Mg \cdot ha^{-1} \cdot y^{-1}$. In addition, 1,880,345 Mg (Tab. 8) were transported during the autumn season. This quantity is the second largest sediment load that was transported during that season with a load reaching 320,000 Mg, with 19% of *SSY*. Moreover, Table 7 shows that the transported sediment load is higher in the wet season as compared to the dry season.

On the other hand, the high values recorded in the winter season, and generally in the wet season, explain the effects of monsoon rains [KHANCHOUL 2006] and severe rainstorms [LEDERMANN *et al.* 2010] in the transport of sediments. In addition, factors such as the morphological characteristics, vegetation, land use and geology of the terrain make Wadi Mazafran a preferred environment for the erosion phenomenon [BOUROUBA 2002].

It is worth noting that most watersheds in the coastal areas of Algeria contain fairly large amounts of sediments, sometimes above 10 $Mg \cdot ha^{-1} \cdot y^{-1}$ [DEMMAK 1982]. The sediment yield observed in this work is greater than the mean annual sediment

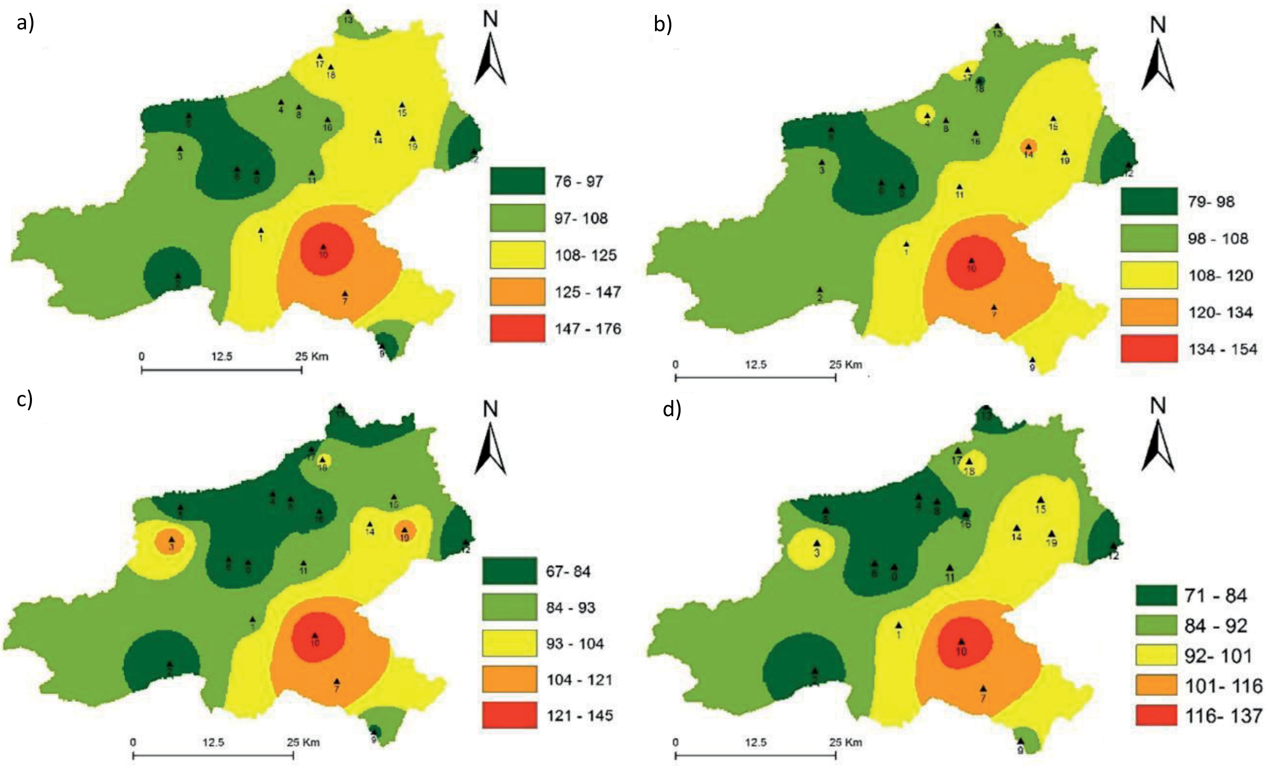

Fig. 9. Spatial distribution of: a) modified Fournier index type 1, b) modified Fournier index of Meddi type 1, c) modified Fournier index type 2, d) modified Fournier index of Meddi type 2; source: own study

yield of other Algerian watershed such as Wadi Sebdou with 9.37 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Bouanani 2004], Wadi Isser with 8.00 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Millares *et al.* 2020], Wadi El Hammam with 1.11 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Cherif *et al.* 2017], Wadi Abd with 1.36 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Achite, Ouillon 2007]. Conversely, these values are relatively low in comparison with the excessive erosion in basins of other Wadis in Algeria, such as Wadi Ebda with 18.75 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Meddi 1999] and 26.10 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Bourouba 1996], Wadi Djer with 32.56 $Mg \cdot ha^{-1} \cdot y^{-1}$ [Bourouba 1998].

RAINFALL AND SEDIMENT YIELD INTERACTIONS

Soil erosion is directly related to the characteristics of rainfall [Liu *et al.* 2018] and to rainfall erosivity [Hedding *et al.* 2019]. The variation in sediment load is well explained by the modified Fournier index (*MFI*), which is not the case for precipitation [Meddi 1992; 2013].

The modified Fournier index values obtained vary between 56.72 and 137.58. The rainfall in the region of study has moderate to high erosivity. These high values may be explained by the significant rainfall occurrence during a very short period of the hydrological year [Ghenim 2013]. The values of the rainfall erosivity index obtained for the Mazafran basin were found similar to those already found in other parts of Algeria and Morocco [Haddou *et al.* 2020], for the same rainfall period. These values are similar to those obtained by Meddi *et al.* [2014] who used the rain aggressiveness index in central Algeria for the period extending from 1950 to 2006.

According to the *PCI* classification, it was found that the study area has a moderate seasonal rainfall with a minimum of 12.53% and a maximum of 22.56%. The highest values were seen in 1982 and the lowest values were observed in 1988. These results are consistent with those reported in Northern Algeria by Meddi *et al.* [2014].

Furthermore, the slopes of the curves are very similar in both cases, which indicates a similar dynamics of the relationship between the *MFI*s and annual precipitation [Amara *et al.* 2020; Bessaklia *et al.* 2018; Taguas *et al.* 2013], for the two types of events. However, as can be observed from the scale factor, marked by parameter a of the adjusted linear relationship, the value obtained is up to 5 times higher for type 1 events than for type 2 events (Fig. 8a). Moreover, the relationship between the annual accumulated precipitation and *PCI* index, for both types of events, is very weak (Fig. 8b), which indicates an opposite behavior of the relationship between the annual and seasonal precipitation concentration indices. Thus, the monthly variation of precipitation during the year is predominant. This change is mainly due to the irregular distribution of precipitation. Concerning the *PCI*, an irregular distribution of precipitation was found in the Mazafran basin. These results agree with those of de Luis *et al.* [2010] for the Mediterranean region of the Iberian Peninsula. Nunes *et al.* [2013] reported the same observation for Southern Portugal.

High precipitation aggressiveness was detected in the Southern part of the study region for both types of years (Fig. 9). It reached the maximum value at the stations of Sidi Rached Helloula (S5), RN4 Chiffa (S8), whereas precipitation aggressiveness was moderate to low in most of the study area. The dominant *MFI* values in the first type are higher than those observed in the second type. The spatial variation observed for that index depends on the annual rainfall in the study region [Laborde 1988]. The change in the precipitation regime may be explained by *MFI*. This change has led to accelerated soil erosion in the Mediterranean basins [Bou Kheir *et al.* 2001; Shaban, Khawlie 1998], which explains the increase in the *MFI* for type 1.

CONCLUSIONS

Wadi Mazafran is characterized by much larger quantities of sediments in comparison with those found in the rest of Algerian coastal rivers. Data relative to water discharge and suspended sediment concentrations for Wadi Mazafran were analyzed. They allow estimating the suspended sediment yield for the period of 19 years.

A strong interannual and seasonal variability of sediment quantities were observed. In addition, the sediment load could be calculated from the sediment rating curves. A good correlation was found between these rating curves. This may give a reasonable approximation of suspended sediment yield estimates and its interannual and seasonal variability. To understand these changes, the sediment rating curves were assessed for the entire study period and were subsequently classified in two periods, based on their responses. As a global perspective, the results obtained indicated that the estimated suspended sediment yield for Wadi Mazafran was around 17.52 $Mg \cdot ha^{-1} \cdot y^{-1}$. This rate is comparable to other rates recorded in the vicinity of the study site.

Furthermore, the findings suggested that type 2 periods dominate the production of sediments in the study area in comparison with type-one periods. However, the periods in which no correlation between the ratings curves presented a very large variability (5–83 $Mg \cdot ha^{-1} \cdot y^{-1}$).

Moreover, the results obtained indicated that the highest suspended sediment load was estimated in winter. This accounted for 56% of the total contributions during the study period. This percentage value could be related to the change in vegetation cover and rainstorms that occurred in the study area.

Furthermore, the analysis of the relationship between the estimated sediment load contribution for each type and the average yearly discharge indicates that the sediment production from type 2 events also has a strong correlation with runoff processes. This relationship is less significant for type 2 periods.

The study investigated the spatial and temporal variability of the rainfall erosivity index represented by the modified Fournier index, and the precipitation concentration index from 20 rainfall stations. In addition, the correlation between the precipitation concentration index (*PCI*) and annual precipitation is very weak for both types of periods. Besides, the variations of the *PCI* indicate that seasonal precipitation does not necessarily follow a constant annual pattern. Moreover, based on the values of the *MFI* that the southern part of the study region,for both types of years, at the stations of Sidi Rached Helloula (S4) and Rn4 Chiffa (S8), presented high precipitation aggressiveness. However, This aggressiveness was low to moderate in most of the study region. Furthermore, there is a strong linear relationship between the Modified Fournier Index and the annual rainfall accumulation.

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