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ORIGINAL ARTICLE

Suspended sedimentary dynamics under Mediterranean semi-arid environment of Wadi El Maleh watershed, Algeria

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Abstract

Soil degradation due to erosion by water is a serious environmental problem for the integrated management of basins, affecting the soil and water resources in Algerian region. Pluvial flood has been increasingly understood as a major threat that has presented a significant risk for many watersheds worldwide, estimation of runoff and sediment yield is primarily required for watershed development planning involving soil and water conservation measures, considering runoff is responsible for sediment detachment and their transport during the erosion processes. In this context, the phenomenon reaches spectacular values in many Algerian watersheds; in this case, it is very severe in flood period, many models have been developed and their application has been spread. In this study, water flow discharge and suspended sediment concentration have been modelled using sediment rating curve approach, this model is the large discussed model; it is the best significant equation for the majority of Algerian basins, this equation which has a power law form (i.e. $C = aQ^b$, where a and b are fitted parameters), explains, more than 72% for the whole floods observed during 17 years in Wadi El Maleh watershed, the flood contribution in annual suspended yield is variable; it can reach more than 92%, which is the case of flood; January 19, 1985, while, at inter-annual scale, the percentage is 24% and 43% in total water and suspended sediment yields, respectively; for all studied floods, a good logarithmic correlation between sediment rating curve parameters is observed, this outcome can help to extrapolate this model to other events.

Keywords Flood · Soil degradation · Sediment rating curve · Wadi El Maleh · Algeria

List of symbols

S_D	Standard deviation
Cv	Coefficient of variation
Wy	Water yield
Sy	Sediment yield
P	Monthly rainfall
R^2	Coefficient of determination
SRC	Sediment rating curve
Q_L	Water flow discharge
Q_S	Sediment discharge
C	Suspended sediment concentration

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Introduction

Being able to quantify the magnitude of sediment processes in Wadis is of primary importance given the repercussions it has both on the natural environment and human activities, such as dam siltation, degradation of aquatic habitats, over flooding, shoreline instability (Grauso et al. 2020). Extreme rainfall events, such as floods, are generated by heavy rainfall and excess runoff removed from streams as they overflow (Ghosh 2013; Ali et al. 2018). These exceptional flooding events are generated by high-intensity rainfall that occurs in a short period of time on watersheds that have steep slopes and low vegetation cover, producing sudden flows at high speed (Xiao 1999), and the variation in frequency and intensity of extreme precipitation will immensely affect social and natural environments (Xu et al. 2009; Zhao et al. 2017, 2019).

Currently, floods have become the overlord catastrophic natural hazard with economic damage and loss of lives, particularly in urban regions (Tesema et al. 2020). They cause very costly disasters in terms of property damage and human casualties and have a serious effect on the economy, agriculture and other human activities (Coskun et al. 2010; Zhao et al. 2019).

Flash floods with high sediment concentrations are common natural events in rivers, which generate hazards in cities and other smaller human communities located near main river channels (EEA 2005; Wilby et al. 2008; Kavian et al. 2016; Guo et al. 2019; Contreras et al. 2020).

Suspended sediments delivered in Wadis and rivers are a key issue in watershed management, they are a natural part of river systems, and contain organic and inorganic materials transported by water (Bridge 2003; Koiter et al. 2013; Fryirs and Brierley 2013; Dean et al. 2016; Vercruysse et al. 2017), their transport in rivers is determined by the interaction between processes operating at multiple scales (Harvey 2002; Fryirs 2013; Vercruysse et al. 2017). Water erosion is process where soil sediments are detached from land surface, transported and deposited to another point under erosive agents (Nillama 2020).

The phenomenon consists of the modification of natural topography due to rainfall intensity and particles cohesion moving from its natural position by destroying the bonds to deposit (Benselama et al. 2018). Erosion can eliminate the fertile topsoil, and cause soil productivity to decline. Soil loss modeling is important for investigating soil loss processes and assessment of soil erosion sensitive for soil and water conservation, management and planning land-use activities (Ashraf 2019). Moreover, runoff and sediment yield are the key components of the watershed modeling (Sharma et al. 2015).

In many Algerian watersheds, the biggest part of the annual sediment yield is observed during the flood period, it represents more than 75% (Djoukbala et al. 2018), and can even reach 98% (Megnounif et al. 2003). The annual sediments quantities exported, as sediment loads from the continents towards oceans has spatial–temporal variability. According to Probst and Bazerbachi (1986), the annual rate of solid transport to oceans is between 5 and 64 million tons. In the Maghreb region, the main damage associated with sediment loss from watersheds is the high rates of dam's siltation, the average annual sediment yield in Maghreb Wadis is estimated at 254 million tons (Probst and Amiotte-Suchet 1992).

Algeria, following the likes of other Mediterranean countries, is classified as an area subject to high soil loss erosion rates (Djoukbala et al. 2019), this rate was estimated at 24% in 2010 (Benblidia et al. 2001), moreover, floods that Algeria has experienced in recent years are among the most significant natural disasters, whose amplitude and frequency tend to become increasingly irregular in space and time, in Morocco, nearly 10% of dams are filled with sediment; in Tunisia, it is about 25% (Megnounif et al. 2003). In India, nearly 120.7 Mha of land is degraded and 70% of it is degraded by water erosion (Kumar et al. 2020).

Wadi El Maleh is among the Algerian rivers that generate a high quantity of sediments, soil loss in Algerians Wadis ranges from 111 to 3029×10^3 kg/km^2/year (Benselama et al. 2019), it can get all the way up to 7200×10^3 kg/km^2/year as reported for Wadi Agrioun (Probst and Amiotte-Suchet 1992).

The goal of this paper is to assess, analyze and discuss the suspended sediments dynamics at flood scale in the Wadi El Maleh watershed. During 17-year period from 1981 to 1998 included in this study, we have identified the major recorded floods, water and suspended sediment yields obtained during these events are compared to the annual yields, water flow discharge and suspended sediment concentration are modelled by the sediment rating curve approach.

Study area characteristics

Main characteristics and location

The Wadi El Maleh watershed is located in the west of Algeria, exactly, in north of department of Ain Temouchent, North–West of Algeria (Fig. 1), situated between (1°9′24″ and 1°26′17″ W) of longitude and between (35°17′22″ and 35°16′37″ N) of latitude.

The watershed is a mix of arable and pastoral farming in lowlands and pastures with low-density sheep grazing in the uplands, as illustrated in Fig. 2, approximately 88% of the Wadi El Maleh watershed area does not exceed 25% of slope.

Morphometric characteristics have been derived from à digital elevation model of 30 m resolution obtained via satellite imagery from Aster DEM using a geographic information system. The main stream for Wadi El Maleh watershed has its origin in high valleys, as it is presented in Table 1; the watershed covers an area of about 932.5 km^2 and has a course of 67.4 km, a perimeter of 194.8 km with a Gravelius compactness coefficient of 1.78 that reflects well the elongated shape of the watershed. A well-defined hydrographic network with à drainage density of 1.43 km/km^2 and a torrential coefficient of 1.43 indicates à torrential regime where the predominant soil erosion gives a strong solid flow.

More than 84% of the watershed area are islands of bare or fallow soil, and 16% is generally allocated to areas covered by cereal and fodder crops, these bare areas are more affected by the dewatering of particles and soil loss, while areas with vegetation cover are the most resistant to this phenomenon.

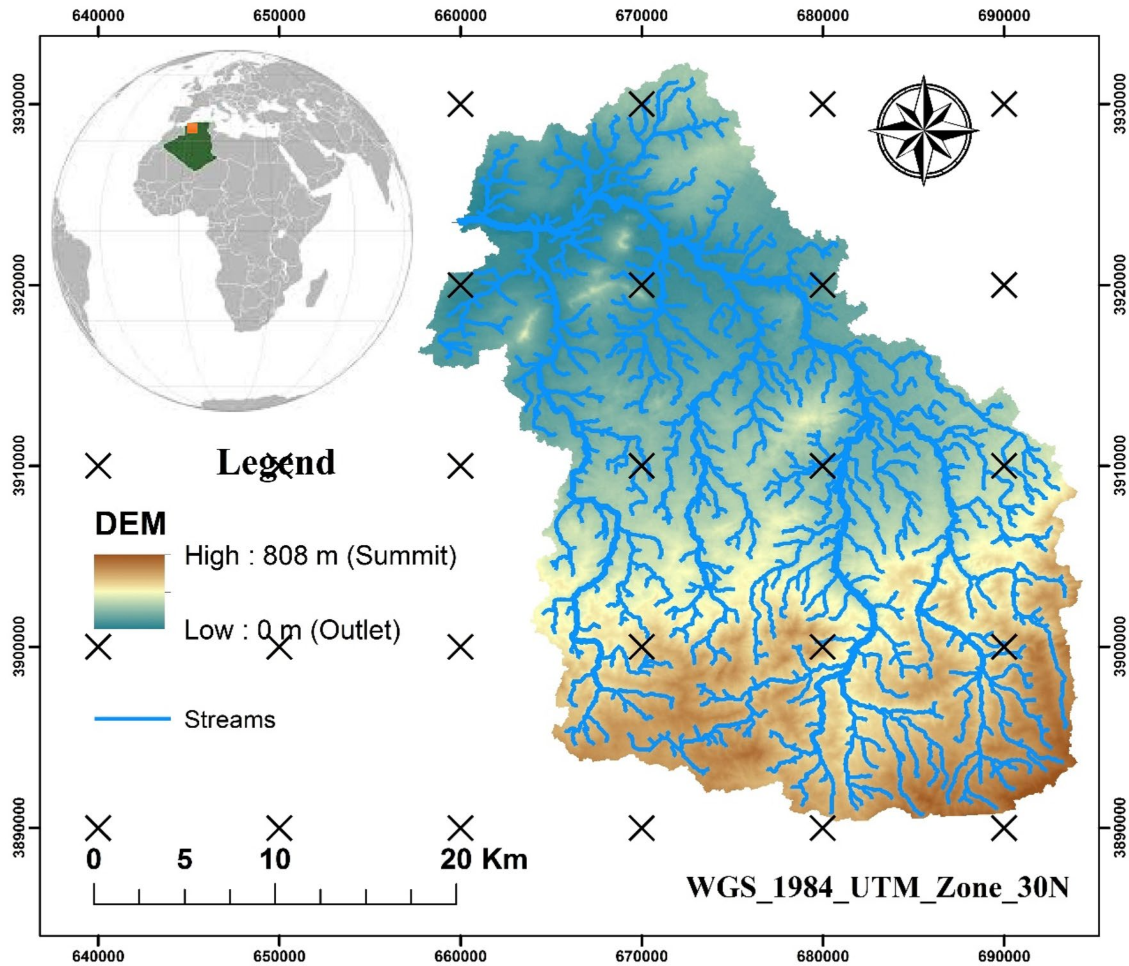

Fig. 1 Wadi El Maleh catchement presentation

Climate and rainfall

The study area is under a Mediterranean semi-arid climate characterized by a hot and dry summer and a relatively mild and humid winter, the mean annual temperature is between 20 and 26.9 °C in maximum, while in minimum, they range from 11.9 to 16.4 °C. Annual rainfall is very irregular (coefficient of variation Cv = 28%), due to the topographic variation in the watershed, it receives annually between 281 mm on the north-facing hill-slopes and 616 mm on those to the south or in interior plains, with an internanual average equal to 483 mm.

The Wadi El Maleh watershed has a dense pluviometric network composed of fourteen rainfall stations, eight are located within the watershed and the remaining six are neighbouring stations (Fig. 3), rainfall data has different measurement periods, ranging from 25 to 76 years. The values of the coefficient of variation for all the rainfall stations in Wadi El Maleh vary between 0.19 and 0.42 with a spatial distribution that varies from south to north.

Hydrological data collection and sampling methodology

The National Agency of Hydraulic Resources NAHR provided water flow discharge and suspended sediment concentration data, the agency is responsible for the all gauging stations and measurements in Algeria. The protocol of sampling is the same in all Algerian rivers.

The Wadi El Maleh is controlled by one gauging station named Turgot Nord situated at the outlet ($X = 149.3$ km, $Y = 244.4$ km (Lambert coordinated) and $Z = 18$ m), the available measurements period is 17 years from 1981 to 1998, water flow discharge was recorded from the water level measured by a limnimetric ladder using à rating curve ($H = f(Q_L)$), during flow measurement or normal runoff, water was manually sampled using a 1 L dip sample, one or two samples were measured at the edge of the Wadi, and the number of samples was adapted to hydrological regime, sampling rate depending on the flow event, during floods, measurement are intensified up to 1 h or even 30 min and

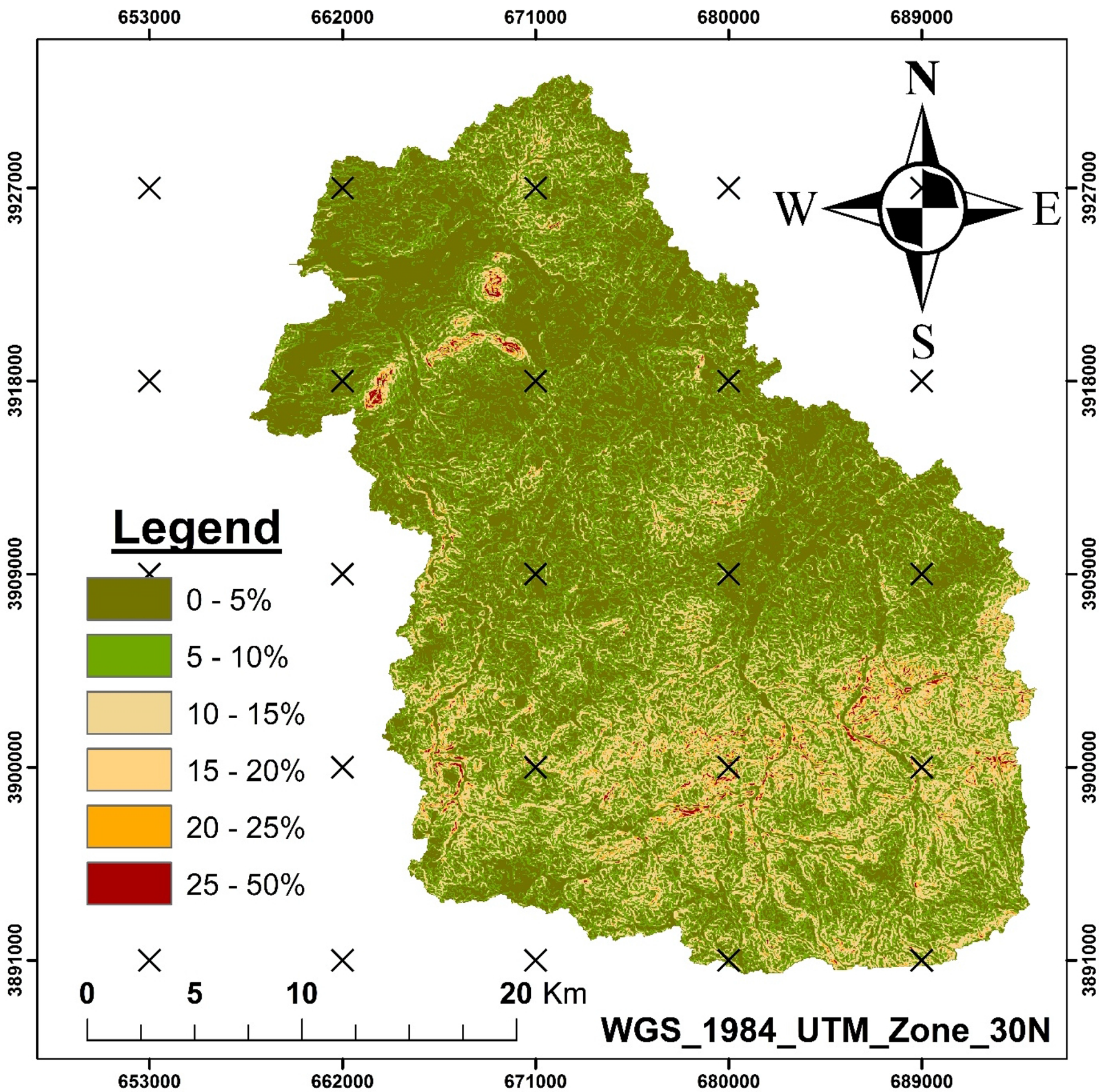

Fig. 2 Slope map of Wadi El Maleh watershed

Table 1 Summary morphometric and characteristics of Wadi El Maleh watershed

Characteristics	Designation	Symbols	Values
Morphometric parameters	Area [km^2]	A	932.6
	Perimeter [km]	P	194.8
	Gravelius compactness coefficient [–]	Kc	1.78
	Equivalent rectangle length [km]	Lrec	86.27
	Equivalent rectangle width [km]	lrec	10.81
Relief parameters	Maximum elevation [m]	H_{max}	808
	Minimum elevation [m]	H_{min}	0
	Average elevation [m]	H_{moy}	283.1
	Mean slope watershed [%]	I_{wt}	152.7
Streams parameters	Length of the main thalweg [km]	L	67.4
	Mean slope of the main thalweg [%]	I_{cp}	11.99
	Drainage density [km/km^2]	Dd	1.21
	Hydrographic density [km/km^2]	F	2.27

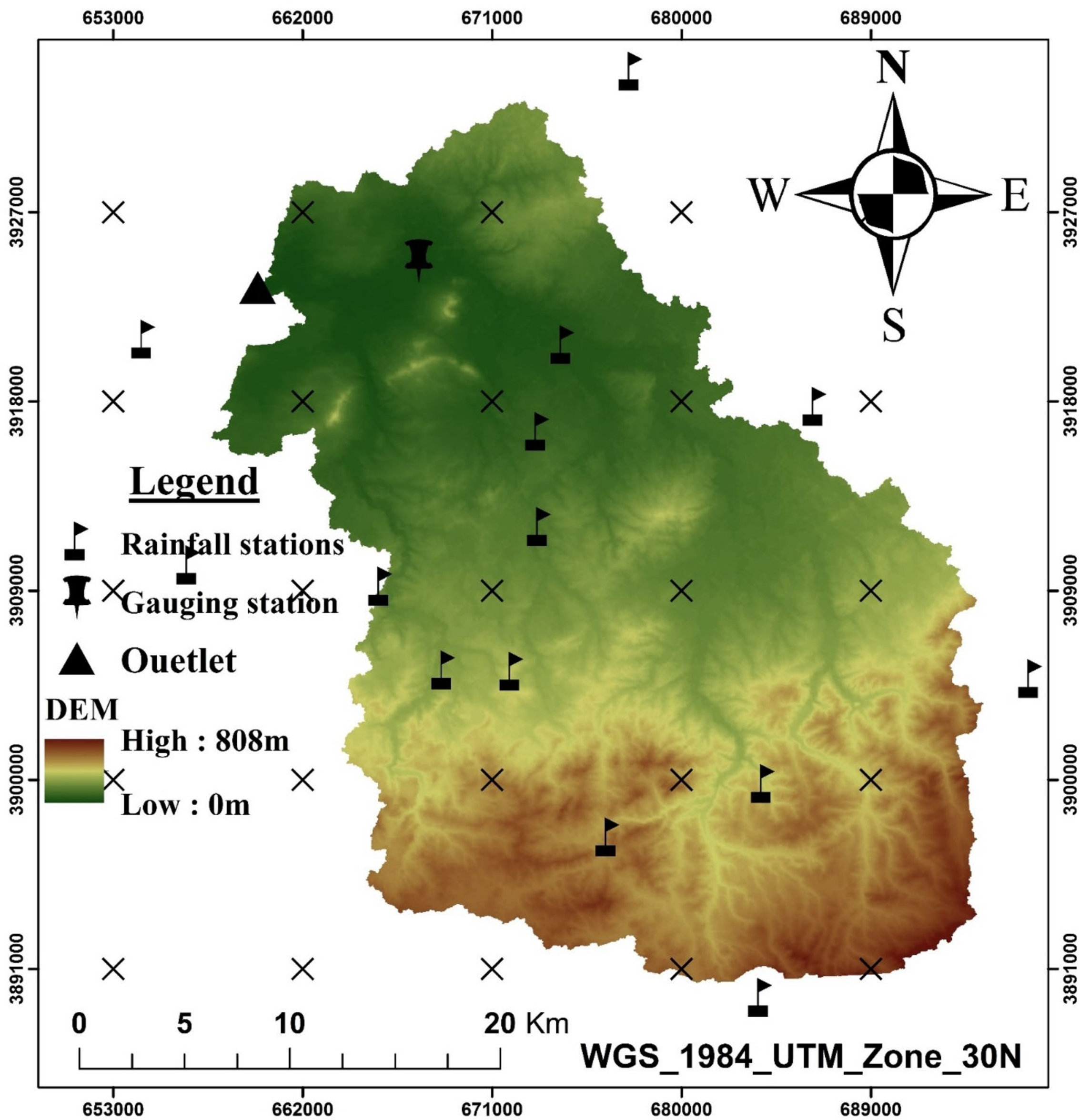

Fig. 3 Rainfall stations location in Wadi El Maleh watershed

sometimes up to 15 min, depending on the speed of the increase in water flow discharges and its level.

Methods

Sediment rating curve model

To characterize patterns and trends in river sediment concentrations, data are often fit with regression techniques, such as the commonly used linear regression between discharge Q_L and suspended sediment concentration C data.

Sediment rating curve is one of most commonly applied models to quantify suspended sediment loads over time and to establish a relationship between water flow discharge and suspended sediment concentration, it is a power law between suspended sediment concentrations and water flow discharge Q_L, and sediment discharge Q_S.

The utility of suspended sediment rating curves in these calculations varies from river to river and is largely a product of the patterns of supply and transport of suspended sediment over multiple time scales (Warrick 2015).

This approach is widely used worldwide, in Japan (Ide et al. 2009; Sadeghi et al. 2008), in Iran (Talebi et al. 2015), in China (Gao et al. 2017; Zheng et al. 2018), in India (Shima and Ramu 2016). Hasbaia et al. (2017) and Benselama et al. (2018) summarize many studies validating this model in Algerian watersheds.

$$C = a Q_L^{b-1}. \quad (1)$$

An empirical relation commonly called the sediment rating curve links the sediment discharge Q_s to the water flow discharge Q_L:

$$Qs = a Q_L^b. \quad (2)$$

Q_S is related to water flow discharge Q_L (Kennedy 1895) by the formula below:

$$Q_S = C \times Q_L. \quad (3)$$

Q_L: water flow discharge measured in m^3/s; $Q_{S:}$ sediment discharge in kg/s; *C:* suspended sediment concentration in g/L.

Suspended sediment yield calculation

Suspended sediment load transported by Wadi El Maleh during a time interval is calculated as:

$$S_Y = \sum_1^n \frac{\left[\left(Q_{i+1}C_{i+1}\right) + \left(Q_iC_i\right)\right]}{2}\left(t_{i+1} - t_i\right). \quad (4)$$

C_i and C_{i+1}: suspended concentrations measured at instants t_i and t_{i+1} in g/L; Q_{Li} and $Q_{\mathrm{Li}+1}$ in m^3/s: water flow discharges measured at instants t_i and t_{i+1}; S_Y: sediment suspended load (ton/year).

Water yield calculation

$$W_Y = \sum_1^n \frac{\left[\left(Q_{i+1}\right) + \left(Q_i\right)\right]}{2}\left(t_{i+1} - t_i\right). \quad (5)$$

Q_{Li} and $Q_{\mathrm{Li}+1}$ in m^3/s: water flow discharges measured at instants t_i and t_{i+1} in m^3/s; W_Y: water yield (m^3/year).

Statistical parameters of studied floods

In semi-arid areas, Wadis flows are generated exclusively by rainfall; they are often dry except during floods, in each rainstorm, when water level rises as the water flow discharge increases to its peak, then, the water level and flow discharge decrease rapidly to return to normal levels or become dry, this type of flow process is defined as a flood event.

As a flood evolves in a river channel, the morphology of the river may be deformed, changed or completely disappear due to the water flow; this latter, can only be considered as an extreme event if it propagates completely from inlet at outlet.

This study focuses on analysis of instantaneous measurements of water flow discharges Q_L, and suspended sediment concentration *C*, measured during the studied flood events, from measured data of water discharge and suspended sediment concentration, during this period (from 1981 to 1998), we have identified just 06 floods.

As it is displayed in Table 2, the statistical parameters of these events show clearly a high variability of water and sediment parameters, where the average flow discharge variability is more that 75%, it is variable from 35 to 103%. The suspended sediment concentration variability is even higher at almost 100%, it even reached 250% in the February 1986 flood, and this verdict is observed in major studied watersheds in Algeria with variable values (Djoukbala et al. 2018; Megnounif et al. 2003).

Results and discussion

In terms of yields, Wadi El Maleh watershed transported about 46.69 million m^3 of water and 1.29 million tons of sediment during floods recorded between 1981 and 1998 (Benselama et al. 2019), while, total yields measured are 194.84 million m^3 and 3 million tons, of water and sediment, respectively; these outcomes show that 24% of total water load and 43% of total suspended sediment load are noted during the floods period, this finding agrees with that reported in many watersheds of Algeria (Megnounif et al. 2003; Djoukbala et al. 2018).

In Wadi Sebdou, the total water yield during flood events over 31 years was 354 mm^3, yielding a mean annual water volume of 11.4 mm^3, the annual floods of maximum flow have drained 68% of total, and sediment flux estimated for all floods recorded during the period (1973–2004) was estimated at 2711×10^3 tons (Megnounif et al. 2013).

In Wadi El Maleh, it is marked that three first observed floods corresponding to high storm event explain more than 80% of annual sediment yield, at inter-annual scale, the floods contribute more than 45% of total sediment transport, for all the studied floods, sediment rating curve (Fig. 4) as

Table 2 Statistical parameters of the recorded floods

Floods date	Variable	Max	Mean	S_D	C_V
November 19, 1985	C	49.46	17.10	13.19	0.77
	Q_L	92.4	38.01	31.34	0.82
November 27, 1997	C	45.3	15.06	16.19	1.08
	Q_L	64.7	24.21	20.66	0.85
February 09, 1986	C	126.2	13.09	32.61	2.49
	Q_L	47.1	12.79	12.45	0.97
January 19, 1988	C	54.6	17.38	19.57	1.13
	Q_L	147.3	33.86	35.05	1.03
March 13, 1995	C	100.6	28.74	38.14	1.33
	Q_L	36.8	17.41	11.43	0.66
May 05, 1992	C	62.9	17.34	23.85	1.38
	Q_L	21.3	16.19	5.68	0.35

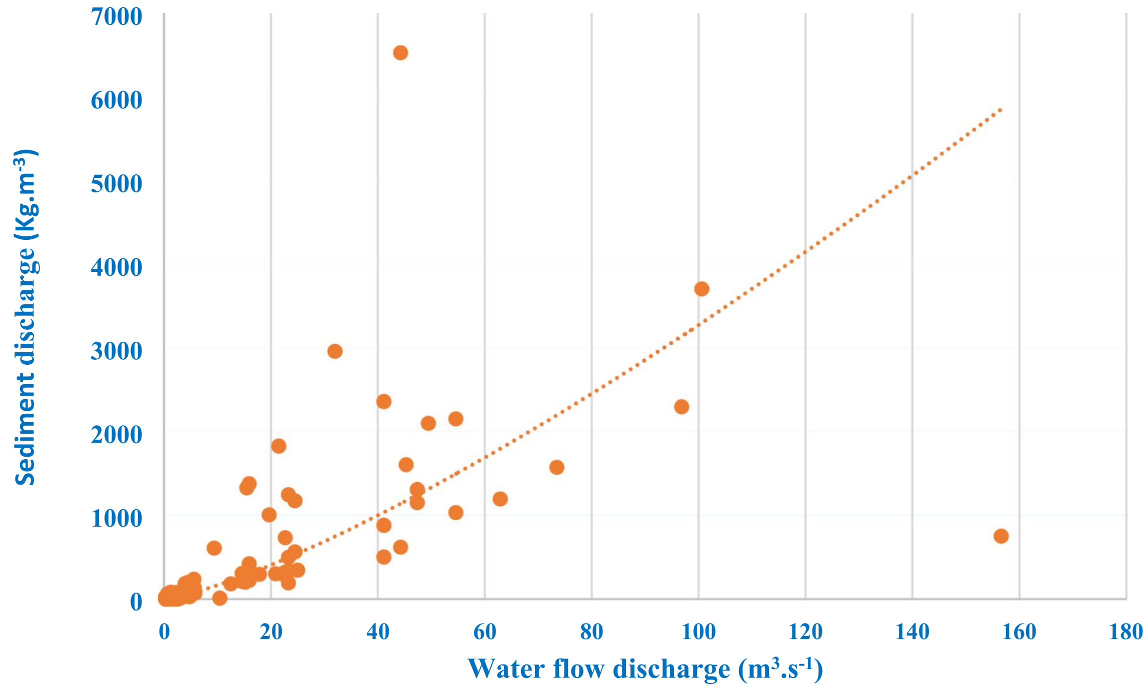

Fig. 4 Sediment rating curve at flood scale

exhibited here above, explains more than 72% of variance data (pairs Q–C), the best fitted law obtained using 126 pairs of (C, Q) data, is written as $Q_s = 8.4218\ Q_L^{1.2946}$ (Fig. 4), on the other hand, for all time scales, this model explains more than 74% of the variance (Benselama et al. 2019). It is generally believed that the steepness of the rating curve is related to the availability of suspended sediment in a certain area (Asselman 2000; Benkhaled and Remini 2003).

For every flood, sediment rating curve clarifies more than 69%, 71%, 82%, 91%, 92%, and 93% of sediment transport variance during the floods of November 1985, February 1986, January 1988, May 1992, March 1995, and November 1997, respectively (Table 3). This result can be explained in semi-arid areas by the dominance of flood runoff in 1 year, scattered values found in other watersheds (Megnounif et al. 2003; Achite and Ouillon 2007; Hasbaia et al. 2017; Djoukbala et al. 2018) are due to other factors, such as slope (Zhao et al. 2019).

The downpour is the most suitable time unit for hydrological analysis in relation to solid transport (Guy 1964; Dean et al. 2016). In Maghreb, particularly in Algeria, highest concentrations of suspended load are not necessarily measured during the flood period, water and sediment values show a high degree of disparity, this disparity results from the difference in lithology, vegetation cover, slope and size of watersheds (Walling 1984).

Changes in sediment rating curve parameters, *a* and *b*, over time have been noted for many rivers systems (Syvitski et al. 2000; Yang et al. 2007; Huang and Montgomery 2013), and there is a general assumption that these changes reflect alteration of the erodibility and/or supply of sediment in the watershed, the power of the river to erode and transport sediment or the spatial scale of the basin (Asselman 2000).

As it is shown in Fig. 5, a better regressive relationship (logarithmic) between two coefficients (a, b) is obtained at flood scale for Wadi El Maleh ($R^2 = 0.87$), this suggests that for one Wadi, suspended sediment process have the same behaviour at flood scale. However, sediment rating curve coefficients (a, b) can be predicted in ungauged tributary or reach using the established model coefficient at the gauging station of the same Wadi. Similar relationship is obtained for 12 (a, b) pairs corresponding to 12 selected floods of Wadi Soubella, in the Hodna interior basin recorded by (Hasbaia et al. 2017). In Wadi El Hammam, higher value of *a* coefficient corresponds to lower value of *b* coefficient and vice versa ($a = 126.73$; $b = -0.81$), ($a = 0.084$; $b = 1.54$), (El Mahi et al. 2017). In fact, sediment rating curve parameters (a, b) varies from one watershed to another and between catchment, they are closely sensitive to time scale (Hasbaia et al. 2017; Benselama et al. 2019), and relationship between sediment rating curve coefficients (a, b) has a great interest, especially for poorly gauged basins, it allows deducing or extrapolating the curve in case of lack of data (Hasbaia et al. 2017).

A global analysis suggested that *a* and *b* are related to river basin characteristics, such as topographic relief and

Table 3 Characteristics of Wadi El Maleh floods

Floods	*P* Monthly (mm)	Wy Annual (mm^3)	Sy Annual (Mt)	Wy Flood (mm^3)	Sy Flood (Mt)	Wy Flood (% of 2)	Sy Flood (% of 3)	Erosion (ton/km^2)	R^2	*a*	*b*
	1	2	3	4	5	6	7	8	9	10	12
19 November 1985	77.9	18.35	0.33	6.98	0.26	38.05	80.74	278.82	0.69	17.95	1.1
09 February 1986	102.4	37.91	0.4	13.99	0.33	36.9	82.93	353.89	0.71	3.94	1.44
19 January 1988	155.9	24.55	0.88	13.55	0.82	55.18	92.95	879.36	0.82	12.66	1.26
05 May 1992	43.6	51.44	0.21	6.45	0.11	12.54	57.14	117.96	0.91	9.21	1,22
13 March 1995	40.6	48.23	1.15	13.24	0.38	27.45	33.06	407.51	0.92	1.47	1.73
27 November 1997	90.3	29.73	0.77	9.61	0.29	32.29	38.84	310.99	0.95	1.94	1.95

continuous suspended sediment concentrations, are valuable because these records allow for calculation of river sediment discharge from the product of continuous sediment concentration, water discharge and log-transform bias correction, if appropriate (Ferguson 1986).

Although some authors have reported that it is difficult to give physical meaning to parameters *a* and *b* (Asselman 2000; Hassan 2014), others have attempted to demonstrate their variation to certain physical and suspended sediment transport parameters. The SRC approach is black box model, and parameters *a* and *b* have no physical meaning (Benselama et al. 2019).

For these authors (Warrick 2015; Hapsari et al. 2019), the factor *a* refers to the erosion severity index which is influenced by soil erodibility linked to channel watershed features, such as topographic relief and runoff. (Hassan 2014; Yang et al. 2007; Hapsari et al. 2019) noted that a high value parameter *a* represents intensively weathered materials, also, a large amount of fine suspended materials, which can be easily transported in Wadi (Higgins et al. 2016).

The coefficient *a* expresses the watershed soil condition and its saturation degree (Walling 1984). The parameter *b* is an index of an erosive river and reflects the new sediment that becomes available when the flow grows (Yang et al. 2007; Hassan 2014; Heng and Suetsugi 2014; Hapsari et al. 2019). It is influenced by the grain size variation of material (Syvitski et al. 2000). High values of this factor reflect a Wadi, which has important erosion and increasing transport as well as increasing flows (Yang et al. 2007; Higgins et al. 2016). The factor *b* directly related to the drainage zone at floods, and expresses the importance of suspended sediment load (Walling 1984).

Conclusion

Suspended sediment transport is a challenge for the development countries, which are under semi-arid climate, not only by high quantities of sediment yield, but also by spatio-temporal variability of the phenomenon, through several studies of watersheds in Algeria, the sediment transport varies from one region to another.

Sediment transport is an event phenomenon, major part of sediment transport occurred in the flood period, Wadi El Maleh watershed transports about 46.69 million m^3 of water and 1.29 million tons of sediment during floods.

At inter-annual scale, floods contribute more than 45% of total sediment transport, one event can transport more than 75% of the annual load, this finding is observed by many studies in Algeria and other semi-arid regions, also, a better regressive relationship (logarithmic) between the two coefficients (*a*, *b*) is obtained at flood scale for Wadi El Maleh ($R^2 = 0.87$).

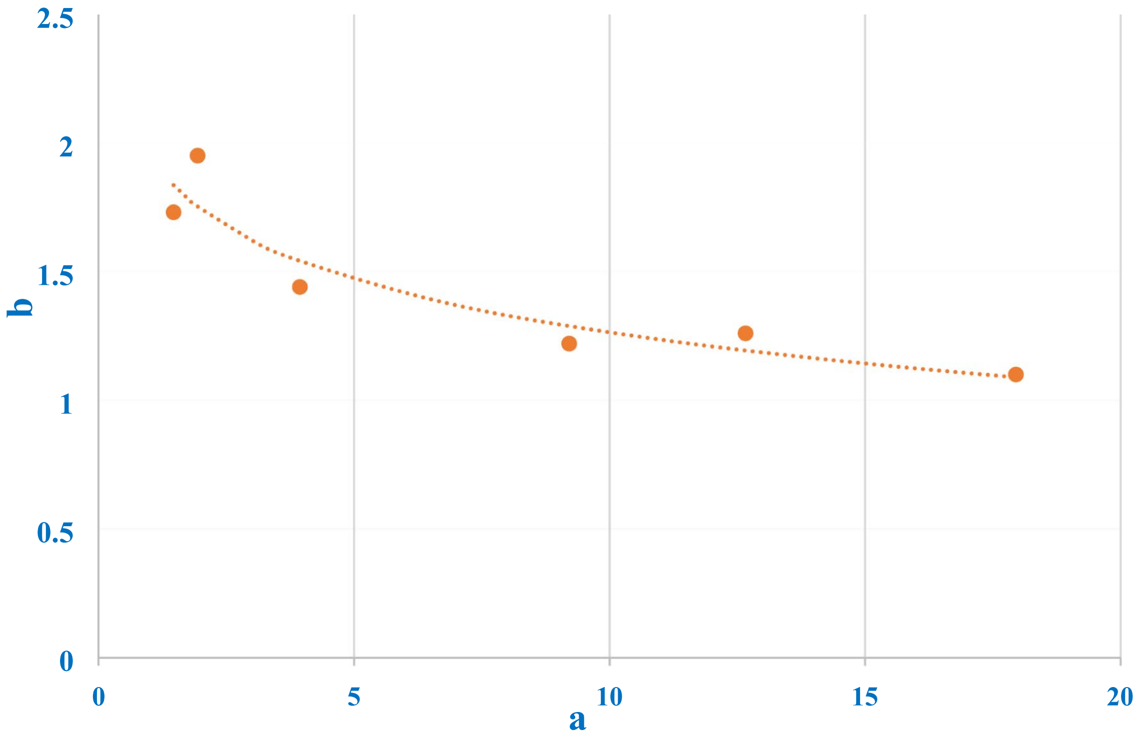

Fig. 5 Logarithmic function of sediment rating curve parameters (*a*, *b*) at flood scale

Sediment rating curve SRC model is widely validated in many Algerian basins at different time scales, in Wadi El Maleh watershed, it explains more than 72% of sediment transport variance during floods. SRC coefficients do not have a universal physical explanation, but they can be expressed by specific relationships, also a good logarithmic relation is obtained between these parameters at the flood scale.

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