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ORIGINAL PAPER

Rainfall irregularity and its impact on the sediment yield in Wadi Sebdou watershed, Algeria

Abdesselam Megnounif[1] · **Abderrahmane Nekkache Ghenim**[1]

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Abstract The impact of changes in rainfall can be studied by means of the sediment transport in the rivers. The link between rainfall irregularity and sediment rating parameters was investigated in the Wadi Sebdou watershed of 256 km^2 located in northwest Algeria. The data set includes rainfall records and cover the period from September 1939 to August 2009. Hydrometric records consist of instantaneous measurements flow discharge, Q, and suspended sediment concentration, C, based on a monitoring program from September 1973 to August 2003. In neighboring gauging stations, the periods of record were either short or discontinuous and may not be representative to assess the potential causes of the suspended-sediment changes. The time evolution of sediment rating parameters was used to improve understanding of the interaction between sediment delivery supplied from internal and external sources to the wadi channel. Our findings indicate that the rating parameters varied by many orders of magnitude, suggesting significant temporal change in both potential of sediment yield and sediment sources. High b-parameter (≅1.12) and low a-parameter values (≅0.018) were observed during the time interval of change from wet to dry period occurred in the mid of 1970s. The growth of vegetation and the well-developed organic soil horizons have reduced runoff and prevented particle detachment and transport. So, the functioning of sediment sources external to the channel was comparable to that of temperate regions. After that transition, the prolonged dryness has led to a higher risk of desertification and critical soil erosion. Therefore, the functioning of sediment sources external to the wadi-flow becomes similar to that observed in arid river systems, while the fluctuation of sediment contribution supplied from hydrographic network suggests a watershed functioning as semi-arid streams. The watershed ability to sediment yield was high toward the mid of the dry period and sediment delivery supplied from sources both internal and external to the wadi channel was copious suggesting a large amount of stored sediment at the beginning of a runoff season and an increased transport capacity of the river.

Keywords Sediment load · Sediment rating curve · Semiarid · Water discharge · Wadi Sebdou · Algeria

Introduction, terminology, and literature review

The amount of suspended sediment transported by a stream is supplied from both external and internal sources to the stream channel. Internal sources include material attributed to weathering of bed material or gullies, while external sources include surface erosion on slopes (Guy 1978). Thus, rivers confer a major role as a key pathway of material transfer on Earth connecting land to the ocean (Gregor 1970). Many issues concern sediment transfer since they act as a vector for a wide variety of organic and inorganic chemical constituents (Ludwig and Probst 1998; Syvitski et al. 2003; Horowitz 2008). Suspended sediment dynamic has important influences on physical and biological processes in watershed systems such as the denudation of the continents, reservoir sedimentation, channel, estuary and harbor silting, as well as the functioning of coastal ecosystems and the evolution of deltas

✉ Abdesselam Megnounif
megnounif_aslam@yahoo.fr

Abderrahmane Nekkache Ghenim
anghenim@yahoo.fr

[1] "Eau et Ouvrage dans Leur Environnement" Laboratory, Tlemcen University, BP 230, Tlemcen 13000, Algeria

(Owens et al. 2001; Walling 2006; Poulos 2011). On the other hand, human activities and more particularly poor land use can negatively impact the global soil resource (Montgomery 2007). The removal of nutrients by soil erosion necessitates the increased application of fertilizer, which in turn diffuses source pollution and the degradation of aquatic ecosystems (Walling 2008). In addition, the water resource exploitation and sediment management, such as reservoir sedimentation, are becoming more important because sediment trapping has dramatic impacts on the ecology and water transparency causing eutrophication of the water bodies (Bashkin et al. 1997; Vörösmarty et al. 2003; Dudgeon et al. 2006).

So, a more complete understanding of the evolution of the key processes influencing the performance of the watershed in terms of sediment yield is an essential for helping researchers and water resources managers to understand sediment transfer and its effect on environmental resources.

The rating curve technique developed by plotting daily suspended sediment concentration against daily discharge on logarithmic coordinates has been widely applied in estimating sediment loads both for small- and large-sized catchments (Walling 1977; Asselman 2000; Horowitz 2003). The resulting model $C = aQ^b$ is created by performing a linear least-square regression of log-transformed suspended sediment concentration and discharge data. The model is commonly referred to as the power curve and the a- and b-coefficients are the sediment rating parameters. Gilroy et al. (1990) showed that the computing sediment discharge using the model $C = aQ^b$ and then multiplying by water discharge is equivalent to computing sediment discharge using the model $Q_S = aQ^{b+1}$. Thus, a site-specific sediment rating curve, $C - Q$ (respectively $Q_S - Q$), is an empirical relation between occasional sediment concentration (respectively sediment discharge) and water discharge measurements (Horowitz 2003). Although the suggested models are considered as "black box" where a and b parameters lack physical meaning (Asselman 2000), some correlations were made and showed that the distribution of the rating parameters are strongly linked to the characteristics of both internal and external sediment sources within the basin (Syvitski et al. 2000 and 2003; Yang et al. 2007). Reid and Frostick (1987), Iadanza and Napolitano (2006) and Yang et al. (2007) among others, argued that the b-exponent fluctuates little from a year to year and is mainly linked to the erosive power of the water flow. According to Leopold and Maddock (1953), the b-value is often used to discuss differences in sediment transport characteristics and indicates the capacity of the flow to erode the hydrographic network (Gregory and Walling 1973; Robinson 1977), and then the b-parameter is mainly supplied from sources internal to the stream channel. The a-parameter depends on the sources external to the stream channel. It is sensitive to the supply of new sediment sources that become available in the river basin (Roehl 1962) and is mostly attributed to the availability of sediment furniture in the catchment or in the stream channel which can be easily depleted by runoffs (Sarma 1986). It has also been addressed that the a-parameter is influenced by the vegetation, land cover change, and the size of catchment areas (Fleming 1969).

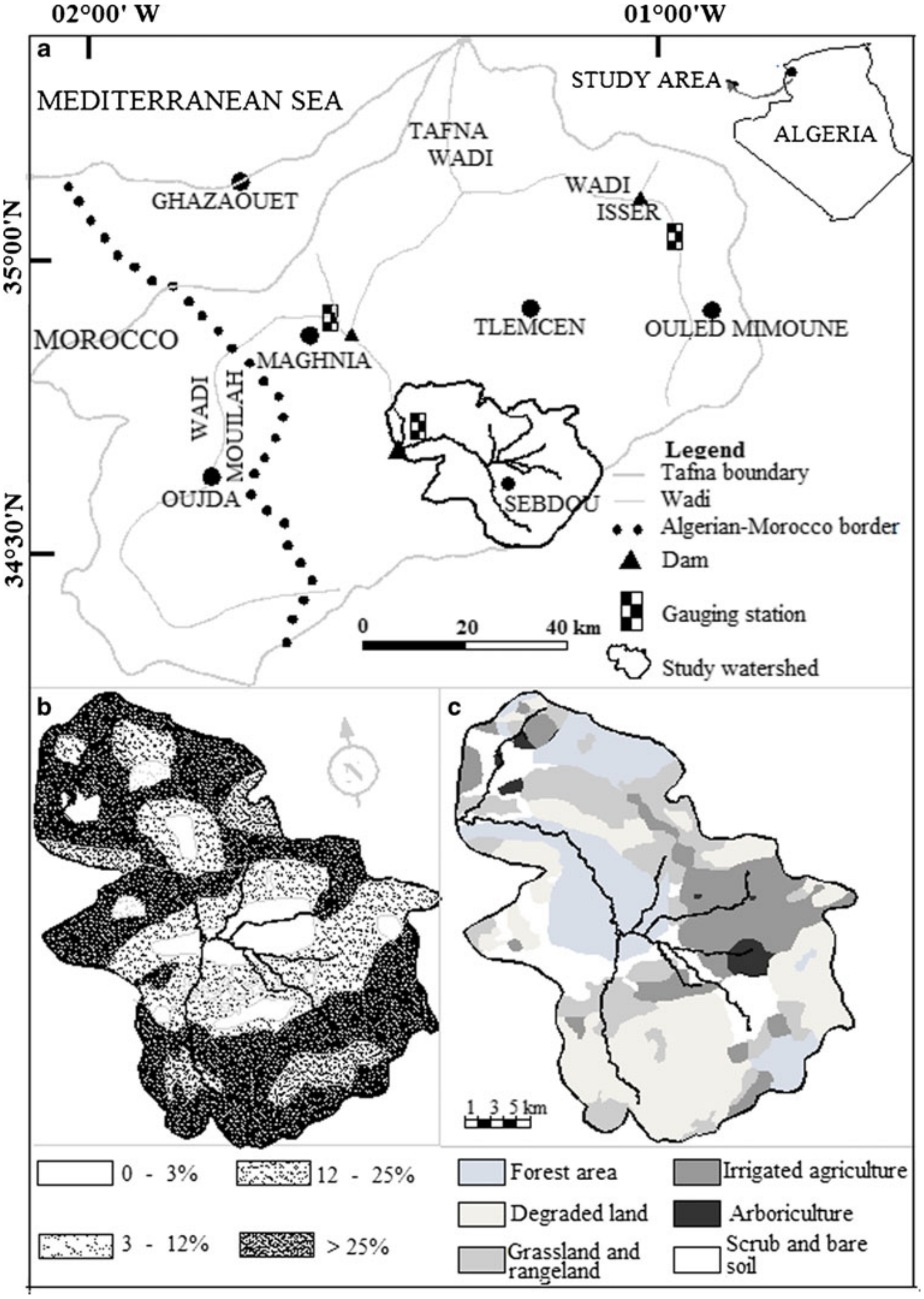
Owing to the widespread alteration and development of the global land surface (Walling and Fang 2003; Syvitski et al. 2005; Zhang and Nearing 2005; Milliman and Farnsworth. 2011), the functioning and ability of rivers to sediment yield are constantly changing (Walling 2006) and the result is a temporal variability of the sediment rating curve (Syvitski et al. 2000; Christensen and Lettenmaier 2007; Warrick et al. 2013), which in turn were used as tools to explore the main changes in sediment sources within the watershed system (Asselman 2000; Yang et al. 2007; Zhang et al. 2012; Zhao et al. 2014). However, critical examples were developed upon the use and utility of the rating parameters and their implication to explain the erodibility of sediment in the watershed and the power of the stream-flow to erode and transport sediment (Warrick 2015). Syvitski et al. (2000) report that a-parameter cannot be used as independent measurements of the y-intercept of rating curves since it is strongly dependent on both b and Q (Asselman 2000; Warrick (2015). Hicks et al. (2000) argue that a better use of rating parameters will be obtained if the regression is conducted with discharge normalized. In lieu of the standard model $C = aQ^b$, Warrick (2015) recommended to assess the rating curve trend using the normalization of discharge $C = \alpha(Q/Q_{GM})^{\beta}$, where Q_{GM} is the geometric mean of the Q-values data.

In Mediterranean regions, rainfall variability alters the erosional system which are managed in semiarid lands by extreme rainfall events (Yair and Raz-Yassif 2004). However, little is known about the response to changes in the rainfall in semiarid ecosystems on the sediment transport. The purpose of this work sheds light on this topic to emphasize on the major changes functioning of a small Mediterranean watershed in terms of sediment yield. Wadi Sebdou (256 km^2) was selected for this study because of the availability of long-term records of rainfall and hydrometric measurements. This study examines the influence of rainfall variability on sediment yield, with a view to analyze the temporal evolution of the main sediment sources within the basin and to explain the potential change of the sediment yield through the rating parameters variation. Further and owing to the comments cited above, the rating parameters derived from both models, the standard and that based on the normalization of discharge, were analyzed.

Region setting and general information

Wadi Sebdou is a part of the Tafna Basin (Fig. 1a). The upper reaches emerges eastward through Jurassic parent material at

Fig 1 The position of the Wadi Sebdou in the Tafna watershed **a** slope map **b** and land use map **c**



an elevation of 1400 m. These tributary wadis join on the Sebdou plain (900 m) and then turn northwest up to the Beni Bahdel dam of 63 millions of cubic meters of storage capacity. Abrupt slopes are mainly localized in the north and south of the basin which correspond to mountains formed during the Alpine orogeny (Fig. 1b). Slopes greater than 25 % represent 49 % of the total watershed area. Wadi Sebdou basin is mainly rural and thinly populated. During the period of investigation, the water pollution was assumed to be minimal, because the population was mainly rural, agriculture mostly traditional, and a little developed industry. The modern agriculture is practiced in small areas due to the dominance of abrupt escarpment.

The mean annual temperature is 17.2 °C (September 1955–August 1992). January is the coldest month with mean temperature of 8.3 °C; the maximum monthly mean, 28.4 °C, was recorded in August. The annual mean potential evapotranspiration is 1390 mm (Bouanani 2004). Annual precipitation averages ~530 mm in the upper reaches of the river flow, but decreases to ~280 mm on the hill-slopes exposed to south or in the interior plains. Like most basins in the Maghreb area, the majority of precipitations in Wadi Sebdou basin, about 92 % of the totals, occurs between October and May, December and January being the wettest months (Megnounif and Ghenim 2013). In the early portions of the rainy season, precipitations are often intense and fall on a dry soil usually more compacted and with poor vegetation (Fig. 1c) promoting runoff with high peak flows as rainwater does not infiltrate into soil readily (Demmak 1982; Jansson 1982). Moreover, the rains exert an important impact on the exposed soils including splashing and the rapid wetting of the desiccated soil causes the aggregates to disintegrate which increases the susceptibility to soil erosion (Martínez-Mena et al. 1998; Barthes and Roose 2002).

Methodology and data

The study was implemented using rainfall and hydrometric data. Rainfall measurements were collected at the Beni Bahdel station located near the outlet of the Wadi Sebdou watershed where hydrometric measurements were made. The data set includes monthly and annual maximum daily rainfall records obtained from the National Office of Meteorology [ONM] agency data and cover the period from September 1939 to August 2009. Hydrometric records consist of instantaneous measurements of water stage, flow discharge, Q, and suspended sediment concentration, C. Hydrometric measurements were made by the National Agency of Hydraulic Resources [ANRH] responsible for gauging stations and measurements in Algeria (www.anrh.dz) which is the primary source of water-resources data.

The hydrometric measurements were made at the Beni Bahdel gauging station, located at the outlet of the Wadi Sebdou watershed and upstream of the Beni Bahdel Reservoir (Fig. 1). The data set contains instantaneous suspended sediment concentration and discharge measurements spanning the period from September 1973 to August 2003. In neighboring gauging stations, series of hydrometric measurements are either short or incomplete and data sets are inappropriate to analyze long-term sediment trend.

The protocol of hydrometric measurements is the same in the Sebdou Wadi than in other rivers of Algeria (Achite and Ouillon 2007). Water stage was monitored by a limnimetric ladder and pressure transmitter which allows a continuous measure of water level. A local stage–discharge relation has been developed in order to derive discharge (Q, in m^3/s). Suspended sediment concentration (C in mg/L) was sampled manually; one or two samples were manually taken at the edge of the wadi. Weekly, the samples were collected and transported to the laboratory and subjected to a standard concentration analysis by filtration and evaporation. The water level was recorded whenever water was sampled. The sampling frequency was adapted to the hydrological regime; when the water level is stable, samples were taken every other day. During the dry season, when water levels and concentrations were very low, interval sampling was taken fortnightly and sometimes lasted up two months during dry summers. During flood periods, the interval samples are supplemented by event samples, as frequently as every half hour. Suspended sediment discharge Q_S expressed is equal to C times Q. In total, 6741 triplet (Q, C, Qs) readings were recorded during the period from September 1973 to August 2003. No preliminary statistic treatment was made to the series of measurement.

Rainfall anomalies observed in Wadi Sebdou watershed were computed by removing the linear least squares line of best fit from the original data (Evans et al. 2009). Extreme years were defined as years that exceed one standard deviation above or below the long-term annual mean. To examine the homogeneity of rainfall records, the Buishand test was applied to: (i) annual rainfall (AR), (ii) annual monthly maximum rainfall (AMMR), and (iii) annual daily maximum rainfall (ADMR). This test is based on the adjusted partial cumulative deviations from the inter-annual mean (Buishand 1982). When the cumulative sum plot shows a clear change of slope, the position of change-points indicates the departure of homogeneity. The sequence of points with positive trend corresponds to a humid period, while negative trend represents the drought period. The influence of intra-annual variability of rainfall on sediment yield was examined using the Precipitation Concentration Index (PCI) (Oliver 1980). This index is defined as follows:

$$\mathrm{PCI} = 100.\frac{\sum_{i=1}^{12} \mathrm{Pm}_i^2}{\left(\sum_{i=1}^{12} \mathrm{Pm}_i\right)^2} \qquad (1)$$

where Pm_i is the precipitation of the month i.

The PCI is used as a surrogate of intra-annual variability of rainfall (de Luis et al. 2001). An increase in PCI values indicates an increasing seasonality of monthly rainfall. According to Ceballos et al. (2004), PCI values from 11 to 20 indicate a seasonal trend and values above 20 indicate a considerable variability of monthly rainfall.

Discharge and suspended sediment concentration were assumed to vary linearly between consecutive measurements. For each value of instantaneous discharge (Q_i) was affected a triplet (Δt_i, ΔR_i, ΔY_i) corresponding to time duration and "elementary contributions" of water and sediment load, estimated by the following equations:

$$\Delta T_i = \frac{1}{2}(t_{i+1} - t_{i-1}) \quad (2)$$

$$\Delta R_i = 0.25[(Q_i + Q_{i-1})(t_i - t_{i-1}) + (Q_{i+1} + Q_i)(t_{i+1} - t_i)] \,\mathrm{x}\, 10^{-6} \quad (3)$$

$$\Delta Y_i = 0.25[(Q_{Si} + Q_{Si-1})(t_i - t_{i-1}) + (Q_{Si+1} + Q_{Si})(t_{i+1} - t_i)] \,\mathrm{x}\, 10^{-6} \quad (4)$$

The x-axis (discharge) was subdivided into successive intervals I_k: <0.1, $0.1-1$, $1-10$, $10-100$, ≥ 100 m^3/s $1-10$, $10-100$, and ≥ 100 m^3/s. The frequency of flows Q_i falling within the class interval I_k was estimated by summing "elementary time duration": $T_k = \sum\{\Delta T_i \;;\; Q_i \in I_k\}$. Similarly, the percentage of water and sediment load supplied by each class interval was estimated using the flowing equations: $R_k = \sum\{\Delta R_i \;;\; Q_i \in I_k\}$ and $Y_k = \sum\{\Delta Y_i \;;\; Q_i \in I_k\}$. Table 1 summarizes flow frequency, water and sediment yield, and mean sediment concentration per class interval I_k.

Let T, a time interval divided into N intervals corresponding to (N + 1) sampling, the total water volume, R, and suspended sediment yield, Y, crossing the outlet during the period T were estimated using Eqs. (2) and (3):

$$R = \sum_{j=1}^{N} \Delta R_i \quad \text{and} \quad Y = \sum_{j=1}^{N} \Delta Y_i \quad (5)$$

To assess the potential change on the temporal evolution of the watershed performance in terms of sediment yield as well as the sediment origin, the rating parameters were examined throughout the successive 5-year intervals. The regression relationships are built between instantaneous values of sediment load and water discharge (Fig. 2). Regressions were conducted with standard and normalized discharge measurement data, hereafter referred as standard and normalized models:

$$\mathrm{Log}(Q_S) = \mathrm{Log}(a) + (b+1)\mathrm{Log}(Q) \quad \text{or} \quad Q_S = aQ^{b+1} \quad (6)$$

$$\mathrm{Log}(Q_S) = \mathrm{Log}(\alpha) + (\beta+1)\mathrm{Log}\left(\frac{Q}{Q_{GM}}\right) \quad \text{or} \quad Q_S = \alpha\left(\frac{Q}{Q_{GM}}\right)^{\beta} \quad (7)$$

where Q_{GM} is the geometric mean of the Q-values series, Log(a)- and Log(α)-parameters are called y-intercepts. The rating parameters derived from both models, standard and normalized, are reported in Table 3. Details of the link between rating parameters derived from the two models are given in the Appendix. Table 2 reports the main hydrological and sedimentological data for the successive 5-year time intervals spanning the period from September 1973 to August 2003.

The choice of 5-year intervals on both sides 1988 is firstly justified by the best correlations obtained between Q_s and Q relationships (Horowitz 2003), and secondly, the year 1988 has shown a considerable amplification on sediment yield (Megnounif and Ghenim 2013).

To highlight the sediment transfer sensitivity to climate variability occurring within Wadi Sebdou watershed, the main rainfall characteristics cited above were analyzed separately and together with the rating parameters for the successive 5-year intervals defined below.

Results

Rainfall characteristics

At the Beni Bahdel station, the annual rainfall recorded during the study period from September 1939 to August 2009 has an average of 467 mm with a standard deviation of 138. Inter-annual rainfall variability was high with a coefficient of variation of 29.7 %. Simple regression method reveals that rainfall has a decreasing trend of 2.4 mm per year, which represents a relative diminution of 0.52 % on the inter-annual average (Fig. 3a). Over the period of rainfall record, the number of extreme humid years represents 15.5 % of the total, while the proportion of extremely dry years is 18.3 % (Fig. 3b). The extreme dry and wet years were occurring in 1944–1945 and 2008–2009, respectively, with anomalous exceeding two times the standard deviation below and over the inter-annual mean. Annual rainfall series has a skewness coefficient of +0.05 close to zero, i.e., the median is close to the average and the rate of recurrence of high and low values is similar. The kurtosis value is negative (−0.51). This means that extreme values are the less frequent but with a higher rate of recurrence in comparison with a normal distribution having the same empirical parameters, average and standard deviation.

Both AMMR and ADMR show high variability with an inter-annual coefficient of variation of 37 and 50 %, respectively. On average, AMMR and ADMR contribute to annual rainfall with the respective rate of 31 and 13 %. According to the high value of the skewness and kurtosis coefficients, the values of ADMR series are generally modest and a majority is less than the mean value of 59 mm. High values are rare with low probability of occurrence; the highest value was 142 mm recorded in Mars 1989.

The Buishand test, sensitive to departure from homogeneity, confirms a significant trend of decreasing rainfall over the period 1974 to 2009 (Fig. 4). As regards to the rainfall anomalies fluctuation, 4 extreme dry years occur before 1974 against 9 years in post 1974, while 9 extreme wet years are observed before 1974 and only 2 years after that date. The sum of anomalies recorded before and after 1974 gives a value of (+)1160 and (−)896 mm, respectively. Change of the sign confirms the transition from wet to dry period and attests the

Table 1 T_k, flow frequency; R_k, water contribution; Y_k, sediment yield; and $\overline{C_k}$, the mean of suspended sediment concentration estimated for the successive class intervals I_k

I_k	T_k (in %)	R_k (in %)	Y_k (in %)	$\overline{C_k}$ (in mg/L)
<0.1 m^3/s	7.0	4.0	0.03	0.7
0.1–1	75.2	51.6	18.7	3.0
1–10	16.9	30.3	23.2	3.2
10–100	0.8	13.4	47.6	15.9
>100	0.011	0.7	10.5	50.2

strong contrast in rainfall behavior before and after 1974. After that date, although the amount of annual rainfall was diminishing, the end of the 1980s was notable for increasing annual daily maximum rainfall and lasted 7 years until 1995 (Fig. 4). The observed changes in ADMR series are less clear in AMMR series, but it can be noted that at the date 1987–1988, the curve of rescaled adjusted partial sums in AMMR move upward of that of AR series, signifying an increase in the rainfall concentration (Fig. 4).

The main rainfall characteristics change considerably over the successive 5-year intervals. Indeed, the mean of PCI values evaluated for successive 5-year intervals show that rainfall was more concentrated during the period (1988–1993) than for the remaining time intervals. Further, this 5-year interval coincided with the highest contributions of monthly and daily to annual rainfall which occurred during the period 1987 to 1994 of increasing ADMR identified by the Buishand test (Fig. 4).

During the hydrometric measurement (1973–2003), the average of inter-annual rainfall was 416 mm and the coefficient of variation was 28.9 %. The precipitation decline was 11 % in comparison with the long period (1939–2009). The AMMR

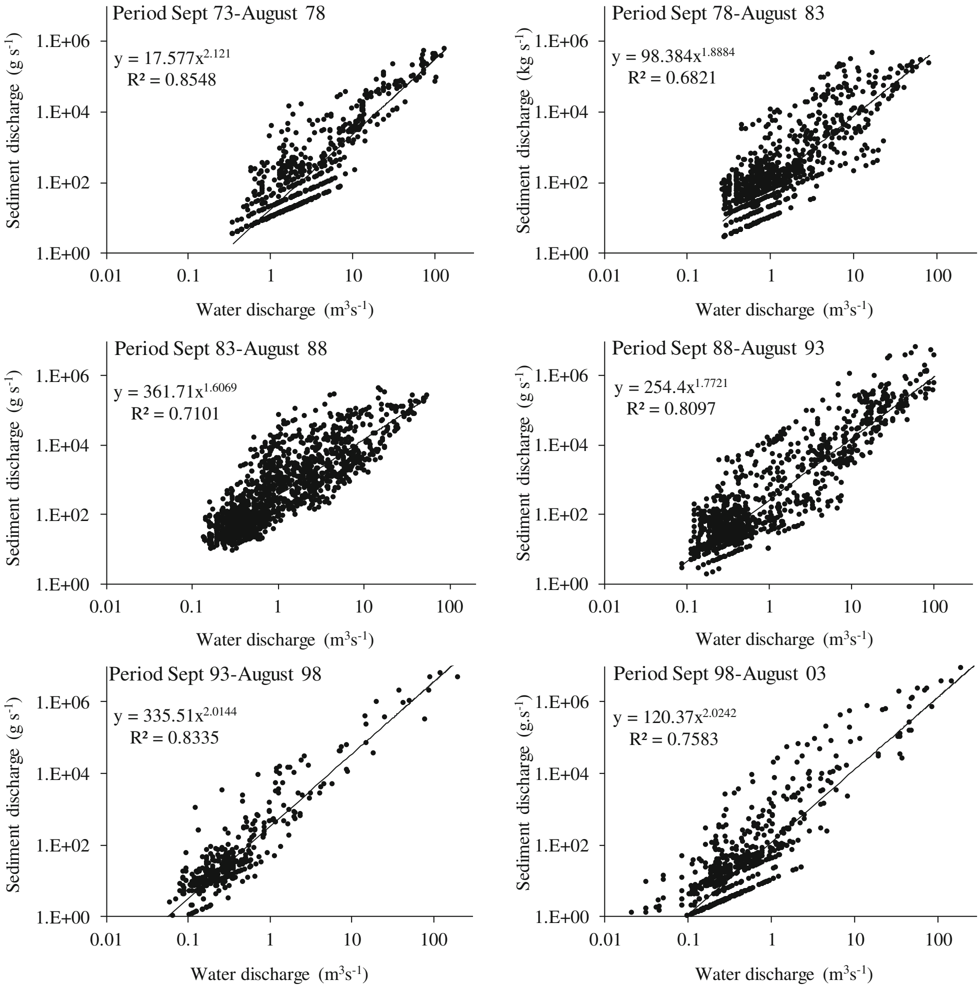


Fig 2 Sediment rating curves developed for successive 5-year intervals (September 1973 to August 2003)

Table 2 Main hydrological and sedimentological data recorded for successive 5-year time intervals

	Nt	Q_{max} (m^3/s)	C_{max} (mg/L)	$Q_{max(C)}$ (m^3/s)	$C_{98\%}$ (mg/L)	$\overline{C}$ (mg/L)	Date
1973–1978	260	131.9	7880	1.72	5340	412	July 1976
1978–1983	207	81.3	30,960	6.89	29,220	865	February 1979
1983–1988	317	55.0	68,660	1.04	34,302	1042	October 87
1988–1993	243	104.6	115,670	30.10	114,298	5671	July 1989
1993–1998	138	204.0	51,340	38.56	51,300	9132	September 96
1998–2003	184	272.6	58,680	6.80	56,880	7389	March 1999

Nt, Number of triplets of instantaneous data (Q, C, Q_S); Q_{max}, maximum discharge; C_{max}, maximum value of instantaneous sediment concentration; $Q_{max(C)}$, the coincident discharge with the max(C); C_{98}, quantile 98 %, i.e., 98 % of the total sediment flux was transported by flows with sediment concentration less than C_{98}; Date, month where is situated C_{max}

series showed a similar behavior. The inter-annual average decreased by 10.3 % and the coefficient of variation, CV, changes from 37 % estimated for the long period (1939–2009) to 38.1 % for the period (1973–2003), while for the ADMR series, the decrease was only 6 %, but the inter-annual variability was amplified (CV = 58. 3 %).

Variability of liquid and solid discharges

During the hydrometric measurement from September 1973 to August 2003, the total water volume drained by Wadi Sebdou was estimated at 465 hm^3 and the associated sediment flux was 2.78 million tons. Over the 30 years of study, water was always presents in the wadi. Low discharges less than 0.05 m^3/s sometimes lasted up 2 months during dry summers and the very low flow was around 0.01 m^3/s. Globally, long periods of time smaller more frequent flows with discharges less than 10 m^3/s produced nearly the same sediment flux than the infrequent flow varying between 10 and 100 m^3/s (Table 1). On average, flows less than 1 m^3/s were the more frequent (81 % of the total annual time) and yielded 56 % of the total water volume carrying 19 % of the total sediment yield. Sediment discharges varying between 10 and 100 m^3/s lasted short time, on average 0.9 % of the total annual time, i.e., 3.2 days per year, but the associated sediment flux was estimated at 47.6 % of the total. These flows were 5 times more turbid than the flow rates within the class interval 1–10 m^3/s. Discharges higher than 100 m^3/s were rare but sometimes very turbid. These flows have an average suspended sediment concentration of 50,200 mg/L. After 1993, most of the annual time, flows, and sediment concentrations were very low. High floods were rare, intense, and turbid (Table 3). For the successive 5-year intervals, the peak of sediment concentration coincided with moderate discharge, which means that high values of sediment concentration are mostly attributed to the abundance of the availability of sediment furniture in the catchment or in the stream channel which can be easily exhausted by runoffs. Table 3 reveals that, apart from the 5 years 1983–1988, the differences between C_{max} and $C_{98\%}$ were minim and suggests that the estimate of sediment contribution was not biased by the maximum value of sediment concentration.

Scatters in the water and suspended sediment discharge relation

The relationships between water and suspended sediment discharge were established for successive 5-year intervals and are shown in Fig. 2. A significant tendency for Q_S to increase with Q was observed at the consecutive time

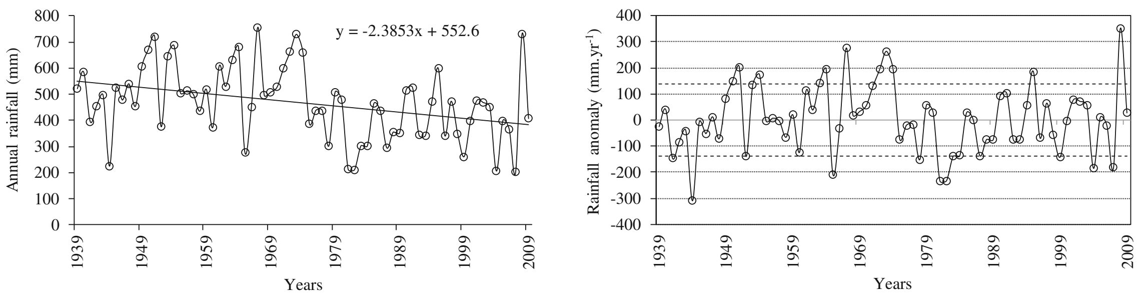


Fig 3 Long-term trend fluctuations of annual rainfall and time series of rainfall anomalies, dashed lines indicate ± one standard deviation. Period from September 1939 to August 2009

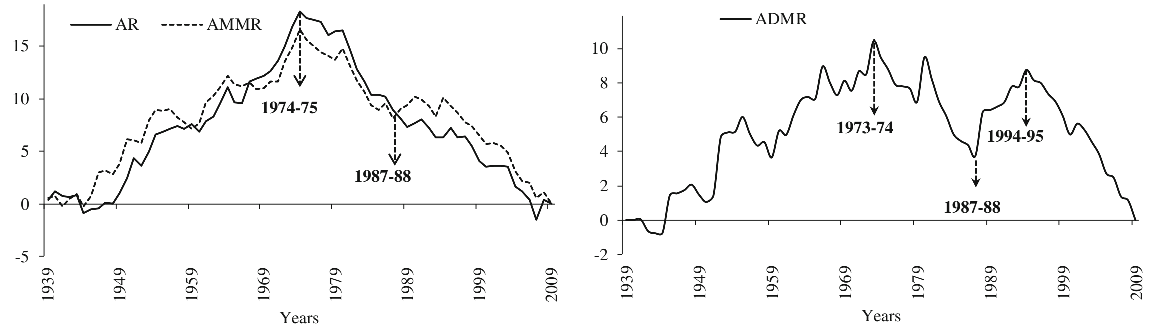


Fig 4 Buishand method for testing the homogeneity of AR, AMMR and ADMR records

intervals, resulting in high coefficients of determination which varies from 0.68 to 0.85.

The 5-year peak discharge ranges from 55.0 to 272.6 m^3/s (Table 3). Before 1993, the 5-year peak discharge was recorded during the wet season of winter and spring and never exceeded 135 m^3/s. The maximum value of water discharge was about 272.6 m^3/s in October 2001 and has generated sediment load of 10.9 Mg/s and coincided with the concentration of 40,300 mg/L. This value is moderate in comparison with the 115,600 mg/L transported by a water discharge of 30 m^3/s. Among the six intervals under consideration, 4 peaks of concentration were occurring outside the wet season. The highest sediment concentration value of 115600 mg/L was recorded in July 1989 (Table 2).

Figure 5 illustrates the time evolution of two statistic parameters, the coefficient of variation and skewness coefficient. First of all, we note that over the 30 years of hydrometric record, both water discharge and sediment concentration showed high irregularity expressed by the coefficient of variation and skewness coefficient beyond 2 and 4, respectively. For water and sediment discharge series, the CV and Skewness coefficients showed a slight decrease throughout the three first 5-year intervals, while these coefficients increased significantly for the following intervals. The substantial increase occurred during the period (1993–1998) for both flow and sediment discharge series. During the last 5 years, the CV coefficient exhibited a moderate increase in scatters for both series while the skewness coefficient showed considerable declining.

The highest 5 years (1988–93) of sediment yield reaches 1.34 million of tones giving a specific suspended sediment yield of 1034 t km^{-2} year^{-1}, while over the long period (1973–2003), the annual average was only about 343 t km^{-2} year^{-1} (Fig. 6).

Time evolution of the sediment rating parameters

Table 2 and Fig. 7 show the chronological variations of sediment rating parameters resulting from the standard and normalized models. Variations of these parameters by many orders of magnitude in either direction signify a noticeable temporal change in both potential of sediment yield and sediment sources. For both models, the y-intercept value varies in opposite direction compared to the b-value exhibiting a clear inverse relationship between the y-intercept and the slope of the regression line (Fig. 7). The two lowest b-values (<1.8) correspond to the tow highest y-intercept values (>2.39) and occur during the period 1983–1993, and the two highest b-values (>2.02) occur during the two periods 1973–1978 and 1998–2003 and coincided with the lowest or moderate y-intercept value depending on the applied model, standard, or normalized. Regarding the y-intercept, the sediment contribution supplied from the catchment varied considerably over time which contrasts with several order of magnitude in a-(respectively α-) values. Indeed, the ratio between the maximum divided by the minimum of a-values (respectively α-values) was above 20 (Table 2), while the b-value fluctuates little. Thus, before 1988, the sediment contribution supplied from the watershed catchment was continuously increasing,

Table 3 PCI values, rating parameters (b, a, α, Log(a) and Log(α)), the geometric mean Q_{GM}, the coefficient of determination R^2, and the τ-ratio evaluated for successive 5-year time intervals (1973–2003)

Period	PCI	b	a	α	Log(a)	Log(α)	QMG	R^2	τ (%)
1973–1978	18.92	1.121	18	26	1.25	1.42	1.41	0.85	13.2
1978–1983	19.58	0.888	98	113	2.00	2.05	1.18	0.68	3.2
1983–1988	18.42	0.607	362	370	2.56	2.57	1.04	0.71	0.4
1988–1993	23.13	0.772	254	246	2.40	2.39	0.96	0.81	−0.6
1993–1998	17.76	1.014	336	116	2.53	2.06	0.35	0.83	−18.3
1998–2003	19.68	1.024	120	45	2.08	1.65	0.38	0.76	−20.5

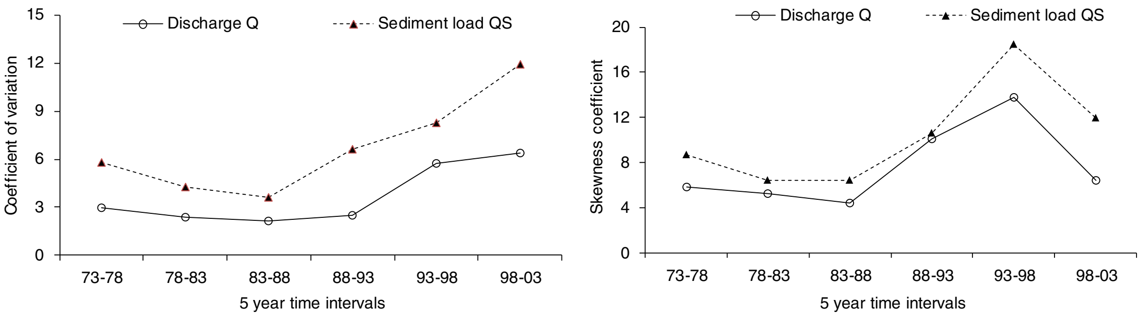


Fig 5 Time evolution of the coefficient of variation CV and skewness coefficient Cs of both water discharge and suspended sediment discharge series (1973–2003)

while the part of sediments derived from the hydrographic network was declining as suggested by the rating parameters. After that date, the stream power was increasingly important with the potential for riverbed erosion and sediment transport. This in turn means that the more the erosive power of the stream-flow increases the contribution from external sediment sources of the channel stream decreases and vice versa.

A comparison of y-intercept expressions (given in the Appendix) reveals that the standard and normalized models will differ by a factor of b * Log(Q_{GM}). The resulting discrepancy, based on view that the Log(a)-parameter is the "standard" y-intercept, was estimated by the following ratio and reported in Table 2:

$$\tau = \left(\frac{\mathrm{Log}(\alpha)-\mathrm{Log}(a)}{\mathrm{Log}(a)}\right).100 \qquad (8)$$

For both models, the behavior of the y-intercept was similar during the period 1973–1993 showing an increasing trend until 1988 and the τ-ratio was negligible for the period 1978–1993. During the decade 1993–2003, the decreasing trend was significant for the normalized model, obvious in Fig. 7 and where the τ-ratio reaches more than 18 %. In global view, the sediment furniture which can easily be transported seems to have a little influence on the τ-ratio.

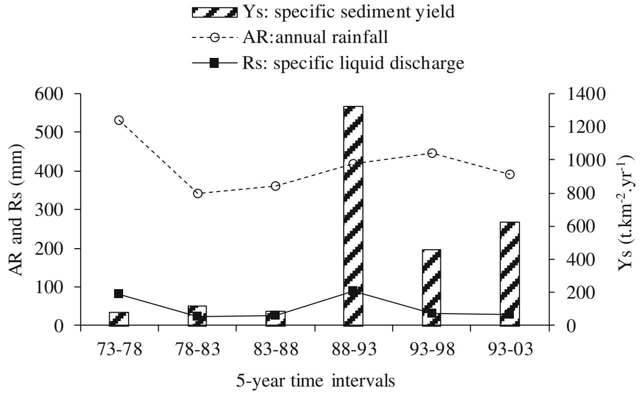


Fig 6 The 5-year contributions of annual rainfall, specific liquid discharge, and sediment yield in Wadi Sebdou watershed (1973–2003)

Rating parameters Log(a) and Log(α) were plotted versus the b-parameter (Fig. 8). Both models exhibit a counterclockwise hysteresis with a subtitle loop for the normalized model. The first limb corresponds to the period before 1988 and was characterized by a negative regression with a good coefficient of determination. This period may be attributed to a diminution of the erosive power of the wadi with a substantial contribution of sediment from the watershed system. After 1988, the limb of the produced curve was over the first limb suggesting a significant contribution of the sediment sources external to the wadi-flow (Fig. 8). However, the two relationships show decreasing regressions. It can be shown that 46 % of the total variation in Log(a) can be explained by the linear relationship between Log(a) and b, while the quality of the relationship was improved using the normalization of discharge and 83 % of the total variation in Log(α) can be explained by the linear relationship between Log(a) and b.

The values of the coefficient of determination R^2 deduced from the Q_S-Q relationship (Fig. 2) were explained by the rating parameters (Fig. 9). It appears that the more the a-parameter is higher; the least value is the coefficient of determination. In contrast, the more the b-parameter is higher and the higher value is the coefficient of determination.

Discussion

Rainfall variability and its consequences on discharge and sediment yield

The study was conducted in Wadi Sebdou a typical Mediterranean basin, which represents one of the few Maghreb basins where a long series of instantaneous discharge and sediment concentration measurements is available (Probst and Amiotte-Suchet 1992; Walling 2008). In addition, the period of hydrometric measurement from September 1973 to August 2003 is interesting with respect to the influence of climate variability and covers the strong temperature increase, which has been recorded since the second half of the 1970s in North West of Africa (Giorgi and Lionello 2008). In the 1970s, a common feature of many studies is declining annual

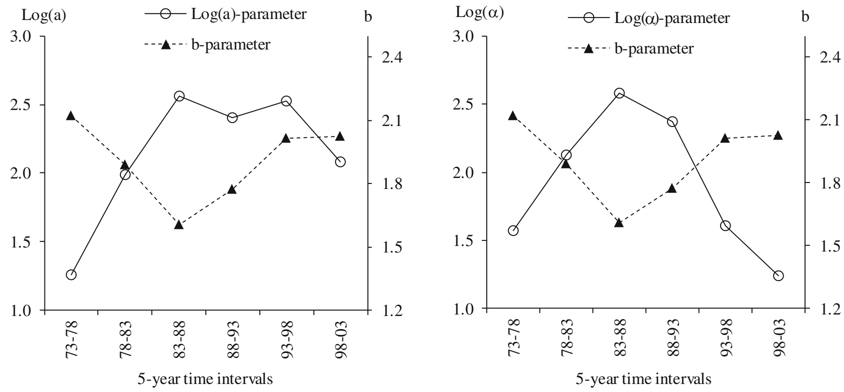


Fig 7 Chronological variation of the rating parameters over time (1973–2003)

precipitation over much of the Western Mediterranean region (Bates et al. 2008). Together with decreasing trend in the annual amount of rainfall, the study region was also marked by an increasing trend to intra-annual irregularity of precipitation. Over the period of hydrometric record (1973–2003), the ADMR series shows three distinct sequences. The first and the third sequences represent declining trend, while the second one exhibits an increasing trend and lasted 8 years from 1987 to 1994. This sequence occurred in the middle of the dry period and coincides with the highest PCI values. Furthermore, the study has pointed to a significant disturbance on the irregularity and the degree of scatter of both water discharge and suspended sediment concentration series. The low degree of scatter for both series corresponds to the time interval 1983–1988 and coincided with the severe drought resulting on consecutive low annual rainfall. Indeed, three of four consecutive dry years were extreme and occurred at the start of the 1980s (Fig. 3). The significant increase of the coefficient of variation and skewness coefficient observed after 1988 suggest high degrees of scatter and seem to be dependent on intra-annual irregularity of precipitations. The two highest values of the skewness coefficient correspond to the two successive 5-year intervals (1988–1998) which overlaps with the increasing trend of ADMR series spanning the period from September 1987 to August 1995. The intra-annual irregularity and declining trend of annual precipitation recorded in Wadi Sebdou watershed reveal the occurrence of long and dry periods without appreciable rainfall and prone to flash flood justified by the increasing trend of the skewness coefficient observed after 1988. Consequently, the increase of frequency and severity of droughts has caused a progressive impoverishment on vegetation sensitive to water availability and has entrained lands to a higher risk of desertification due to increased aridity. Then, soils were exposed to critical erosion where several orders of magnitude increases in rates of soil loss and sediment yield have been recorded over the 5-year interval 1988–1993 (Fig. 6). This statement is in perfect agreement with the results of the IPCC report (Bates et al. 2008) and where it was mentioned that the 1990s were notable for recurrent droughts and intense rainfall in the western Mediterranean. The increase of the degree of scatter evident in Fig. 5 is maybe the consequences of the trend toward warmer conditions over the Mediterranean region noticeable by increases in both precipitation intensity and frequencies of extreme precipitation events as reported by Bates et al. (2008) and corroborate the finding of Yair and Raz-Yassif (2004) whose cited the rainfall-runoff conversion processes as a main consequence of intra-annual variability.

Variability of the rating parameters

In logarithm domain, the sediment rating curve $C = aQ^b$ is a straight-line defined by the equation $\log(C) = \log(a) + b\log(Q)$. The b-parameter provides information on the sediment transport regime; when the b-value is more than one, the rating curve $C = aQ^b$ exhibits a concavity upwards in arithmetic domain and suggests a rapid increase in suspended sediment concentration when discharge increases, while

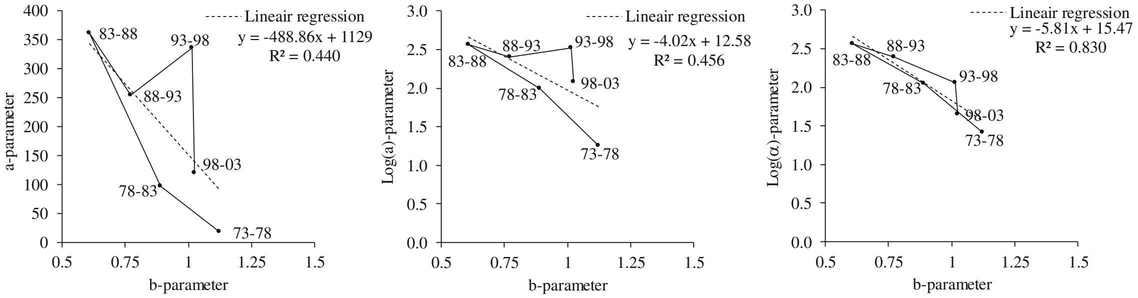


Fig 8 Time evolution of the y-intercept value (a, Log(a) and Log(α)) versus the b-value for successive 5-year intervals (1973–2003)

deceleration is observed when the b-value is less than one and the concavity of the rating curve is downwards. On the other hand, the y-intercept, Log(a), is commonly used to assess patterns and trends of sediments available in the watershed system and which may be transported by discharges below 1 m^3/s. So, this parameter describes the global state of the external sediment source and is closely associated to the amount of easily eroded and transported materials. This sediment furniture is considered a non-capacity load and is limited by the availability of hillslope material (Asselman 2000; Syvitski et al. 2000). However in this study, it is well shown in the Appendix that the y-intercept measurement cannot be used as independent measurements of the external sediment source to the channel stream and the Log(a)-value provide misleading results from the strong dependence of a on both b and Q. In lieu of Eq. (6) called the standard model, Warrick (2015) recommends to improve the sediment rating curve using discharge normalized formulations of Eq. (7) called normalized model. An ideal way to do this is to conduct the regression: $\mathrm{Log(C)} = \mathrm{Log}(\alpha)+ \beta \mathrm{Log}(Q/Q_{GM})$ where Q_{GM} is the geometric mean of the Q-values series. So, from normalized model, the y-intercept is linked the values of b and Q_{GM}. Because the b-value is almost universally positive (Syvitski et al. 2000), the sign of $\mathrm{Log}(\alpha)-\mathrm{Log(a)}$ will be positive for all Q_{GM} greater than 1 m^3/s, and the sign changes for all Q_{GM} smaller than 1 m^3/s, while both models are equivalent if $Q_{GM} = 1$ m^3/s. In Wadi Sebdou, for the successive 5-year intervals, the Q_{GM}-value varied from 0.35 to 1.40 m^3/s. This suggests that for both models, chronological variations of the rating parameters exhibit similar shape as reported in Fig. 7. The discrepancy between Log(a) and Log(α) will be significant as Q_{GM} moves away from 1 m^3/s.

The present study has shown that Wadi Sebdou reacts strongly to the widespread alteration and development of the land surface and hydrologic changes that may result from rainfall irregularity. Indeed, an examination of the chronological variation of the rating parameters has indicated that the functioning and ability of the watershed to sediment yield were substantially different before and after 1988 (Fig. 7). Prior to this date, the erosive power of wadi-flow gradually decreased while the sediment furniture from hillslopes increased. After that date, the sediment budget resulting from mechanisms acting on the drainage basin decreased and the wadi capacity to sediment transport increased. These could be the result of change in the wadi-flow regime manifested by a progressive long-term aggradation of the wadi-bed due to extra-sediment sources accumulated before 1988. The followed period was characterized by an increase in wadi power with the potential for wadi-bed erosion and sediment transport.

To assess the significance of potential changes in the sediment loads occurring within the Wadi Sebdou watershed, the temporal variations of the rating parameters a and b, evaluated for the successive 5-year intervals, were examined and compared to those obtained by Reid and Frostick (1987) and proposed to classify a wide variety of drainage systems encompassing arid, semiarid and humid areas. Except the first 5 years (1973–1978), the y-intercept Log(a) values were above 2.00, which correspond to parameters describing streams in arid areas (Fig. 8). The period (1973–1978) showed the lowest Log(a) value of 1.25, which belongs to [−2.40 1.60] the proposed interval for temperate and humid areas (Reid and Frostick 1987). It should be noted that the first quinquennial (1973–1978) overlaps the end of the wet period and the beginning of the dry period observed in the 1970s (Fig. 4). During this period, the functioning of external sediment source was comparable to that of temperate regions, but within the prolonged drought period a transition was made and the functioning becomes similar to that observed in arid systems. On the other hand, 5 out of 6 values of b-parameter fluctuate between 0.7 and 1.4. This interval is positioned between the highest value of 0.7 suggested for temperate and humid climate and the lowest value of 1.4 proposed for the arid climate (Reid and Frostick 1987). So, the functioning of the Wadi Sebdou watershed is recognized to semi-arid area.

For both models, the coefficient of determination is equivalent (see Appendix). Our finding reveals that the coefficient of determination is closely related to the b parameter that describes the erosive power of the wadi. According to Warrick (2015), the transport of sediments derived from the channel network is highly dependent on discharge and capacity of the stream to move sediment from the bed of its channel. However, the high a-value is synonymous with high variance and a low coefficient of determination. This fact can be explained by the high variability of external sediment sources which depend on several processes operating in the watershed system and is corroborated by the importance of the availability of sediment easily eroded and transported (Williams 1989; Megnounif et al. 2013). This is obvious when one considers that many sources external to stream-channel are governed by processes acting independently of runoff mechanisms. At event scale, sediment yield is related to the flood duration as well as its time of occurrence (Asselman 2000; Megnounif et al. 2013). Indeed, between storms, new sediment source became available for transport. Therefore, the component of the wash-load necessitates a time of preparation (Rovira and Batalla 2006), while mass movement and bank caving occur under very high soil moisture and high antecedent rainfall conditions (Seeger et al. 2004). Further, appreciable quantities of sediment deposited under low flow conditions may be available to subsequent flood events for transport within the channel (Megnounif et al. 2013). Consequently, the quality of the sediment rating curve is mainly altered by the strong a-value (Fig. 9). At least two phenomena explain this statement. Firstly, the wash load is considered a non-capacity load and is limited by the availability of hillslope material (Williams 1989). Secondly, the contribution of groundwater to dilute existing suspended sediment concentrations in drainage system (Warrick 2015).

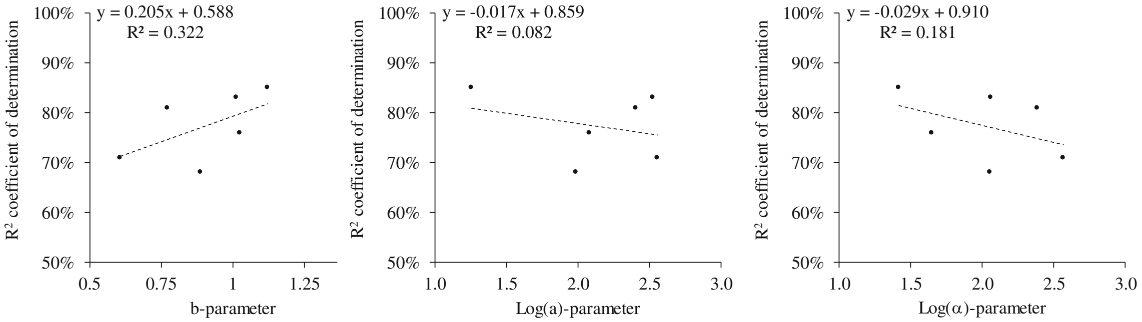


Fig 9 Contribution of sediment supplied from internal and external sources to the channel and its impact on the accuracy of the rating curves

For both models, the y-intercept values show negative correlation with the b-values (Figs. 7 and 8). This issue has been highlighted by Rannie (1978), Thomas (1988), Asselman (2000), Achite and Ouillon (2007), and Yang et al. (2007), who noticed a clear negative linear correlation between Log(a) and b. Asselman (2000) has emphasized on the importance of the steepness of the rating curve, which combines between soil erodibility and erosivity of the river. This study reveals that the quality of the relationship was highly improved using the normalization of discharge and display subtle counter-clockwise loop close to a single curve.

Interestingly, the present study reveals that the watershed ability to sediment yield may be explained not only by the rating parameters but also the intra-annual irregularity of rainfall and water discharge. Indeed, the highest 5-year sediment yield occurred during the period 1988–1993 (Fig. 6) in which moderate rating parameter values were exhibited. This 5-year interval coincided with the high 5-year mean of PCI values and belonged to the period 1987–1995 manifested by a significant trend of increasing intra-annual variability of rainfall. Because of the prolonged drought, soils have been often compact with poor vegetation, promoting high peak flows and favoring high mechanical erosion which results in important weathering in the hydrographical network as affirmed by the increase of b-parameter observed after 1988. Consequently, during the period 1988–2003, the sediment contribution yielded in the Wadi Sebdou watershed was eight times greater than that produced in the prior period. The literature review contains several studies, which demonstrates the impact of aridity on rates of soil loss and sediment yield (e.g., Langbein and Schumm 1958; Scott 2006) and reported that the sediment delivery is highly correlated to the irregularity of flows (Shakesby et al. 2002; Achite and Ouillon 2007). In this context, Achite and Ouillon (2007) and Vachtman et al. (2012) considered the irregularity of flow as the primary forcing factor in the rate of sediment supply.

Conclusion

The results have shown the variability of the suspended sediment transported in the Wadi Sebdou watershed. The variability appears to be mainly related to the rainfall irregularity. Temporal analysis of the rating parameters of water discharge–suspended sediment discharge relationships for instantaneous values spanning the period from September 1973 to August 2003 provides insight into the timing and contribution of sediment sources throughout the drainage system. Significant changes were detected in the watershed ability to sediment yield and the rating curve steepness has provided information on the sediment transport regime.

Significant changes were detected in the watershed ability to sediment yield and the remarkable variations coincided with major changes in rainfall behavior. The decrease of annual rainfall trend, observed after 1974, was accompanied by an increasing intra-annual variability mainly manifested by an increase rainfall concentration within a year and resulted in recurrent long and dry period which make soil more compact with poor vegetation. The increase in rainfall irregularity trend has entrained lands to a higher risk of desertification due to increased aridity and then exposed soils to critical erosion. So, rainfall irregularity has altered the sediment transport regime. At the start of the 1970s, the functioning of external sediment source was comparable to that of temperate regions, but within the prolonged drought period, a transition was made and the functioning becomes similar to that observed in arid systems.

Both internal and external sediment sources to the wadi channel showed clear evidence of significant changes observed after 1988. Sediment sources external to the wadi channel have substantially increased in comparison with the prior period. In the same way, the transport capacity of the wadi has sensitively increased. In addition, the R^2 statistic used as an indicator of the goodness of fit for water discharge–suspended sediment discharge regression was mainly dominated by the powerful erosive of wadi flow. The more the transport capacity is high; the coefficient of determination is good. In contrast, the copiousness amount of stored sediment at the beginning of a runoff season decreased the quality of sediment rating relation.

This paper has highlighted the influence of rainfall irregularity in the runoff process in semi-arid environments and its impact on sediment yield. However, we need to go much further in understanding the interplay of sediment sources and transfer from external to internal sediment sources. For that purpose, wadi management projects requires further studies in the future to analyze the data in the context of high temporal variability of semiarid environments followed up over longer periods of time.

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Appendix

Linear model

Given a set of n points (X_i, Y_i) on a scatterplot, a simple linear regression is a statistical technique used to found the best-fit line, $Y = a + bX$, that models, $Y-X$, the relationship between a dependent variable Y and an independent variable X. The regression coefficients a and b are calculated from the following statistical moments.

$$\begin{cases}
\overline{X} = \dfrac{1}{n} \sum\limits_{i=1,n} x_i & (1) \\
\overline{Y} = \dfrac{1}{n} \sum\limits_{i=1,n} y_i & (2) \\
\overline{X^2} = \dfrac{1}{n} \sum\limits_{i=1,n} x_i^2 & (3) \\
\overline{X.Y} = \dfrac{1}{n} \sum\limits_{i=1,n} x_i y_i & (4) \\
\mathrm{Cov}(X,Y) = \dfrac{1}{n} \sum\limits_{i=1,n} \left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right) = \overline{X.Y} - \overline{X}.\overline{Y} & (5) \\
\mathrm{Var}\,(X) = \sigma_X^2 = \dfrac{1}{n} \sum\limits_{i=1,n} \left(x_i - \overline{X}\right)^2 = \overline{X^2} - \left(\overline{X}\right)^2 & (6)
\end{cases}$$

The a- and b-parameters and the coefficient of détermination R^2 are estimated by the following équations:

$$\begin{cases}
b = \dfrac{\mathrm{Cov}(X,Y)}{\mathrm{Var}\,(X)} & (7) \\
a = \overline{Y} - b\overline{X} & (8) \\
R^2 = \dfrac{\mathrm{Cov}^2(X,Y)}{\mathrm{Var}\,(X)\mathrm{Var}\,(Y)} & (9)
\end{cases}$$

If the variable X is changed to $X = Z - t$ where t is a constant, it can be deduced that:

$$\overline{X} = \overline{Z} - t;\ \mathrm{Cov}\ (X,Y) = \mathrm{Cov}\ (Z,Y) \text{ and } \mathrm{Var}\ (X) = \mathrm{Var}\ (Z) \qquad (10)$$

So, coefficients of regression line, $Y = \alpha + \beta Z$, that models the relationship $X-Z$, are defined as follows:

$$\begin{cases}
\beta = b & (11) \\
\alpha = a - bt & (12)
\end{cases}$$

From Eq. (9) and (10), it can be deduced that the coefficient of determination, R^2, remains unchanged.

It is concluded that, when X is translated by a length "t," the regression line and more particularly the y-intercept are translated by a length "b*t," where the b-value is the slope. The quality of the regression remains unchanged.

Power model

The power regression, $C = aQ^b$, is non-linear model and requires the log transformation of variables X and Y data prior to the determination of a- and b-parameters. So, the power regressions $C = aQ^b$ and $\mathrm{Log}(C) = \mathrm{Log}(a) + b\mathrm{Log}(Q)$ are equivalent. The Log(a) value is the y-intercept and b is the slope. The value of the y-intercept is obtained for $Q = 1$.

Let $Q = w.q$, then $\mathrm{Log}(Q) = \mathrm{Log}(q) + \mathrm{Log}(w)$. When conducting two regression models $C = aQ^b$ and $C = \alpha q^\beta$, regression parameters are related by the following equations:

$$\begin{cases}
\beta = b & (13) \\
\mathrm{Log}(\alpha) = \mathrm{Log}(a) + b\mathrm{Log}(w) & (14) \\
\alpha = a.w^b & (15)
\end{cases}$$

Hence, y-intercept values derived from the two previous models will differ by a factor of $b * \mathrm{Log}(w)$. It can be noted that the discrepancy, denoted $\Delta|_{Q=1}$, depends on the b-value

$$\Delta|_{Q=1} = \mathrm{Log}(\alpha) - \mathrm{Log}(a) = b\mathrm{Log}(w) \qquad (16)$$

Applying Eq. (12), it can be shown that the point $\left(\overline{\mathrm{Log}(Q)}, \overline{\mathrm{Log}(C)}\right)$ is solution to the equation Log(C) = Log(a) + bLog(Q). Further, $\overline{\mathrm{Log}\ (Q)}$ is the center of mass of the Log(Q) data.

$$\overline{\mathrm{Log}(Q)} = \frac{1}{n}\sum_{i=1,n}\mathrm{Log}(Q_i) = \mathrm{Log}\left(\left(\prod_{i=1,n}Q_i\right)^{\frac{1}{n}}\right) \tag{17}$$

Note that $Q_{GM} = \left(\prod_{i=1,n}Q_i\right)^{\frac{1}{n}}$ is the geometric mean. Thereby, the geometric mean is the optimal normalization parameter because it is the center of mass of the Log(Q) data.

The Following are some examples to illustrate the changes in the y-intercepts values:

- If one proceeds to change the unit of Q, example: $Q = 1000q$, the difference is given by: $\Delta|_{Q=1} = \mathrm{Log}(\alpha) - \mathrm{Log}(a) = b\mathrm{Log}(1000)$
- If the variable Q is normalized using the geometric mean, $q = \frac{Q}{Q_{GM}}$, then the difference is as follows: $\Delta|_{Q=1} = \mathrm{Log}(\alpha) - \mathrm{Log}(a) = b\mathrm{Log}(Q_{GM})$. So:

$$\beta = b \quad \text{and} \quad \alpha = a.Q_{GM}{}^{b} \tag{18}$$

References

Achite M, Ouillon S (2007) Suspended sediment transport in a semiarid watershed, Wadi Abd, Algeria (1973–1995). J Hydrol 343:187–202. doi:10.1016/j.jhydrol.2007.06.026

Asselman NEM (2000) Suspended sediment dynamics in a large drainage basin: the river Rhine. Hydrol Process 13:1437–1450

Barthes B, Roose E (2002) Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47:133–149

Bashkin VN, Erdman LK, Abramychev AY, Sofiev MA, Priputina IV, Gusev AV (1997) The input of anthropogenic airborne nitrogen to the Mediterranean Sea through its watershed. UNEP, Athens, MAP Technical Reports Series No. 118, 94 p

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p

Bouanani A (2004) Hydrologie, transport solide et modélisation. Etude de quelques sous bassins de la Tafna (NW–Algerie). Ph.D. Thesis, Tlemcen University, Algeria, 250p

Buishand TA (1982) Some methods for testing the homogeneity of rainfall records. J Hydrol 58:11–27

Ceballos A, Martíınez-Fernández J, Luengo-Ugidos MA (2004) Analysis of rainfall trends and dry periods on a pluviometric gradient representative of Mediterranean climate in the Duero Basin. Spain J Arid Environ 58:215–233

Christensen NS, Lettenmaier DP (2007) A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrol Earth Syst Sci 11(4):1417–1434

de Luis M, García-Cano MF, Cortina J, Raventós J, González-Hidalgo JC, Sánchez JR (2001) Climatic trends, disturbances and short-term vegetation dynamics in a Mediterranean shrubland. For Ecol Manag 147:25–37

Demmak A (1982) Contribution à l'étude de l'érosion et des transports solides en Algérie septentrionale. Thesis, Docteur-Ingénieur, Univ. Paris, France

Dudgeon D, Arthington AH, Gessner MO, Kawabata MO, Knowler Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MJL, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81:163–182. doi:10.1017/S1464793105006950

Evans AD, Bennett JM, Ewenz CM (2009) South Australian rainfall variability and climate extremes. Clim Dyn 33(4):477–493

Fleming G (1969) Design curves for suspended load estimation. Proc Inst Civ Ing 43:1–9

Gilroy EJ, Kirby WH, Cohn TA, Glysson GD (1990) Discussion of uncertainty in suspended sediment transport curves by McBean and Al-Nassri. J Hydraul Eng 116(1):143–145

Gregor CB (1970) Denudation of the continents. Nature 228:273–275

Gregory KJ, Walling DE (1973) Drainage basin form and process. Edward Arnold, London, 458 p

Guy HP (1978) Fluvial sediment concepts. U.S. Geol. Survey, Prof. Paper, Chapter C1, 53p.

Hicks DM, Gomez B, Trustrum NA (2000) Erosion thresholds and suspended sediment yields: Waipaoa River basin, New Zealand. Water Resour Res 36:1129–1142

Horowitz AJ (2003) An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrol Process 17:3387–3409

Horowitz AJ (2008) Determining annual suspended sediment and sediment-associated trace element and nutrient fluxes. Sci Total Environ 400:315–343. doi:10.1016/j.scitotenv.2008.04.022

Iadanza C, Napolitano F (2006) Sediment transport time series in the Tiber River. Phys Chem Earth 31:1212–1227

Jansson MB (1982) Land erosion by water in different climates. Report 52, Universitet Naturgeografiska Institutionen, Uppsala University, Sweden.

Langbein WB, Schumm SA (1958) Yield of sediment in relation to mean annual precipitation. EOS Trans Am Geophys Union 39(6):1076–1084

Leopold LB, Maddock TJr (1953) The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey, Professional Paper 252, 56p.

Ludwig W, Probst JL (1998) River sediment discharge to the oceans: present-day controls and global budgets. Am J Sci 298:265–295

Martínez-Mena M, Williams AG, Ternan JL, Fitzjohn C (1998) Role of antecedent soil water content on aggregates stability in a semi-arid environment. Soil Tillage Res 48:71–80

Megnounif A, Ghenim AN (2013) Influence des fluctuations hydro-pluviométriques sur la production des sédiments : Cas du bassin de la haute Tafna. Rev Sci Eau 26(1):53–62. doi:10.7202/1014919ar

Megnounif A, Terfous A, Ouillon S (2013) A graphical method to study suspended sediment dynamics during flood events in the Wadi Sebdou, NW Algeria (1973–2004). J Hydrol 497:24–36. doi:10.1016/j.jhydrol.2013.05.029

Milliman JD, Farnsworth KL (2011) River discharge to the coastal ocean—a global synthesis. Cambridge University Press, Cambridge, 384pp

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci 04(13):268–272

Oliver JF (1980) Monthly precipitation distribution: a comparative index. Prof Geogr 32:300–309

Owens PN, Walling DE, Carton J, Meharg AA, Wright J, Leeks GJL (2001) Downstream changes in the transport and storage of sediment-associated contaminants (P, Cr and PCBs) in agricultural and industrialized drainage basins. Sci Total Environ 266:177–186

Poulos SE (2011) An insight to the fluvial characteristics of the Mediterranean and Black sea watersheds. In: Lambrakis N, Stournaras G, Katsanou K (Eds) Advances in the research of aquatic environment. Springer. 191–198

Probst JL, Amiotte-Suchet P (1992) Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa). Hydrol Sci J 37:621–637

Rannie WF (1978) An approach to the prediction of suspended sediment rating curves. In: Davidson-Arnott R, Nickling W (eds) Research in fluvial systems. Geoabstracts, Norwich, pp 149–167

Reid I, Frostick LE (1987) Discussion of conceptual models of sediment transport in streams. In: Thorne CR, Bathurst JC, Hey RD (eds) Sediment transport in gravel-bed rivers. Wiley, New York, pp 410–411

Robinson AR (1977) Relationships between soil erosion and sediment delivery. Erosion and solid matter transport in inland waters. IAHS Bull 122:159–167

Roehl JW (1962) Sediment source areas, delivery ratios, and influencing morphological factors. IAHS Publ 59:202–213

Rovira A, Batalla RJ (2006) Temporal distribution of suspended sediment transport in a Mediterranean basin: the Lower Tordera (NE Spain). Geomorphology 79(1–2):58–71. doi:10.1016/j.geomorph.2005.09.016

Sarma JN (1986) Sediment transport in the Burhi Dihing River, India. In: Hadley RF (Ed) Drainage basin sediment delivery. IAHS Publ. 159: 199–215

Scott S (2006) Predicting sediment transport dynamics in ephemeral channels: a review of literature. ERDC/CHL CHETN-VII-6. U.S. Army Engineer Research and Development Center, Vicksburg, http://chl.erdc.usace.army.mil/chetn

Seeger M, Errea MP, Beguerıà S, Arnaez J, Martıà C, Garcıà-Ruiz JM (2004) Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. J Hydrol 288(3–4):299–311

Shakesby RA, Coelho COA, Schnabel S, Keizer JJ, Clarke MA, Lavado Contador JF, Walsh RPD, Ferreira AJD, Doerr SH (2002) A ranking methodology for assessing relative erosion risk and its application to dehesas and montados in Spain and Portugal. Land Degrad Dev 13:129–140

Syvitski JPM, Morehead MD, Bahr DB, Mulder T (2000) Estimating fluvial sediment transport: the rating parameters. Water Resour Res 36:2747–2760

Syvitski JPM, Peckham SD, Hilberman R, Mulder T (2003) Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sediment Geol 162:5–24. doi:10.1016/S0037-0738(03)00232-X

Syvitski JPM, Vörösmarty C, Kettner AJ, Green P (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308:376–380

Thomas RB (1988) Monitoring baseline suspended sediment in forested basins: the effects of sampling on suspended sediment rating curves. Hydrol Sci J 33:499–514

Vachtman D, Sandler A, Herut B, Greenbaum N (2012) Dynamics of suspended sediment delivery to the eastern Mediterranean continental shelf. Hydrol Process. doi:10.1002/hyp.9265

Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. Glob Planet Chang 39:169–190

Walling DE (1977) Assessing the accuracy of suspended sediment rating curves for a small Basin. Water Resour Res 13(3):532–538

Walling DE, Fang D (2003) Recent trends in the suspended sediment loads of the world's rivers. Glob Planet Chang 39:111–126

Walling DE (2006) Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology 79:192–216. doi:10.1016/j.geomorph.2006.06.019

Walling DE (2008) The changing sediment loads of the world's rivers. Ann Warsaw Univ Life Sci SGGW Land Reclam 39:3–20

Warrick JA, Madej MA, Goñi MA, Wheatcroft RA (2013) Trends in the suspended-sediment yields of coastal rivers of northern California, 1955–2010. J Hydrol 489:108–123

Warrick JA (2015) Trend analyses with river sediment rating curves. Hydrol Process 29:936–949

Williams GP (1989) Sediment concentration versus water discharge during single hydrologic events in rivers. J Hydrol 111:89–106

Yair A, Raz-Yassif N (2004) Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. Geomorphology 61: 155–169. doi:10.1016/j.geomorph.2003.12.003

Yang GF, Chen ZY, Yu FL, Wang ZH, Zhao YW (2007) Sediment rating parameters and their implications: Yangtze River, China. Geomorphology 85:166–175. doi:10.1016/j.geomorph.2006.03.016

Zhang XC, Nearing MA (2005) Impact of climate change on soil erosion, runoff, and wheat productivity in central Oklahoma. Catena 61(2): 185–195

Zhang W, Wei X, Zheng J, Zhu Y, Zhang Y (2012) Estimating suspended sediment loads in the Pearl River Delta region using sediment rating curves. Cont Shelf Res 38:35–46. doi:10.1016/j.csr.2012.02.017

Zhao G, Mu X, Strehmel A, Tian P (2014) Temporal variation of streamflow, sediment load and their relationship in the Yellow River Basin, China. PLoS ONE 9(3), e91048. doi:10.1371/journal.pone.0091048