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Suspended sediment transport in a semiarid watershed, Wadi Abd, Algeria (1973–1995)

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Summary A quantification of the fine sediment budget of a wadi (dryland river) in NW Algeria is presented for a period of 22 hydrological years (1973–1995). The climate is Mediterranean over the Wadi Abd basin (2480 km^2), the mean annual precipitation is 250 mm and the mean annual discharge is 1.0 $m^3\,s^{-1}$ at the gauging station. Regression relationships between water discharge Q and suspended sediment concentration C are calculated from 1432 paired measurements in the Wadi Abd, leading to power-law equations of the type $C = a\,Q^b$. The variability of coefficients a and b, calculated for 138 floods and flood stages, is analyzed. The median value of b is 0.757, indicating that C is almost proportional to $Q^{3/4}$. Given that the (a, b) pairs are correctly aligned ($r^2 = 0.578$), the coefficients a and b are not independent. Regression relationships between daily Q and daily suspended sediment concentration and discharge Q_s are calculated from 702 input data. The performances of these regression relationships are shown to be equivalent, leading to over-estimations of 20–25% of the suspended sediment flux. The non-biased C–Q sediment rating curve is used to extrapolate a time series of C measurements, and thus to analyze the long-term patterns in suspended sediment transport. Average sediment wash-down (136 t $km^{-2}\,yr^{-1}$) is similar to the mean global value. The ratio of sediment wash-down to the river water discharge is 10.7×10^6 t km^3, 20 times greater than the average ratio in the Earth's eastern hemisphere, and illustrates the highly erosive power of wadis. Variability is shown to be significant at the seasonal scale (CV = 89%) and higher at the interannual scale (CV = 139%). The fine sediment flux mainly occurs in autumn (48.4%) and spring (32.7%). Although precipitation decreased, it was more irregular from one year to another over the period 1985–1995 than during the period 1973–1985, and the Wadi Abd, which was a perennial river, became intermittent in the late 1980s. This increasing irregularity is accompanied by: an amplification of the variations of discharge, an increase in the average discharge of approximately 20% during the second period, and a higher and more irregular suspended particulate flux. The mean annual suspended

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sediment yield is shown to be highly correlated with the standard deviation of mean daily discharge calculated per year ($r^2 = 0.989$). The highly significant interannual variability points to the difficulty of defining a suitable period to calculate a reference value for sediment budgets. It also emphasizes the absolute necessity of continuing a series of measurements over longer time periods to study fluctuations in the context of climate change.

Introduction

The volume and types of particles eroded and transported by the rivers exhibits great geographical and temporal variability. The stakes associated with erosion and particulate transport are numerous. These include impacts on ground fertility, transfer, storage and fate of nutrients and contaminants, changes in water quality trends, aquatic habitats, silting up of channels, reservoirs and harbours, and reductions in hydroelectric equipment longevity (Williams, 1989; Ouillon, 1998; Horowitz, 2003). In the Maghreb (North Africa), problems essentially relate to the silting up of the dams, which reduces the water storage capacity and the hydraulic potential by 2–5% per year (Kassoul et al., 1997). A correct estimation of the sediment volume carried by a river is therefore necessary for an adapted water resources management strategy. A greater working knowledge of long-term variations of sediment loads in a variety of rivers is also necessary for an assessment of the current trends in global land-ocean sediment transfer in the context of climate change (Walling and Fang, 2003). Sediment transport is well documented in perennial rivers in temperate or humid climates but is far less studied in dryland streams, also called wadis or oueds, despite their known high transport efficiency (Reid and Laronne, 1995).

Table 1 Targeted papers relevant to sediment transport in wadis

Reference	River basin or region	Ephemeral or intermittent	Duration of monitoring	Suspension and/ or bedload	Main contribution
Schick (1977)	Tunisia, Peru, Nile	Both			Review
Sutherland and Bryan (1990)	Katiorin, Kenya	Ephemeral	1 year	Suspension	Particle-size analysis of suspended sediment
Laronne et al. (1994), Reid and Laronne (1995), Powell et al. (2001)	Yatir, Negev	Ephemeral	Flash floods	Bedload	Quantification of bedload, armouring and bedload grain size distribution
Reid and Frostick (1997)	Numerous	Ephemeral			Review
Clapp et al. (2000)	Yael, Israel	Ephemeral	33 years	Both	Long-term sediment generation rates versus sediment yield
Terfous et al. (2001)	Mouilah, NW Algeria	Intermittent	16 years	Suspension	Temporal variability of sediment transport
Touaïbia et al. (2001)	Haddad, Algeria	Intermittent	22 years	Suspension	Temporal variability of sediment transport
Achite and Meddi (2004)	Mina, Algeria Haddad, Algeria	Intermittent	22 years	Suspension	Temporal variability of sediment transport
Megnounif et al. (2003)	Sebdou, NW Algeria		5 years		Temporal variability of sediment transport
Alexandrov et al. (2003a)	Eshtemoa, Negev	Ephemeral	6 years	Suspension	Temporal variability of sediment transport
Benkhaled and Remini (2003)	Wahrane, Algeria	Intermittent	13 floods	Suspension	C–Q rating curves
Amos et al. (2004)	Burdekin, Australia	Intermittent	1 flood (15 days)	Both	Detailed sediment transport during one flood
Cohen and Laronne (2005)	Rahaf-Qanna'im, Israel	Ephemeral	Several floods	Both	Sediment transport during high discharge events
Alexandrov et al. (2007)	Eshtemoa, Negev	Ephemeral		Suspension	Relationship between C–Q curve and rainfall type

Few studies have been published on sediment transport in rivers in semiarid zones. Probst and Amiotte-Suchet (1992), in their review of suspended sediment transported by wadis in the Maghreb, underline the lack of available data for such river types. Other reviews have also been published by Schick (1977), and Alhamid and Reid (2002) and a brief description of these and other papers is given in Table 1. Nevertheless, data from these systems is still fragmentary and further study of both the quantification of solid transport in semiarid basins and its variability is clearly required. Therefore, the purpose of this paper is to quantify suspended sediment transport in a semiarid catchment area, the Wadi Abd basin in Algeria, and to analyze its temporal variability over a 22-year period. Wadi Abd is a tributary of the Wadi Mina and contributes to the silting of the Sidi M'hamed Benouada dam.

For the gauged sites, suspended sediment yield is computed from rating curves established from long-term measurement series (Walling, 1977; Ferguson, 1986; Jansson, 1996; Asselman, 2000; Achite, 2002; Horowitz, 2003). In ungauged rivers, suspended sediment yield may be computed from models where basic physiographic factors (climate, soils and top cover) are taken into account (Poliakov, 1935; Lopatin, 1952; Lisitisyna and Aleksandrova, 1972; Merritt et al., 2003). In the Mediterranean region, the quantification of sediment transport by a river is rendered difficult by the temporal variability of water flow. In these semiarid environments, most of the river discharge occurs during flash floods, and obtaining samples during these quick events is often difficult (Schick, 1977; Reid and Laronne, 1995; Serrat et al., 2001). For long observation periods (>15 years), average annual suspended sediment yield is equal to the arithmetic mean value of observed annual suspended sediment yield.

In this paper, regression relationships are built between instantaneous and daily values of concentration and water discharge, and also between daily suspended sediment discharge and water discharge from data collected at the gauging station of Ain Hamara in the Wadi Abd during a 22-year period (1973—1995). These regressions are discussed with a primary focus on the coefficients involved in the sediment rating curve and their temporal variability. A secondary discussion focuses on the comparison of statistical performances of C—Q and Q_s—Q relationships. The regressions are compared to those from other rivers, and are then used to (a) obtain a long-term estimate of suspended sediment discharge from daily water discharge values at the gauging station during the 1973—1995 period; and (b), analyze the variability of the mean suspended sediment flux at seasonal and interannual scales over a 22-year period.

Study area: the Wadi Abd

General information

The Wadi Abd basin is located in the north western part of Algeria, draining an area of 2480 km^2 (Fig. 1). It is located between 34°40′ N and 35°25′ N, and 0°20′ E and 1°10′ E.

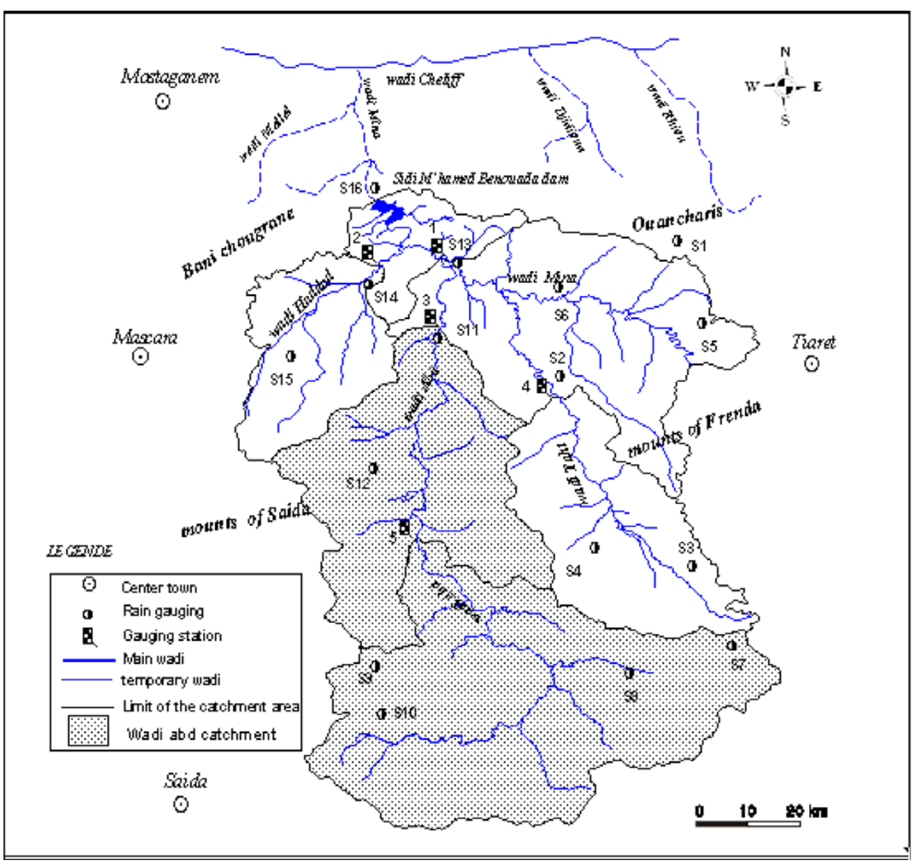

Figure 1 The Wadi Abd catchment area. Ain Hamara gauging station is station 3.

Table 2 Main characteristics of the Wadi Abd basin

Parameters	Unit	Value
Basin area	km^2	2480
Mean elevation	m	711
Minimum elevation	m	288
Maximum elevation	m	1339
Mean slope gradient	%	0.48
Length of the main wadi	km	118
Drainage density	$km\ km^{-2}$	3.70

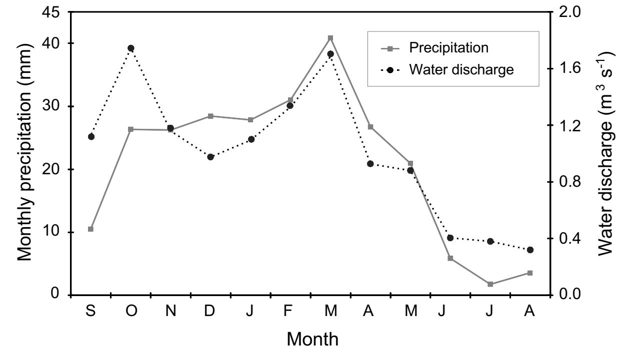

Figure 2 Variability of mean monthly precipitation and water discharge. (precipitation in S11, water discharge in 3, see locations in Fig. 1).

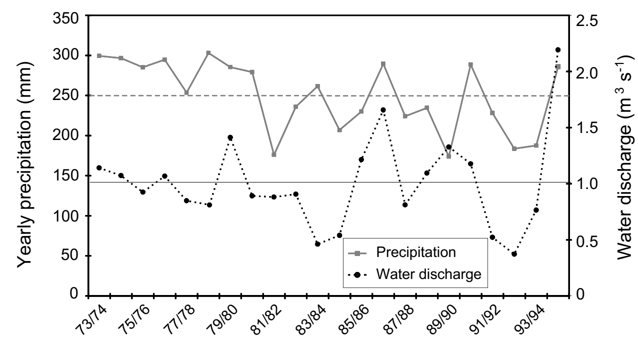

Figure 3 Variability of annual precipitation and mean annual water discharge. (precipitation in S11, water discharge in 3, see locations in Fig. 1) Horizontal lines are average values.

The main physiographic characteristics are reported in Table 2. The Wadi Abd is a tributary of the Wadi Mina; the Wadi Mina is a main tributary of the Wadi Chelif, Algeria's principal river. The basin can be divided into two major zones: mountains (Mounts of Saida in the South and Mounts of Frenda, Tiaret, in the North), and the plain of Mina.

The Wadi Abd has been selected for this study because of the availability of rainfall and hydrometric records. The available hydrological data consists of the mean daily water discharge ($m^3\ s^{-1}$), coincident measurements of water discharge ($m^3\ s^{-1}$) and suspended sediment concentrations ($kg\ m^{-3}$). The data has been provided by the National Agency of Hydraulic Resources (ANRH, Alger).

Geology, vegetation and topography

The Wadi Abd catchment area is predominantly made up of Upper Jurassic (marl-limestone, 45.9% of the surface), large zones of Middle Jurassic (calcareous and karstic dolomites, 20.2%) and Pliocene (7.4%) (Achite, 1999).

The Jurassic zone of the Southern basin is eroded and nearly 50% of its surface is covered by a varying density of vegetation. The forests cover 5.8% of this zone, mainly with young plantations of Aleppo pines (*Pinus halepensis*). Two forms of scrub cover 32% of the catchment area: scrub with *Pistacia* and *Olea*, and scrub with *Tetraclinis*. In addition to the natural vegetation, the herbaceous vegetation mainly consists of cereal crops which form the principal permanent cultures (Kouri, 1993; Mahieddine, 1997).

The basin relief exhibits slopes between 0.12% and 0.25% on the Jurassic mountains (Achite, 1999). Water erosion is mostly intensive in the northern and western mountainous parts of the Wadi Abd basin.

Climate, rainfall and runoff

The climate is Mediterranean and is characterized by a wet and dry season. The rainy season is from October to March, and the dry season lasts from April to August/September (Fig. 2). Annual precipitation is highly irregular, varying between 174 mm yr^{-1} and 303 mm yr^{-1} (Fig. 3). Mean annual precipitation is 250 mm, with a coefficient of variation (denoted hereafter CV and defined as the ratio of the standard deviation to the mean) of 17.6% between 1973–74 and 1994–95. Mean annual discharge at the Ain Hamara gauging station (see location in Fig. 1 and data in Fig. 3) was 1.0 $m^3\ s^{-1}$ for the same period of observation. The interannual variability, characterized by a CV of 41% during the 22-year period, was higher than that of yearly precipitation (Fig. 3). This demonstrates an amplification of the mean annual discharge compared to annual precipitation. For example, although annual rainfall was approximately 20% higher than average, mean yearly discharge varied between + 61% (1986–87) and +112% (1994–95). In contrast, lower than average annual rainfall was accompanied by a highly dispersed mean annual discharge (see Fig. 3).

Hydroclimatic fluctuations affected the basin producing a wetter period from 1973 to 1980 and a drier period from 1981 to 1993 (except 1986 and 1990) (Fig. 3). It is of interest to place this variability in the context of a longer time scale and at a regional scale. An extensive comparison between the study area in North Africa and Central and West Africa during the second half of the 20th century shows that this hydrological variability is consistent. Several researchers (e.g. Laraque et al., 2001; L'Hote et al., 2002) show that discontinuities occurred on a 10-year scale since the 1950s. There was a phase of surplus river discharge in the 1960s in Central Africa, a discontinuity at the beginning of the 1970s at the start of a period of dryness in the Sahel and lower discharge in Central Africa. This was followed by a second discontinuity, initiating a phase of further reduced discharge at the beginning of the 1980s in Central Africa, while the dryness continued in the Sahel. In the Wadi Abd basin, the reduction in annual precipitation from 1981–82 is clear compared to the previous years: average precipitation was 287 mm yr^{-1} over the period 1973–74/1980–81 and 225 mm yr^{-1} over the period 1981–82/1993–94. 1994 has been singled out as an anomalous year in the Sahel (L'Hote et al., 2002) and in the Wadi Abd basin increases in precipitation and flow were measured during the autumn of 1994 and spring 1995 (Fig. 3).

Hydrological and suspended sediment data

Suspended sediment concentrations (hereafter denoted C) were measured in the Wadi Abd at Ain Hamara station during different hydrological conditions (low discharge to severe flood events). During each sampling, the instantaneous water discharge (hereafter denoted Q, expressed in $m^3\,s^{-1}$) was also measured.

At the gauging station, the river flows through in a single 46 m wide channel. The flow is generally measured with a winch by gauging a section over 5–8 verticals with between 2 and 6 measurements per vertical. At night, during holidays, or during some floods, the discharge was derived from a limnimetric height using a local abacus. During the 22 considered hydrological years, the Wadi Abd did not overflow the flood plain at the gauging station.

To determine sediment concentrations, water was manually sampled using a simple 0.5 L or 1 L dip sample. One or two samples are taken by measurement in the middle of the wadi and/or at its edge. Suspended matter concentrations are determined by filtration of the samples on pre-weighted fiberglass filters (0.45 μm, Whatman GF/F), then dried and weighed. The average concentration of the section is assumed to be the concentration. Other available long-term data for the Algerian wadis were collected according to the same protocol (Touaıbia et al., 2001; Benkhaled and Remini, 2003; Megnounif et al., 2003). When the discharge flow exhibited little variation, only one sampling was performed per day at noon. The sampling rate arbitrarily increased with the flow until reaching a sampling frequency every 15 mn or 30 mn at the peak of a flood.

In our database (1973–1995, 1432 paired C and Q measurements), water discharge varied from 0.09 $m^3\,s^{-1}$ to 352 $m^3\,s^{-1}$ and C varied from 0.14 kg m^{-3} to 118.5 kg m^{-3}. Instantaneous flow was continuously recorded at Ain Hamara gauging station during the period 1973–1995. The duration of runoff events in the Wadi Abd at Ain Hamara station, which last at least 10 days, enabled us to study the hydrology from daily discharges.

The size distribution of suspended particles demonstrates a predominance of silts and clays. The mean class of grain diameter ranges from 4.35 to 5.82 μm (very fine silt). Clay represents more than 20% of the total population of particles. Sand is present in small quantities (<5%).

Flow regime of the Wadi Abd

Dryland rivers (i.e. the rivers of arid and semiarid regions, Davies et al., 1994) can be perennial, intermittent or ephemeral (see terminology used in ecological studies in Uys and O'Keeffe, 1997). Ephemeral rivers are defined as those that run for short periods after rain has fallen high in their catchment area (Day, 1990). An intermittent river is defined as having relatively regular, seasonally intermittent discharge, i.e. a river that experiences a recurrent dry phase of varying duration. Rivers that flow less than 20% of the year can be considered as ephemeral, and those that flow between 20% and 80% as intermittent (Matthews, 1998).

The flow regime of the Wadi Abd has been studied from the daily river discharge at Ain Hamara station. From 1973 to 1985, water was always present in the Wadi except for 12 days in 1979–1980 and 1 day in 1981–1982. There were 51 days without any water in the Wadi in 1985–86, 0 in 1986–87, 48 in 1987–88, 50 in 1988–89, 91 in 1989–90, 102 in 1990–91, 60 in 1991–92, 109 in 1992–93, 117 in 1993–94 and 96 days in 1994–95.

The Wadi Abd was thus a perennial river until the late 1980's and thereafter became an intermittent river, with an average of 72.4 days over 10 years with no flow per year (i.e. 20% of time). The number of days with no flow went up and reached 96.8 days per year (26% of the year) over the last 5 considered years, i.e. from 1990 to 95. The headwater tributaries of the Wadi Abd show the same water regime.

Independently of the main study, which focuses on sediment fluxes, the observation of a changing flow regime during the 1980s is an important result that needs to be emphasized in the context of climate change. The possibility that these observations were not artificially introduced by changes in sampling or measurement methods was examined. Water flow regime results from three inter-dependent factors: intrinsic natural variability, anthropogenic impacts on the catchment (such as changes in agriculture, vegetation cover, irrigation), and climate change. In the Wadi Abd basin, the changes in water flow regime were due to a very long period of drought beginning in the early 1980s which resulted from climate change or a long-term intrinsic natural variability.

Models and methods

Suspended sediment discharge, which is equal to C times Q, is hereafter denoted Q_s and is expressed in kg s^{-1}. Most quantitative studies of suspended sediment load are based on an empirical relationship between C and Q after logarithmic transformation of the data (Ferguson, 1987; Hasnain, 1996) or between Q_s and Q (Restrepo and Kjerfve, 2000), leading to equations of the type:

$$C = aQ^b \tag{1.a}$$

or

$$Q_s = a'Q_s^{b'} \tag{1.b}$$

The a'-coefficient should be equal to a and the difference in the b and b' coefficients should be 1.0 if the mean of the product $Q_s = C^*Q$ is equal to the product of the means. However, this is often not rigorously verified as C and Q are not completely independent.

Here, two complementary approaches were successively adopted. In a first part (Section ''Instantaneous suspended concentration versus river discharge''), we analyze the variability of coefficients a and b flood by flood from coincident measurements of C and Q. The resulting values make it possible to analyze the variability of the sediment rating curve of Wadi Abd for 138 complete or partial floods. They also make it possible to compare the Wadi Abd's behaviour with other rivers.

In a second part (Section ''Daily suspension flux versus river discharge''), as multiple pairs of (C, Q) values have been measured for some days, the C, Q and Q_s values for these days are averaged. Our 1432 paired C and Q measurements were performed for 702 days. Their respective averages, per day, result in 702 values of C, Q and Q_s referred to as ''mean daily concentration'', ''mean daily water discharge'' and ''mean daily solid discharge'', respectively. ''Mean'' is defined by:

$$\text{mean}(x) = \bar{x} = \frac{1}{p}\sum_{i=1}^{p} x_i \tag{2}$$

Note that these averages are based on coincident available C and Q data, and not on a true average value resulting from continuous measurement throughout the day, as was the case for the daily discharge. Regression relationships are built from mean daily values which are then compared and discussed. The evaluation of the relationships is based on the following criteria: stdev is defined by:

$$\text{stdev}(x) = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2} \tag{3}$$

From these equations, the mean normalized bias (MNB) and the normalized root mean square (rms) error, in percent, are calculated following:

$$\text{MNB} = \text{mean}\left(\frac{y_{\text{calc}} - y_{\text{obs}}}{y_{\text{obs}}}\right) \times 100 \tag{4.a}$$

$$\text{rms} = \text{stdev}\left(\frac{y_{\text{calc}} - y_{\text{obs}}}{y_{\text{obs}}}\right) \times 100 \tag{4.b}$$

where y_{calc} is a variable calculated using a regression relationship and y_{obs} is the value measured in situ (for C) or directly derived from in situ measurements (for $Q_s = C \times Q$). MNB is an indicator of systematic error and rms an indicator of random error.

Sediment rating curves

Instantaneous suspended concentration versus river discharge

The 1432 instantaneous (C, Q) values lead to a regression type Eq. (1.a) where $a = 2.180$, $b = 0.626$, $r^2 = 0.445$. The regression coefficient is low because the complete data set includes many (C, Q) pairs for very dispersed, very low flows and whose significance is not important for this study since the suspended sediment flux occurs primarily during floods.

To focus our analysis on the major transport episodes, we have calculated the specific regression relationship for each flood. For floods where sufficient data are available, we have plotted all available (C, Q) data flood by flood and have examined their evolution from beginning-to-end of each flood. For 98 floods, one rating curve was sufficient to represent the variations in (C, Q), for floods that did not present any hysteresis ($r^2 > 0.35$, median $r^2 = 0.777$). For 13 floods, it was necessary to define distinct phases (40 on the whole) with separate (a, b) pairs: rising, temporary stages if any (e.g. beginning of falling before a new rising), falling. To distinguish different flood stages, successive (C, Q) data are considered to form a single ''stage'' if they are significantly correlated ($r^2 > 0.35$, 36 flood stages) or have been taken within a short duration (with $n > 6$ and a maximum of a few hours duration when flood duration is on average of ten days, 4 flood stages). We thus obtain 138 (a, b) pairs calculated from, on average, 8.2 (C, Q) pairs (minimum: 3, median: 7) with an average r^2 of 0.747, and a median of 0.792.

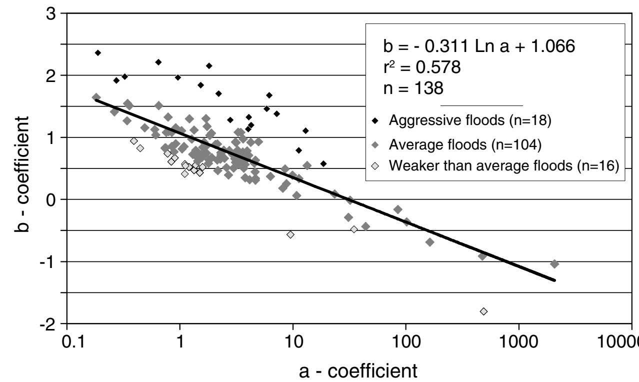

Figure 4 Correlation between slope/intercept values of suspended sediment rating curves fitted using power-law regression relationships.

The 138 values obtained are reported in Fig. 4. All episodes considered, the median value of (a, b) pairs is (2.154, 0.757). The relative variation calculated with the whole of the instantaneous values (2.180, 0.626) is 1.2% for a and 20.9% for b. The value of b indicates that, from a global point of view, C is almost proportional to $Q^{3/4}$ in the Wadi Abd during the flood episodes.

The (a, b) pairs calculated for different floods are somewhat correctly aligned ($r^2 = 0.578$, $n = 138$, see Fig. 4); the coefficients a and b are thus not independent. In the Wadi Abd, a and b are connected by the regression relationship:

$$b = -0.311 \ln a + 1.066 \tag{5}$$

Separating out the most aggressive floods from the least aggressive floods, we can study their specific behaviour and determine their seasonal variation and/or criteria of occurrence. A flood which, for a given coefficient a (resp. b), has a coefficient b (resp. a) appreciably higher than an average flood, carries a higher sediment load than an average flood; this is referred to as an ''aggressive'' flood. On the contrary, a flood which, for a given coefficient a (resp. b) has a coefficient b (resp. a) appreciably lower than an average flood, carries a lower sediment load than an average flood and is now referred to as a ''weaker than average'' flood. A flood is considered as ''aggressive'' if its couple (a, b) fulfils the criterion: $b + 0.311 \ln a - 1.066 > 0.4$, while a ''weaker than average'' flood fulfils the criterion: $b + 0.311 \ln a - 1.066 < -0.4$. The coefficient 0.4 is an arbitrary choice; for example, floods #1 and #2 with $b_2 + 0.311 \ln a_2 = b_1 + 0.311 \ln a_1 + 0.4$ are such that $b_2 = b_1 + 0.4$ if $a_1 = a_2$, or $a_2 = 3.6a_1$ if $b_1 = b_2$. According to these arbitrary criteria, the 138 floods and flood stages are divided into 104 ''average'', 18 ''aggressive'' and 16 ''weaker than average'' floods (see Fig. 4).

The rating parameters characteristic of each type of flood are shown in Table 3. It is particularly noticeable that

Table 3 Parameters of the suspended load versus discharge regression relationship for the floods or flood stages of the Wadi Abd

	N	Median regression coefficients		b versus a	
		a	b	Regression relationship	r^2
All of the floods	138	2.154	0.757	$b = -0.311 \ln a + 1.066$	0.578
''Average'' floods	104	2.307	0.736	$b = -0.297 \ln a + 1.001$	0.829
''Aggressive'' floods	18	3.408	1.568	$b = -0.320 \ln a + 1.842$	0.746
''Weaker than average'' floods	16	1.162	0.531	$b = -0.376 \ln a + 0.584$	0.970

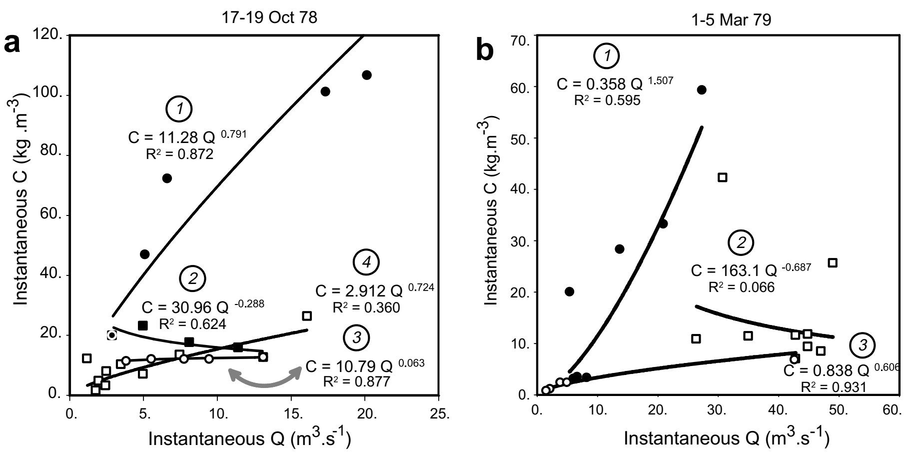

Figure 5 Suspended sediment rating curves fitted using power-law regression relationships during different phases of a flood. (a) 17th—19th October 1978; (b) 1st—5th March 1979. Distinct stages are chronologically numbered within circles.

the (a, b) pairs of aggressive floods are dispersed ($r^2 = 0.746$, $n = 18$), while the (a, b) pairs of ''weaker than average'' floods are remarkably linear ($r^2 = 0.970$, $n = 16$). During aggressive floods, C is almost proportional to $Q^{3/2}$ since $b = 1.568$, while for the least aggressive floods, C is almost proportional to $Q^{1/2}$ ($b = 0.531$). Average floods practically behave like the median flood calculated for the whole dataset, with C almost proportional to $Q^{3/4}$. The remarkable linearity of the (a, b) pairs for the ''weaker than average'' floods seems to indicate that a minimal threshold of erosion of the catchment area exists.

How do the phases of a flood follow one another in the Wadi Abd and is there a seasonal variation of these phases? To illustrate this question, Fig. 5 shows distinct stages of two floods. A multi-peak flood is presented in Fig. 5a: stage 1, decrease of flow on 17th Oct. 1978 from 7.30 to 10 h (the rise during the previous night was not sampled); stage 2, rise until 11.10 h; stage 3, decrease until 14.15 h. After an increase of flow which was not sampled, stage 4 corresponds to the final falling which spread out between 17th Oct. 17 h and 19th Oct. 15 h. The flood presented in Fig. 5b is less complex and shows a clockwise hysteresis: a rise of flow (stage 1, from 1st March 1979 16 h to 2nd March 12.30 h), a stage of high flow (stage 2, from 2nd March 13 h to 21 h, is one of the 4 stages of short duration and of poor correlation within the global data set; the other phases in Fig. 5 are such as $r^2 > 0.35$), then the falling (stage 3 from 2nd March 22 h to 5th March 12 h).

In Fig. 6, the (a, b) pairs of the main floods of 1978—1979 are compared to the median pair of the same hydrologic

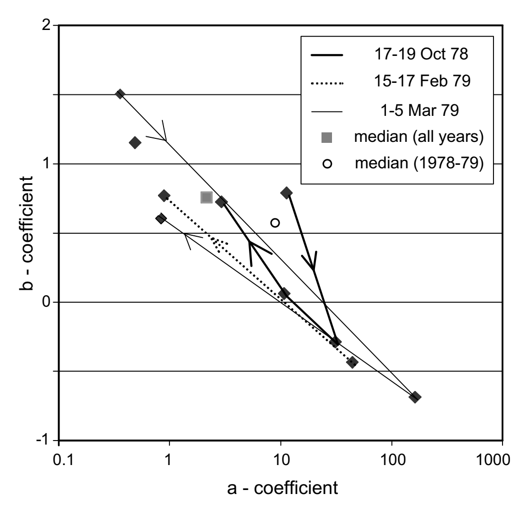

Figure 6 Pairs of (a, b) values for the main floods of the Wadi Abd in 1978—79.

year and also to the median calculated over 22 years (1973—1995). The (a, b) pairs for the flood of October 78 (Fig. 5a) are as follows: stage 1 is ''aggressive'', stages 2 to 4 are ''average''; for the flood of March 79 (Fig. 5b), stages 1 and 2 are ''average'', stage 3 is ''weaker than average'' (Fig. 6). The flood of March 1979 (Fig. 5b) shows a clockwise hysteresis, with a higher particulate load during the rising stage than during the falling stage, at an equivalent flow (see Williams, 1989 for a general typology of the relationship between concentration and discharge during hydrologic events). Benkhaled and Remini (2003) have analyzed the hysteresis episodes of C–Q relationships on another Algerian basin, the Wadi Wahrane basin, for 13 floods. They show a significant prevalence of hysteresis of clockwise type (8 out of 13). A systematic analysis of the entire data for the Wadi Abd was not conducted during this study. However, we have observed that the pair (a, b) during a flood (including several falling phases as in Oct. 1978) is generally translated in an a–b diagram by a shift either to the left (a decreases, as in Oct. 1978, see Figs. 5a and 6), or towards the bottom (b decreases, as in March 1979, see Figs. 5b and 6). This reduction in a or b probably indicates that the suspended sediment concentration (resulting from erosive power and sediment supply) of the Wadi Abd decreases at the end of the flood. The successive positions of the pair (a, b) on the a–b diagram also make it possible to visually compare between floods. As an example, Fig. 6 shows a left-shift of the spring flood as compared to the autumn flood, demonstrating that the autumn flood is more aggressive. These examples observed in 1978–1979 illustrate the tendency generally noted on Wadi Abd: the first stages of a flood are more ''aggressive'' than the last, and the floods of autumn are more ''aggressive'' that the floods of spring.

We have tested the predictive capacity of the median pairs of coefficients (a, b) obtained for the 3 flood types (average, aggressive, weaker than average) to estimate the instantaneous concentration from instantaneous discharge, if the type of flood is known. In the majority of ''aggressive'' and ''weaker than average'' floods, the choice of an adapted pair decreases the error in the calculation of C compared to the use of the total median pair. However, none of the three median pairs is adapted to give a correct estimation of C for flood stages such as $b < 0$. Negative values of b correspond to a particular case where C and Q evolve conversely, with C increasing while Q decreases and vice versa. None of the median pairs (all of which are $b > 0$) can reproduce this generally transitory behaviour which occurs during an intermediate phase in between the rise and fall of the flood (see two examples in Fig. 5a and b). If one wants to determine pairs of (a, b) coefficients by flood type, it is necessary to restrict the three already defined types of floods by $b > 0$ and to add a fourth type corresponding to the transitional stages where C and Q are in negative correlation. The calculation of the median couple for the 11 phases of such floods out of 138 provides $a = 84.72$ and $b = -0.48$.

Daily suspension flux versus river discharge

The regression relationship between the mean daily C and the mean daily Q is ($r^2 = 0.463$, $n = 702$):

$$C = 1.710\ Q^{0.750} \tag{6}$$

where C is expressed in g L^{-1} and Q in m^3 s^{-1}. C is dependent on two main factors: water discharge and supply. The r^2 value means that the variations of C are explained by up to 46% by those of Q. More than 50% of the variability in C is explained by the supply of sediments to the river system, with supply determined by the occurrence or absence of recent floods, seasonal variations of vegetation cover and other parameters.

The best-fit regression relationship between mean daily sediment discharge and mean daily water discharge is a power-law relationship of the type of Eq. (1.b) given by ($r^2 = 0.826$, $n = 702$):

$$Q_s = 1.712\ Q^{1.769} \tag{7}$$

The a and a' coefficients in Eqs. (6) and (7) differ by 0.11%, and $b' = b + 1.019$. To estimate Q_s from the entire Q data available, one can apply Eq. (7) directly, or determine C using Eq. (6) then multiply the result by Q. In the relevant literature, the second alternative is used more frequently than the first because the coefficient of correlation of Q_s–Q is superior to that of C–Q. We have applied the two methods to our data set.

The first application relates to the data set being used to establish the regression relationships. The Q_s–Q relationship provides Q_s values which are on average 48.5% higher than the measurement derived Q_s values (MNB = 48.5%, rms = 133%). The C–Q relationship provides C values that are on average 48.1% higher than the C measured values (rms = 132%) which, multiplied by Q, provide values of Q_s on average 45.7% higher than Q_s values derived from measurements. Statistical comparison between 702 measured Q_s and C–Q derived values of Q_s is based on log-transformed data to encompass the several-orders-of-magnitude variation in Q_s. Statistics such as regression slope (1.011) and intercept (−0.0022), coefficient of determination (r^2 = 0.827) and rms error (100%) provide a numerical index of model performance which can be compared to those of other models and other rivers (such statistics are commonly used to compare bio-optical algorithms (see the example of O'Reilly et al., 1998)). The difference between predicted and observed values is calculated on the entire data set and, therefore, does not take into account the absolute values of Q_s. In fact, the most important aspect in the reconstitution of the solid discharge rates relates to the episodes of highest flow whose contribution is essential both to estimation of total flux of river-driven particles and for the analysis of its variability on seasonal and interannual scales. When the cumulated values of suspended load for the 702 considered days are compared using the two methods of reconstitution (by summing the predicted mean daily solid discharges), an over-estimation of 25.7% is obtained compared to the ''measured'' daily suspended loads by the use of the Q_s–Q relationship, and of 21.8% by the use of the C–Q relationship.

Several lessons can be learned from these results:

1. Since the average relative error (~48%) is higher than the absolute error of the cumulated solid discharge (~25%), the relative errors are weaker during high flows than during low ones. This is easily explained by the increased scattering of the concentrations during low discharge relative to those during high discharge, and because the episodes of high discharge, which are fewer, force the regression relationship more than do the points of low discharge.
2. With our data set, the reconstituted time series are more likely to over-estimate the low solid discharges than the high ones. This will decrease the variation of suspended load of seasonal or interannual origin.

3. An over-estimate of about 25% in the calculation of the suspended load cumulated over 702 days can be easily seen as high. Nonetheless, this performance, which one may describe as ''average'', does not require any specific knowledge other than the liquid discharge which can easily be gauged, since a simple regression relationship has now been established. Since the variability of C in the Wadi Abd is explained up to only 46% by the flow, we estimate that the performance of the reconstitution is acceptable. To achieve a finer precision, the integration of other explanatory factors than the discharge only is needed which would require the building of a more complex model.
4. Although the Q_s—Q correlation is higher than that of the C—Q relationship, the performance of the two methods of prediction of Q_s is equivalent. This is due to the fact that the former is biased, and the latter is not. The use of a non-biased C—Q relationship introduces an uncertainty in C, but when Q_s is calculated from C, no additional error is introduced because the value of Q multiplied by C was measured. The use of the C—Q relationship and the multiplication of C by Q thus appears to introduce less errors than using the law Q_s—Q, even though the Q_s—Q relationship presents a higher correlation.

Moreover, we may also note that the pair (a, b) established using mean daily concentration and water discharge, (1.710, 0.750), differs slightly from that calculated for the flood phases, (2.154, 0.757). While the b-coefficient remains unchanged, the a-coefficient is reduced by 20.6% when considering the mean daily variables. The different methods of calculation can partly explain the discrepancy between both pairs, since the pair (a, b) relative to the mean daily variables results from a best-fit regression relationship, while the other is the median of the (a, b) pairs calculated from a collection of flood episodes. The fact that at low discharge, concentrations, which are generally lower than those estimated by the regression relationship, are considered within daily values but not as flood phase values (which include only high sediment load episodes) is probably the main reason for discrepancy between both (a, b) pairs.

Comparison to other rivers

Comparisons of a and b among sites are delicate because the dimension of a [here expressed in (kg m^{-3})(s m^{-3})^b for every given example] depends on the value of b (dimensionless). Nevertheless, these comparisons make it possible to have a greater understanding of the respective physical significances of a and b which depend on multiple factors (Frostick et al., 1983; Syvitski et al., 2000; Asselman, 2000). Syvitski et al. (2000) have compared rating parameters at 57 gauging stations in North America, 1 in Europe and 1 in China. They examine the rating equations in comparison to the long-term character of the suspended sediment load in the rivers and show that the rating coefficient a is inversely proportional to the long-term mean discharge and is secondarily related to the average temperature and the basin's topographic relief. They also show that the rating exponent b correlates most strongly with the average air temperature and basin relief and is weakly correlated with the long-term load of the river. Their explanation is that each river undergoes higher-frequency variability that is controlled by weather patterns and channel recovery from extreme precipitation events.

Rating parameters a and b of a river strongly depend on flow regime and do not vary in the same proportions (Table 4). Generally, b stays in range 0.3—2.5, while a can vary by several orders of magnitude (e.g. Reid and Frostick, 1997). Frostick et al. (1983) have shown that the coefficient b is smaller in arid zone flash floods (usually $b < 1$) as compared to typical perennial systems draining temperate regions where $b > 1$. Intermittent rivers in semiarid environments seem to have b-coefficients lower than 1, similar to ephemeral rivers in arid zones (Table 4). The rating parameters calculated for the Katiorin basin in Kenya (Sutherland and Bryan, 1990) and for the Eshtemoa in the northern Negev Desert (Alexandrov et al., 2003a) are such that $b + 0.311 \ln a - 1.066$ gives 0.40 on the Katiorin and 0.24 on the Estemoa, respectively. This means that these floods are slightly more ''aggressive'' than the average floods of the Wadi Abd. Another interesting comparison is that in the three basins, the variations in discharge explain only about 50% of the variance in suspended sediment discharge (49% for the Eshtemoa, 52% for the Katiorin and 46.3% for the Wadi Abd).

Eqs. (6) and (7) provide little understanding of the physical processes that underlie the sediment transport. However, physical explanations on shapes of C—Q relationships, either linear or non-linear (concave or convex), can be found in the literature (e.g. Williams, 1989; Sichingabula, 1998; Morehead et al., 2003). In particular, the available studies underline the influence of preceding discharge or antecedent moisture, which tends to generate quick or delayed runoff. This then causes rapid or slow increases in sediment concentration in concert with discharge changes as well as affecting the variability in the amount of easily erodible sediment stored in the channel.

The high-frequency variability (at the flood event) of the rating parameters is also examined in the present study. It appears that their alignment demonstrates that a and b are not independent and that one cannot interpret one without the other, as is sometimes found in the literature. The alignment of the (a, b) pairs for the sediment rating curves either at a station, or at several stations of the same catchment area, has already been described by Asselman (2000) for the perennial Rhine River and its tributaries. Asselman obtains the following relationships: $b = -0.296 \ln a + 0.467$ (Andernach station, Rhine), $b = -0.393 \ln a + 0.577$ (Cochem station, Mosel) and $b = -0.462 \ln a + 0.736$ (Rockenau station, Neckar). The slope for the relationship in the Wadi Abd (Eq. (5), see Fig. 4) is consistent with these values, although the intercept is higher.

Concerning the wadis in Algeria, Touaïbia et al. (2001) present rating curves based on a long-term series of flow and concentration measurements at two stations close to Ain Hamara, one of which is located downstream from Ain Hamara, the other is located in the neighbouring sub-catchment of the Wadi Haddad. All the mean monthly relationships that they obtain from instantaneous values have a higher factor a and a smaller factor b than in the present study. The high values of b (together with low values of a) have been obtained for the months where there is an increase in precipitation after 3 months of low water level,

Table 4 Examples of coefficients (a, b) in the rating curve $C = a\,Q^b$, where C (concentration of suspended sediment) is expressed in g L^{-1} and Q (water discharge) in $m^3\,s^{-1}$

Reference	River	Semiarid basin	Rainfall (mm yr^{-1})	a	b	Complementary information
Chikita (1996)	Ikushunbetsu, Japan	No	1418	4.28×10^{-3}	2.11	Sediment discharge dominated by the riverbank erosion in snowmelt runoff
Morehead et al. (2003)	North Saskatchewan, Alberta	No	Not given	1.3×10^{-5}	1.58	
Asselman (2000)	Rhine, Germany	No	600–2500	$7.7 \times 10^{-7} - 1.7 \times 10^{-6}$	1.22–1.44	From 4 stations along the Rhine River
Achite and Ouillon, this paper	Abd, Algeria	Yes	250	1.71	0.75	From daily values
Touaïbia et al. (2001)	Haddad, Algeria	Yes	249	5.79–25.13	0.36–0.74	Monthly values
				3.62	0.44	Median of monthly values
Alexandrov et al. (2003a)	Eshtemoa, Israel	Yes	220–350	16.98	0.43	
Sutherland and Bryan (1990)	Katiorin, Kenya	Yes	640	43	0.30	

(a, b) provided by Chikita (1996); Morehead et al. (2003) and Asselman (2000) resulted from instantaneous C and Q measurements.

in July in the Wadi Haddad and in February in the Wadi Mina (El-Abtal station). Conversely, the low values of b, which are not associated with the highest values of a, are obtained for the months that follow a period of at least two months of high flow (in December and March in the Wadi Haddad, in December in the Wadi Mina). It should be noted that these variations of b on a monthly scale are consistent with the short-term variations of b that we have observed on the C–Q curves during a flood (Fig. 5). This is also in agreement with the variations between rising and falling discharge episodes observed in the Rhine River by Asselman (2000). This reinforces the assumption of a strong relation between coefficients a and b.

Annual sediment wash-down and its variability

Annual suspended sediment budget

The average value of the suspended sediment flux for the Wadi Abd basin calculated from the reconstructed time series of suspended sediment transport is 339×10^3 t yr^{-1} for the period 1973–1995. This corresponds to a specific suspended sediment yield, which is the ratio of suspended load to basin area, of 136 t $km^{-2}\,yr^{-1}$. The specific suspended sediment yield is also called ''sediment wash-down'' or ''suspended solids yield'' in the literature.

Suspended sediment flux should not be confused with the rate of soil erosion as sediment eroded from upland soils is progressively stored in the river valley (Milliman and Meade, 1983). Moreover, it seems that, globally, the two quantities are inversely affected by anthropogenic impacts, with soil erosion accelerating while sediment flux to the coastal zone is globally decreasing (Syvitski, 2003).

Nor should suspended sediment flux be confused with the total sediment delivery which results from bedload charge, suspended sediment, and dissolved sediment (Serrat, 1999). Bed load is generally assumed to be a minor part of particulate matter flux, accounting for only approximately 5–10% (Eisma, 1998; Syvitski et al., 2003; see also ref. quoted in Coynel et al., 2004). However, bedload transport seems to be extremely variable in dryland rivers. Reid and Laronne (1995) have reported very high bedload rates in a gravel bed ephemeral river, that are orders of magnitude higher than in its more humid counterparts. On the other hand, Serrat (1999) noted that bedload sediment volume was less than 1% of the suspended load in an intermittent river of Mediterranean type. In the Wadi Abd, the small proportion of sand in suspension (<5% of dry weight of suspended particles) does not allow us to conclude on the relative importance of transport in suspension and bedload transport. The value of 136 t $km^{-2}\,yr^{-1}$ may only be considered as an estimate of the fine sediment flux for the Wadi Abd Basin. The value of 136 t $km^{-2}\,yr^{-1}$ is similar to the global mean sediment wash-down, of the same order as the sediment wash-down in South America, and far higher than the mean sediment wash-down in Africa (see Table 5). These regional values are average values and it must be remembered that the specific sediment yield is known to decrease with the drainage basin area (see Fig. 1 in Jiongxin and Yunxia, 2005). The suspended sediment yield for the Wadi Abd basin has been also compared to values provided for other catchments in the Mediterranean basin (Table 5); it is similar to the values reported for other basins in Algeria and Israel.

The specific sediment yield Y, which is generally expressed in t $km^{-2}\,yr^{-1}$, can also be expressed in kg $km^{-2}\,day^{-1}$ to permit cross-site comparison using quantiles of its distribution that can not be expressed on a yearly basis (Meybeck et al., 2003). In the Wadi Abd, the average daily suspended solids yield is 374 kg $km^{-2}\,day^{-1}$ and the median daily sediment fluxes over the period 1973–1995 (Y_{50}) is 28 kg $km^{-2}\,day^{-1}$. The resulting flux variability as defined by their ratio is 13.4, which is typical of high suspended solids flux variability on the daily-scale following the classification proposed by Meybeck et al. (2003).

Lastly, it is of interest to jointly analyze river flow and sediment wash-down. The average water discharge calcu-

Table 5 Suspended sediment yield of several regions and catchments in the Mediterranean basin

References	River basin or Region	Area (km^2)	Rainfall ($mm\ yr^{-1}$)	Suspended sediment yield ($t\ km^{-2}\ yr^{-1}$)
Tamrazyan (1989)	Global	135.1×10^6		120
Milliman and Meade (1983)	Global	88.6×10^6		150
Tamrazyan (1989)	Africa	30.3×10^6		32
Tamrazyan (1989)	Eastern hemisphere (Africa, Europe, Asia, Australia)	92.8×10^6		133
Tamrazyan (1989)	South America	18.1×10^6		138
Tamrazyan (1989)	Equatorial region (10°N—10°S)			153
Tamrazyan (1989)	Asia	43.4×10^6		242
Tamrazyan (1989)	Tropical region (10—30°N)			253
Probst and Amiotte-Suchet (1992)	Maghreb (drainage basins into the Mediterranean Sea)			400
Serrat et al. (2001)	Têt, France	1380	750	40
Serrat (1999)	Agly, France	1045	700	103
Bourouba (1997)	Leham, East Algeria	5600	154	104
Bourouba (1998)	Medjerda, East Algeria	217	598	113
Clapp et al. (2000)	Yael, Israel	0.6	30	113—138
Terfous et al. (2001)	Mouilah, NW Algeria	1680	300	126
Achite and Ouillon, this paper	Abd, Algeria	2480	250	136
Ghachi (1986)	Seybousse, East Algeria	6450	577	137
Megnounif et al. (2003)	Upper Tafna, West Algeria	256	419	1120

lated over the 22-year period is $1.00\ m^3\ s^{-1}$ or $0.0315\ km^3\ yr^{-1}$. As a result, the ratio of the sediment wash-down to the river water flow is $10.7 \times 10^6\ t\ km^{-3}$ for the Wadi Abd. This is 20 times higher than the average ratio in the eastern hemisphere of the globe and 28 times its value over the globe as a whole (without the Antarctic) (Tamrazyan, 1989). This is an illustration of the highly erosive power of wadis (Ouillon, 1998).

Seasonal variability

The results obtained over the 22 hydrological years of observation show that there is a significant variation of sediment transport at the intra-annual scale (CV = 88.7%, Fig. 7). Almost half of suspended solid transport occurs in autumn (48.4%) and approximately a third of the annual flux in spring (32.7%). The total flux in winter and summer is lower than 20% of the annual flux. The two seasons favourable to solid transport correspond to the two seasonal peaks of discharge which take place in October and March (Fig. 2). The floods in autumn are more aggressive than the floods in spring because they follow a season of much lower discharge. The flow is on average $0.37\ m^3\ s^{-1}$ during the three summer months and $1.14\ m^3\ s^{-1}$ in winter. The high variability in rainfall is also probably responsible for the changes in vegetation that in turn directly influence the erosive capacity of rainfall. Solid transport thus occurs mainly in autumn after a long dry season characterized by high temperatures, by destruction of ground aggregates and, by reduced vegetation cover (Rakoczi, 1981). In winter, rainfall and average discharge are significant but most of the erodible particles are transported by the first floods of the preceding autumn. It is thus necessary to await the high rainfall in March and the associated big floods so as to observe high erosion.

A review of several factors that control seasonal variations in suspended sediment transport is given by Alexandrov et al. (2003b). In particular, these seasonal variations can be analyzed by regarding the seasonal climatic variations and weather forcing. In the Negev, Alexandrov et al. (2007) show that rainfall episodes in autumn and spring, which result from high intensity convective or convectively-enhanced storms, are characterized by high concentrations and low correlation with water discharge. On the other hand, winter rainfall, which results from low intensity frontal storms, is accompanied by lower concentrations that are correlated with water flow. In the Wadi Abd basin, sufficient weather data for a historical analysis of rainfall events is unavailable. However, the previous analysis is consistent with that of Alexandrov et al. (2007) since the history of flow during the months preceding a flood results from variations in precipitation.

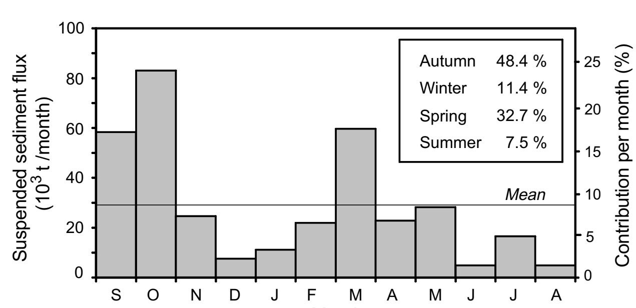

Figure 7 Intra-annual variability of suspended sediment transport and contribution in percent of monthly suspended sediment flux to the annual suspended sediment flux.

The seasonal variation of suspended particulate transport in the Wadi Abd is comparable with that observed for other wadis of the region. The same seasonal variation is inferred by Touaïbia et al. (2001) at one station downstream from the Ain Hamara station in the Wadi Mina, and in a neighbouring sub-catchment basin. In the Upper-Tafna river basin (another small basin in North-West Algeria), Megnounif et al. (2003) indicate that 43.7% of the annual suspended sediment flux occurs in autumn and 36.4% in spring. The seasonal variation of solid transport is high in the wadis, and is also highly significant in other areas subjected to strong seasonal variations of flow. These strong seasonal variations could be the result of monsoons or melting snow (e.g. Vaithiyanathan et al., 1992; Hasnain and Thayyen, 1999).

Interannual variability

The 22-year variation of suspended sediment transport shows a significant interannual variability (CV = 138.8%, Fig. 8), that is greater than the seasonal variability. The annual suspended sediment yield variability expresses an amplification of the variations of discharge (CV = 41%) which are themselves the result of an amplification of precipitation variability (CV = 17.6%) (see Fig. 3 and Table 6). Fig. 8 clearly shows the considerable increase in the annual suspended sediment yield in 1985–1986, which then continues for 6 years. The average annual load is 127×10^3 t yr^{-1} for the period 1973–1985, and 593×10^3 t yr^{-1} for the period 1985–1995 (Table 6).

Wadis are known to have, among the rivers, the greatest interannual variability. Milliman and Meade (1983) have emphasized that catastrophic floods in wadis can, in just a few days, evacuate much more sediment than in an average year. To illustrate the interannual variability of the sediment concentrations, we have calculated for each year the ''discharge-weighted total suspended solids'', also called ''representative annual suspended particulate matter concentration'' (Meybeck et al., 2003; Coynel et al., 2004), denoted SPM* and calculated from daily suspended matter fluxes weighted by daily discharges following:

$$\mathrm{SPM}^* = \frac{\sum_{i=1}^{n} C_i Q_i}{\sum_{i=1}^{n} Q_i} \tag{8}$$

The 22 values of annual SPM* calculated over the period 1973–74/1994–95 vary between 2.01 g L^{-1} and 29.63 g L^{-1}. These are among the highest values in the world (see Fig. 4 in Walling and Kleo, 1979) and are typical of semiarid environments (Meybeck et al., 2003). The variation of annual SPM* is close to that of annual sedimentary flow shown in Fig. 8, although having a reduced difference between maxima and minima as indicated by a lower coefficient of variation (90.3% against 138.8%). The 22 annual SPM* values show a positive correlation with the mean annual discharge (Fig. 9a). Note that the discharge-weighted value of SPM* calculated over the period 1973–1995 (and not over a year) is the same quantity as the ratio of the sediment wash-down to the river water flow, i.e. 10.7 g L^{-1} (see Section ''Annual suspended sediment budget'').

To understand the interannual variability in suspended load, it is advisable to jointly analyze the statistical data of the variables: rainfall, discharge, and suspended load flux for the whole of period 1973–1995 and separately over the periods 1973–1985 and 1985–1995 (Table 6). The second period corresponds to a phase of lower annual precipitation starting in 1981–1982 (see Fig. 3 and Section ''Climate, rainfall and runoff''). Although, weaker than average, precipitation is more irregular from one year to the next over the period 1985–1995 than over the period 1973–1985. This increasing irregularity is accompanied by: an amplification of the variations of discharge, an increase in the average discharge of approximately 20% during the second period, a change in flow regime (Section ''Flow regime of the Wadi Abd''), and a higher and more irregular suspended particulate flux. The increasing irregularity of precipitation on an annual scale is probably a major factor in increased soil erosion. Dynamic data of the zone's vegetation is not available, but the increase in discharge and in partial erosive capacity (only based on transport into suspension) could be the result of a reduction in vegetation cover or its density induced by the decrease in rainfall from 1981–82 onwards. Over the 22 years of the data set, we thus observe a tendency towards an increase in suspended sediment yield accompanied by a small reduction in rainfall and an amplification of its variations on an annual scale.

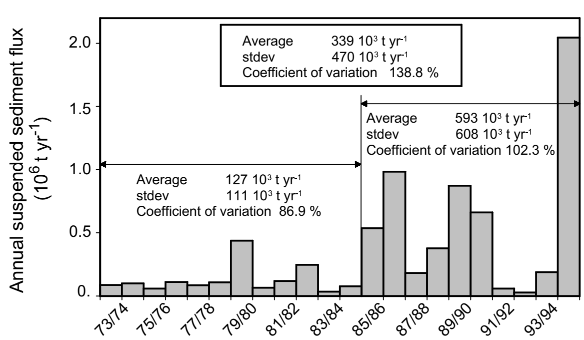

Figure 8 Interannual variability of suspended sediment flux (1973–1995) at the Ain Hamara gauging station.

Table 6 Summary of statistical data for annual precipitation at Station S11 (see Fig. 1), mean yearly discharge at Station 3 (see Fig. 3) and annual suspended sediment yield at the Ain Hamara gauging station

	1973–1995			1973–1985			1985–1995		
	Precip. (mm yr^{-1})	Q (m^3 s^{-1})	Q_s (10^3 t yr^{-1})	Precip. (mm yr^{-1})	Q (m^3 s^{-1})	Q_s (10^3 t yr^{-1})	Precip. (mm yr^{-1})	Q (m^3 s^{-1})	Q_s (10^3 t yr^{-1})
Mean	250	1.00	339	264	0.91	127	233	1.11	593
Stdev	44.0	0.41	470	40.2	0.25	111	43.7	0.54	608
CV (%)	17.6	41.0	138.8	15.2	27.9	86.9	18.8	48.5	102.6

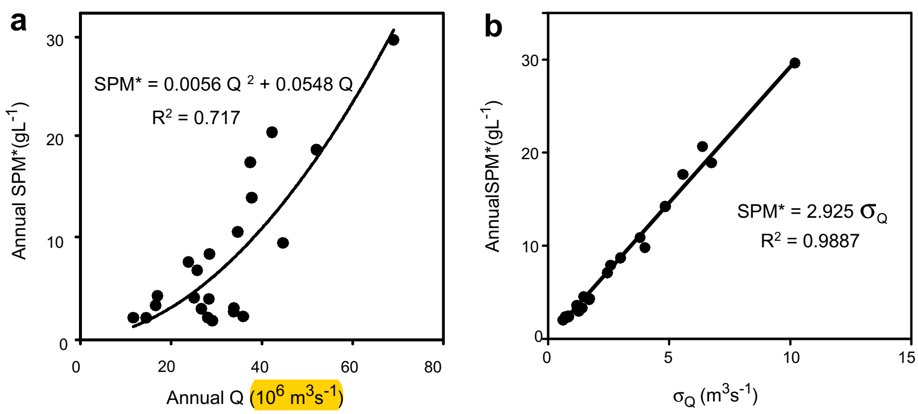

Figure 9 Variation of the representative annual suspended particulate matter concentration against: (a) the annual discharge and (b) the standard deviation of mean daily discharge calculated per year, at the Ain Hamara gauging station (1973—1995).

The influence of climate on mean annual suspended sediment yield is generally analyzed from mean annual precipitation (Walling and Kleo, 1979). Langbein and Schumm (1958) have shown that suspended sediment yield (per unit area of basin) is at a maximum when precipitation is about 250—350 mm yr^{-1} (10—14 in yr^{-1}, i.e. in semiarid areas). In the Wadi Abd basin, annual rainfall was between 250 and 300 mm yr^{-1} from 1974 to 1980—1981 and thereafter generally decreased. If annual precipitation is the main factor explaining suspended sediment yield, the latter should have decreased during the second period while in actual fact it increased. We have tried to compare suspended sediment yield with annual precipitation but have found no significant tendency ($r^2 < 0.1$ whatever the type of regression considered). However, we observed that the flow regime changed in the late 1980s, that the discharge slightly increased, and that the discharge variability considerably increased. In an attempt to quantify this effect, plotting the annual suspended sediment yield Q_s versus the CV of monthly discharge calculated per year yields to the following regression relationship ($r^2 = 0.532$, $n = 22$):

$$\text{Ln } Q_s = 1.872 \text{ CV} + 3.888 \tag{9}$$

It shows that 53% of the increase in the suspended sediment yield can, potentially, be explained by the increasing variability of the monthly discharge. As only 46% of the variations of C can be explained by those of Q and that more than 50% of the variability in C is explained by the sediment supply to the river system (see Section ''Daily suspension flux versus river discharge''), the CV of monthly discharge calculated on a yearly basis, a proxy for the discharge seasonality and the flow regime, may be considered as a partial indicator of the sediment supply to the river. We also analyzed SPM* versus the CV of monthly discharge and obtained the following regression relationship ($r^2 = 0.716$, $n = 22$):

$$\text{Ln SPM}^* = 1.563 \text{ CV} + 0.303 \tag{10}$$

The correlation between these two variables is higher than between sediment yield and the CV of monthly discharge. This illustrates the strong influence of flow regime on mean concentration in a semiarid basin.

The discharge-weighted mean annual concentration SPM* was analyzed against several parameters so as to better understand how an increase in mean yearly discharge from 0.91 m^3 s^{-1} to 1.1 m^3 s^{-1} could result in an increase of suspended sediment yield from 127×10^3 t yr^{-1} to 593×10^3 t yr^{-1}. Linear regression relationships of SPM* provided r^2-values <0.1 against the annual precipitation and maximum of daily precipitation within a year, 0.46 against the 90th percentile of daily discharge (Q_{90}) calculated per year, 0.73 against the maximum of daily discharge per year, and 0.84 and 0.88 for the 95th percentile Q_{95} and the 98th percentile Q_{98} of the daily discharge per year, respectively. Q_{95} was 1.58 m^3 s^{-1} on average from 1973 to 85 and became 2.82 m^3 s^{-1} from 1986 to 95; Q_{98} was 3.76 m^3 s^{-1} on average from 1973 to 85 and became 10.96 m^3 s^{-1} from 1986 to 95. SPM* is thus highly correlated with the 10 to 15 highest daily discharges in a year, the latter of which increased more than the mean yearly discharge.

Finally, as the 1973—1995 period was characterized by increases both in discharge-weighted mean annual concentration and in number of days per year without water in the river and Q_{95} (the two latter parameters indicating an increase in discharge scattering), we have tried to analyze yearly SPM* against the standard deviation of the daily discharge per year (σ_Q). A remarkable linearity was found between both values ($r^2 = 0.9887$, see Fig. 9b). This suggests that the suspended sediment yield on the Wadi Abd is drastically forced by the discharge variability.

The significance of the interannual variability indicates that it is absolutely necessary to continue this type of series of measurements over longer periods in small rivers, as has been done in the case of large rivers, if studying fluctuations in the context of climate change is to be achieved. In addition, this result points to the difficulty in defining a suitable period to calculate a ''standard'' or reference value of sediment yield from which the deficits or excesses will be used in water resources management, as has been demonstrated for other hydrological parameters (e.g. Paturel et al., 2003; Syvitski, 2003).

Conclusion

Soil erosion constitutes a major aspect of landscape degradation in semiarid Mediterranean environments. Sediment yield in semiarid areas is highly variable because precipitation and runoff are themselves highly variable.

In order to estimate the monthly or annual suspended sediment transport of rivers and to analyze their variability, sediment rating curves based on measured concentrations and discharge data can be constructed. This study shows that non-biased C–Q regression relationships are as precise as the more frequently used biased Q_s–Q relationships. An extensive dataset from the Wadi Abd basin was analyzed and provided an estimation of the sediment wash-down of 136 t km^{-2} yr^{-1} for the 1973–1995 period which is of the same order as the global mean sediment wash-down. However, suspended sediment transport variability in the Wadi Abd basin is high on the seasonal scale (CV = 88.7%) and even higher on the interannual scale (CV = 138.8%). The annual sediment yield variability expresses an amplification of the variations of discharge (CV = 41%) which are themselves the result of an amplification of precipitation variability (CV = 17.6%). We note that, over 22 years, the increasing irregularity of precipitation at the annual scale (and the resulting changes in discharge variability) is likely a major factor influencing the increase in the discharge-weighted mean annual concentration. Finally, the ratio of sediment wash-down to river water discharge, 10.7×10^6 t km^{-3}, is 20 times higher than the average value for Eastern hemisphere (Africa, Europe, Asia and Australia).

This highly erosive power in semiarid environments induces repercussions both in the eroded zone (impoverishment of substrates) and in the receiving zone (dam filling). Thus, it is clear that, the targeting of sediment management strategies is a key requirement in semiarid regions because of both high erosion and limited resources available. For that purpose, sustainable management of water and soil resources requires effective use of predictive models and an ability to analyze the data in the context of high temporal variability of semiarid environments. Data series such as those presented in this paper should be encouraged and should be followed up over longer periods of time. This will be especially important for the study of variability in the context of climate change.

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