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Recent changes in climate, hydrology and sediment load in the Wadi Abd, Algeria (1970–2010)

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Abstract

Here we investigate the changes of temperature, precipitation, river runoff and sediment transport in the Wadi Abd in NW Algeria over a time series of 40 hydrological years (1970–2010). Temperature increased and precipitation decreased with the reduction in rainfall being relatively higher during the rainy season. A shift towards an earlier onset of first rains during summer was also found with cascading effects on hydrology (hydrological regimes, vegetation etc) and thus on erosion and sediment yield. During the 1980s, the flow regime shifted from perennial to intermittent with an amplification of the variations of discharge and a modification of the sediment regime with higher and more irregular suspended particulate flux. Sediment flux was shown to almost double every decade from 1970s to 2000s. The sediment regime shifted from two equivalent seasons of sediment delivery (spring and autumn) to a single major season regime. In 2000s, autumn produced over 4 times more sediment than spring. The enhanced scatter denotes an increase of hysteresis phenomena in the Wadi Abd that is probably related to the change in the hydrologic regime. The increased erosion of the watershed is accompanied by a decrease in the coefficient *b* of its rating curves and a decrease in the erosive power of the river. At the end of the period, due to the irregularity of the discharge, the ability of a rating curve to derive suspended sediment concentration from river discharge was poor.

1 Introduction

Fluvial and estuarine suspended sediment fluxes have been dramatically changing under the combined effects of anthropogenic activities and climate change. On a global scale, recent changes showed a trend towards increasing land erosion and decreasing fluxes to coastal waters (Walling and Fang, 2003; Vörösmarty et al., 2003; Wang et al., 2006). The sediment flux trapped in regulated basins with reservoirs is higher than 50 % (Vörösmarty et al., 2003). Locally, it can reach more than 60 % after the impoundment of one single dam like on the Red River (Vinh et al., 2014), and more than 80 % on rivers with many dams (86 % on the Yellow River, Wang et al., 2007; > 95 % on the Ebro river, Durand et al., 2002). Other engineering activities (meander cutoffs, river-training structures, bank revetments, soil erosion controls) also affect significantly the sediment fluxes and can participate to shift from a transport-limited system to a supply-limited system, like on the Missouri-Mississipi (Meade and Moody, 2010).

With increasing temperature and evaporation, climate change tends to accelerate the water cycle and modify hydrologic regimes (Bates et al., 2008). Precipitation intensities and the frequency of extreme events are projected to increase under climate change, leading to more frequent flood events of higher magnitude that will, in turn, affect patterns of erosion and deposition within river basins (Tucker and Slingerland, 1997; Pruski and Nearing, 2002; Tockner and Stanford, 2002; Coulthard et al., 2012). Recent studies focused on the impact of climate change on sediment transport (e.g. Gomez et al., 2009; Hancock, 2009; Walling, 2009; Hancock and Coulthard, 2011; Knight and Harrison, 2013; Lu et al., 2013). Syvitski (2003) showed on an example that sediment transport may increase due to the increasing discharge or decrease because of the enhanced temperature. Studies compared the trends in hydrological and sediment time-series to the land use changes (Wang et al., 2007; Memariam et al., 2012; Gao et al., 2012). Climate projections are consistent on warming and acceleration of the water cycle (IPCC, 2013) but they remain to be defined on sediment transport where projections shows a high uncertainty (Shrestha et al., 2013; Lu et al., 2013). This is in part due to the fact that climate affects many patterns involved in sediment yield, such as surface moisture availability, weathering processes and rates, and the nature of the riparian vegetation (Nanson et al., 2002).

While sediment transport is well-documented in perennial rivers in humid or temperate climates, its study in semiarid areas is still fragmentary due to the difficulty of sampling during flashfloods. Amongst the factors favoring erosion (slope, nature of rocks, relief, climate, human activities), climate is recognized to be the main factor in semi-arid mediterranean areas of Algeria which experience short and intense rain episodes, high evaporating power of wind, prolonged droughts and freezing and thawing cycles (Touaibia, 2010; Houyou et al., 2014). Erosion is extremely active and the ratio of sediment wash-down to river discharge is at least one order of magnitude higher than at global scale (Achite and Ouillon, 2007). One of the main impacts of this high erosion is the rapid silting up of reservoirs (up to 2 to 5 % per year, Kassoul et al., 1997; Touaibia, 2010) with important consequences on water resources management in a region where 85 % of rain evaporates (Benhamiche et al., 2014). The high temporal variability and recent changes in forcings mean that it is necessary to study sediment dynamics in such environments over time-periods of several decades in order to document and understand the changes in sediment regime.

In this context, this paper extends to cover a 40 year period (1970–2010) the analysis of sediment transport changes of a wadi already studied over a 22 year period (1973–1995 in Achite and Ouillon (2007) hereafter referred as AO2007). The hydrologic gauging station is located upstream from a dam and is not affected by any major management. This river sub-basin is also particularly suitable for such study because its hydrologic regime was shown to have drastically changed between the 1970s and the 1980s. Precipitation decreased and became more irregular, the flow regime shifted from perennial to intermittent with 26 % of dry days in average in 1990–1995, amplified variations of discharge, and a modified sediment regime with higher and more irregular suspended particulate flux, 4.7 times higher over 1985–1995 than over 1973–1985. AO2007, showing the advantage of working over 22 years of measurement, however, stressed the difficulty of defining a reference period, and the need to extend the study period longer. The objectives of this additional study are to (1) describe the precipitation, discharge and sediment flux variability of the Wadi Abd basin over a 40 years period, (2) detect the rupture if any in temperature, runoff and sediment yield, (3) determine the relationship between the sediment load and the runoff flow over the last 40 years, (4) detect when a shift occurred in the runoff-sediment load relationship, (5) analyze the possible causes of the change in flow regime and its consequences on suspended sediment discharge, (6) assess the use of rating curves and the physical signification of its parameters when a river is experiencing a transition and turns from a perennial regime to an intermittent regime.

2 Study area: the Wadi Abd

2.1 General information

The Wadi Abd, located in the North-Western of Algeria, is a tributary of the Wadi Cheliff, the major river of Algeria (Fig. 1). The length of the Wadi Abd's main stream is 118 km and its basin area is 2480 km^2. The Wadi Abd supplies downstream the Sidi Mohamed Benaouda (SMB) reservoir which basin area is 4900 km^2. The Wadi Abd catchment area is formed of erodible sedimentary rocks from Upper Jurassic (45.9 % of its surface), Middle Jurassic (20.2 %) and Pliocene (7.4 %). Soft bottom sedimentary deposits from the Quaternary cover 13 % of the basin along the wadi (Tescult International, 2004).

The climate is Mediterranean and characterized by a dry season from April to August/September, and a wet season from September to March. The hydraulic deficit is very high. Annual precipitation is 264 mm on average while the mean evapotranspiration over the SMB basin is 1525 mm (Tescult International, 2004).

The main physical, geological, topographical and vegetation characteristics of the river and watershed, and a location map as well, are provided in AO2007. Seven hill reservoirs were built in the Wadi Abd basin from 1986 to 2004 for agriculture (irrigation, livestock watering) or for fire fighting measures. Their total cumulated capacity is 0.88 hm^3, representing 2.3 % of the yearly averaged discharge at Ain Hamara station. These small reservoirs are now silted up to 70 % of their volume.

The watershed mainly consists of steep slopes with very sparse vegetation or bare soil. The main land use is natural environment (73 %; 17 % of forests + 56 % of scrub and bare steppe soils), cultivated lands cover about 26 % and agglomerations 0.4 %. 123 000 inhabitants were living in the Wadi Abd basin in 2008 (average density:

49 inhabitants km^{-2}), 44 % of them living in the city of Takhmaret. The Wadi Abd is thus little influenced by human activities, in view of its extensive surface that is subject to severe natural erosion.

2.2 Data

Long-term series of temperature measured at 3 stations in Algeria were extracted from CRUTEM4 (Jones et al., 2012; Osborn and Jones, 2014). These stations are located at Chlef (36.20° N, 1.30° E – 1951–2011), Miliana (36.30° N, 2.20° E – 1922–2011) and Dar El Beida (36.70° N, 3.30° E – 1856–2011). The annual average temperatures were calculated for each station from the 12 monthly averages. 20 missing monthly data over 480 did not allow us to exactly calculate mean measured yearly temperature at Chlef, the nearest station from the Wadi Abd. In order to estimate the change per decade at Chlef either at the yearly or seasonal scale, the 20 lacking values were extrapolated from the monthly temperatures measured at Miliana and Dar El Beida using the relationships between the monthly average temperatures at Chlef and Miliana, and Chlef and Dar El Beida. Such relationships established at the annual scale are shown on Fig. 2. The resulting estimates of temperature at Chlef at seasonal and yearly scales allowed us to estimate changes by decade over the period 1970–2010.

Rainfall and hydrometric records were provided by the National Agency of Hydraulic Resources (ANRH). Time series of rainfall data are available at 6 stations within the basin: S1 Ain Kermes (altitude: 1162 m), S2 Rosfa (960 m), S3 Sidi Youcef (1100 m), S4 Tiricine (1070 m) S5 Takhmaret (655 m) and S6 Ain Hamara (288 m). 9076 coincident instantaneous measurements of water discharge (namely Q, in $\mathrm{m}^3\,\mathrm{s}^{-1}$) and suspended sediment concentrations (C, in $\mathrm{g\,L}^{-1}$) were recorded at the Ain Hamara gauging station between September 1970 and August 2010. Water depths were measured continuously and a calibration between water level and discharge was regularly performed from velocity profiles. Concentrations derived from water samples taken at one or two points, after filtration on pre-weighed Whatman Glass Fibre Filters (GFF) filters, oven-dried and weighed again following the protocol described by A02007 and Megnounif et al. (2013). From these coincident instantaneous data, average arithmetic values were calculated per day so as to obtain 1213 pairs of "mean daily" (C, Q) values.

The Atlantic Multidecadal Oscillation (AMO) index is an index of North Atlantic temperatures. The monthly unsmoothed values used in this study were calculated by NOAA, Earth System Research Laboratory, Physical Sciences Division/ESRL/PSD1 (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/).

3 Models and methods

3.1 Trends

The analysis of trends was conducted following a method fully described by Stahl et al. (2010) and Déry et al. (2005) for river runoff. The Kendall–Theil Robust Line furnishes a linear equation from a time-series of n measurements such as

$$y = mt + b \tag{1}$$

where t is time (year), y denotes the hydrological parameter (precipitation, river discharge, sediment discharge), and m is the magnitude of the trend over this period. m is calculated as the median of all slopes m_k of consecutive pairs of values:

$$m_k = \frac{y_j - y_i}{t_j - t_i} \tag{2}$$

where $k = [1, n(n-1)/2]$, $i = [1, n-1]$, $j = [2, n]$. This slope is often referred to as the Sen slope (Sen, 1968). The significance of this trend at a level p was calculated following Ziegler et al. (2003).

3.2 Rating curves

C and Q measurements were used to define rating curves that estimate C from measured values of Q, according to a common approach (e.g. Walling, 1977; Asselman, 2000; El Mahi et al., 2012; Tebbi et al., 2012; Louamri et al., 2013). The most suitable model is a power law of the type $C = aQ^b$ for which the coefficients (a, b) determined empirically account for the effectiveness of erosion and transport. In this paper, the rating curve established from the 1213 daily averages of C and Q data available for the period 1970–2010 enabled the estimation of C then Q_s ($Q_s = C \times Q$) for the whole period from the measured daily Q values.

Considering the change in hydrologic regime during the study period, we wondered if the estimate of C and Q_s per sub-periods like decades could be better adapted than globally. We therefore applied the 4 rating curves established for the 4 decades to the time series of daily Q to obtain daily C and then daily Q_s. This method (B) enabled us to compare the estimated solid discharge with the value provided by the global relationship established from 40 years of data (method A). The average error for daily Q_s values was 51 % using method A and 42.1 % using method B. However, the cumulative flux of suspended matter over the 1213 days for which daily data are available was over-estimated by 3.1 % using method A while it was under-estimated by 5 % using method B. A comparison of the estimates by these two methods showed that method B is not reliable for high discharge during the last decade because of an increase in scattering of the C, Q pairs. The relationship obtained over the last decade (2000–2010) lead to an under-estimation of Q_s of 23 % over the 314 days for which daily C and Q are known. In contrast, the global algorithm from method A led to an under-estimation of the same cumulated Q_s by only 3.5 % over the same period. The relationship established over 40 years was therefore used for this study.

It should be noted that although method A provides some daily solid discharges from the 1213 daily Q values with a high error (the average error being 51 %) it enabled the reconstruction of good trends of Q_s values over more than 7 orders of magnitude

(Fig. 3). However, the temporal variability of the coefficients *a*, *b* of the rating curves calculated over years or decades will be discussed in light of the variability of the forcings and their sediment transport consequences, to better understand their physical meaning.

3.3 Average loads

In order to analyze the temporal variability of suspended sediment flux, we use the average concentration resulting from the ratio between the solid and the liquid flow rate, denoted (SPM*), which can be defined for any integration period (day, month, season, year).

3.4 Study of breaks: double mass curve

Double-mass curves were used to determine long term trends and changes in the hydro-sedimentary regime (Searcy and Hardison, 1960; Walling, 1997, 2006).

4 Interannual variations of temperature, precipitation, river discharge and flow regime

The statistics of hydrological parameters at Ain Hamara gauging station over 1970–2010 are reported in Table 1.

4.1 Temperature

Temperature in Northern Algeria at the three stations of Chlef, Miliana and Dar El Beida increased from the 1970s onwards (Fig. 4). On average, temperature was higher at Chlef (between 17.5 and 20.3 °C) than at Dar El Beida (15–18.5 °C) and Miliana (14.5–18.5 °C). In average, temperature at Chlef increased by 0.96 °C between 1970–85 and 1985–2010, and by 1.17 °C from the 1970s to the 2000s (Table 2). The increase was, on average, 0.87 °C between the 1970s and the 1980s which is more than four times the difference between the 1980s and the 1990s (+0.19 °C) and the 1990s and the 2000s (+0.12 °C). As has been shown on a global scale, the decade of the 2000s was the warmest (IPCC, 2013).

4.2 Precipitation

Annual precipitation at Ain Hamara station was highly irregular, varying between 165 and 506 mm yr^{-1} (Table 1, Fig. 5). Mean annual precipitation (*P*) was 264 mm, with a coefficient of variation (CV) of 27 % between 1970–1971 and 2009–2010. The interannual variations of *P* (Fig. 5) showed trends towards a decrease of rainfall (–1.86 mm yr^{-1} on average over 40 years, $p < 0.05$). *P* decreased by 15 % (from 310 to 264 mm) between 1970s and 2000s if we consider the values averaged over decades (Table 2). However, a more precise analysis shows that rainfall greatly decreased from 1970s to the next decade (from 310 to 231 mm, –25 %), then slightly increased in the two following decades (average of 250 mm yr^{-1} in 1990s and 264 mm yr^{-1} in 2000s, see Table 2).

The average precipitation over the 6 rainfall gauging stations within the basin was 273 mm yr^{-1}. Their interannual variations were consistent and showed a similar variation to Ain Hamara station. Amongst decades, the coefficient of variation varied between 12 and 20 %. Five out of 6 stations show a decrease in precipitation between 1970–1985 and 1985–2010, the average deficit being equal to 3.7 %.

4.3 River discharge and flow regime

The mean annual discharge at the Ain Hamara gauging station was 1.18 m^3 s^{-1} over the 40 year period of observation (Table 1). The interannual variability of yearly averaged values of discharge (CV = 44.4 %, see Table 1) was higher than that of yearly precipitation. Yearly averaged values of *Q* showed a trend towards an increase of river flow (+11.3 L s^{-1} yr^{-1} on average over 40 years, $p < 0.01$; Fig. 5). The averaged values over decades decreased between the 1970s and the 1980s, then increased (Table 2). Globally, they increased by 25 % (from 1.16 to 1.45 $m^3 s^{-1}$) between 1970–80 and 2000–2010.

The detailed analysis of the daily river discharge shows that the river was perennial in the 1970s and then became intermittent during the 1980s (Fig. 6). The driest year occurred in 1993–1994 with 117 days of fully dry river. On Fig. 6, the very low river discharges (around 0.01 $m^3 s^{-1}$) were not considered as days of dry river.

The "wet discharge", denoted Q_w, i.e. the yearly average river discharge of the days of running river (and not calculated over the full year) was also calculated (Table 2). Over the 40 year period when Q increased by 25 %, Q_w averaged over 10 years increased by more than 35 % from 1970–1980 to 2000–2010 (from 1.16 to 1.57 $m^3 s^{-1}$).

Q and Q_w increased as did the number of dry days (and consequently the intra-annual variability) and their intra-decade variability (Table 2). Two indicators of intra-annual discharge variability are shown in Fig. 5: Q_{98}, the 98th percentile of annual flows calculated from daily discharge and the standard deviation of daily discharge within each year (σ_Q). Q_{98} increased from an average of 4.37 $m^3 s^{-1}$ over the period 1970–1980 to 13.94 $m^3 s^{-1}$ over the period 2000–2010, a factor 3.2 increase. Q_{98} is also a good indicator of changes in sediment transport as it occurs during the highest flood events that occur each year.

4.4 Summary: changes of hydrologic forcings

These results indicate that four significant changes occurred during the 40 year period in the Wadi Abd basin (Table 2): (1) an increase of temperature at Chlef by 1.17 °C between the 1970s and the 2000s, (2) a decrease in precipitation of 15 % over 4 decades, (3) an increase in average annual flow of 25 % over the same period, or 35 % if we consider only the days when the river is not dry, (4) a change in the flow regime, from a perennial regime to intermittent regime. The pivotal year after from which the river experiences dry weeks is the hydrological year 1985/86 with 49 days with no flow. This number increased in the following years (Fig. 6).

5 Interannual variation of sediment delivery

5.1 Rating curve

The rating curve obtained from 1213 pairs of daily averages gave:

$$C = 2.270Q^{0.647} \tag{3}$$

where C is expressed in $\mathrm{g\,L^{-1}}$ and Q in $\mathrm{m^3\,s^{-1}}$. 43 % of the variations of C are explained by those of Q ($r^2 = 0.431$). The rating curve obtained between Q and Q_s shows a much higher determination coefficient ($r^2 = 0.831$) but is biased since $Q_\mathrm{s} = C \times Q$. Nevertheless, both relationships give estimates of Q_s values from Q with less than 1 % difference which is less than the uncertainty of Q_s.

5.2 Yearly sediment fluxes and concentrations

5.2.1 Decadal variability of Q_s

Q_s increased from 180 to $1130 \times 10^3\,\mathrm{t\,yr^{-1}}$ between the 1970s and the 2000s (Table 2). The increase from one decade to the next is remarkably regular: +85 % between the 1970s and the 1980s, + 84 % between the 1980s and the 1990s, +84 % between the 1990s and the 2000s and is statistically significant ($+19.7 \times 10^3\,\mathrm{t\,yr^{-1}}$ in average, $p < 0.05$). Specific degradation follows the same trend increasing from $72\,\mathrm{t\,km^{-2}\,yr^{-1}}$ in the 1970s to $455\,\mathrm{t\,km^{-2}\,yr^{-1}}$ in the 2000s.

5.2.2 Variability of mean annual load SPM*

The average value of SPM* calculated over the period 1970–2010 from daily concentration and discharge is 12.3 g L^{-1}. The 40 annual values of SPM* calculated for each year vary between 2.5 and 50.2 g L^{-1} (Tables 1, 2). Their interannual variation was smaller than that of solid discharge because annual SPM* is the ratio of the annual Q_s to the annual Q (which increased less than Q_s). The variability of SPM* was thus smaller than that of annual Q_s (CV = 86.0 % instead of 123.3 % over 40 years).

5.2.3 Analysis of ruptures

The double mass plot enabled us to identify changes in the sediment response of the stream (Fig. 7). A major break occurred in 1985–1986. A secondary break was noticed in 1991–1992, but the entire period 1985–1986/2009–2010 may be considered as a single period (with the relationship "cumulated Q_s" = 0.021 "cumulated Q" – 9.417, R^2 = 0.989). The period 1985–1986/1991–1992 may thus be considered as a transient event towards a new regime.

The response of sediment flow to various constraints (changes in precipitation, hydrology, plant, agricultural practices etc.) differs clearly from that of discharge from the year 1985–1986 onwards. This break corresponds to the first year of dry river over a long period in summer (49 days). This initiates a phase of intermittent flow regime. The averaged parameters for the two periods 1970–1985 and 1985–2010 were added to the tables, in addition to average values throughout the full study period and values for decades to illustrate the dynamics of the hydrological and hydro-sedimentary change.

5.3 High dependency of the solid discharge on *Q* variability

The variability of Q and Q_s or SPM* at different time scales were compared. AO2007 showed that the variation over 22 years of yearly SPM* depended at 71 % on the yearly discharge and at 73 % on the 95th percentile of daily discharge within the given year Q_{95}. This means that SPM* was mainly driven by the 10 to 15 highest daily discharges in a year suggesting a strong correlation between yearly Q_s and the discharge variability. Finally, they showed a remarkable linearity between SPM* and the standard deviation of the daily discharge per year (σ_Q).

Yearly SPM* and yearly σ_Q still showed a strong linearity over 40 years ($r^2 = 0.956$, Fig. 8a). A higher correlation was obtained between yearly Q_s or SD, the specific degradation, and yearly σ_Q ($r^2 = 0.991$, Fig. 8b). This is one of the most important conclusions from this river where the solid discharge depends on discharge following a rating curve: the yearly solid discharge is more closely dependent on the discharge variability than on discharge values.

6 Variation of the seasonality of climatic and hydrological parameters

The yearly values of temperature at Chlef increased on average but the monthly averages showed high discrepancies. Temperature from March to November increased with a maximum of increase in June (+3.30 °C on average between the 1970s and 2000s), it remained quite constant in December and February and decreased by 0.98 °C in January over the same period. Considering the average values per season, winter values (December–February) decreased by 0.33 °C between the 1970s and the 2000s, while spring values (March–May) increased by 1.66 °C, summer values (June–August) by 2.22 °C and fall values (September–November) by 1.29 °C. In summary, annual temperature differences increased with minimum temperatures down slightly and maximum temperatures rising sharply. The increase was most marked in July–August.

Averaged seasonal values of P, Q and Q_s for each decade are given in absolute values and in percent of the yearly values in Table 3. The seasonal relative contribution of P, Q and Q_s centered and averaged over 9 consecutive years are presented in Fig. 9. The monthly values of P, Q and Q_s per decade over 40 years also clearly illustrate the absolute changes in intensity and in seasonality of the river regime (Fig. 10). The main conclusions of the analysis of T, P, Q and Q_s variations are the following:

- Rainfall decreased in spring and increased in autumn. Precipitation in autumn increased from 22 to 30 % at the expense of spring rains (decreasing from 41 to 29 %). It is striking to note that for the decade 2000–2010 precipitation was the same in autumn and in spring (78 mm) while for the decade 1970–1980 spring rainfall was 87 % higher than in fall (128.2 vs. 68.5 mm; see Table 3 and Fig. 9a).

  Average monthly rainfall from six weather stations in the river basin for 1970–1985 and 1985–2010 (Fig. 11) illustrates the changes. Two marked seasons typical of a Mediterranean climate are present (a dry season and a rainy season) but the following changes are observable: (1) gaps between seasons decrease, as indicated by the CV of monthly rainfall from 57.3 % in 1970–1985 to 45.9 % in 1985–2000. There is a decrease of spring rains (March–May) and at the beginning of the cold season (November–December) and the strengthening of rain in the warm season (July–October) and in winter (January–February), (2) advancement of the rainy season as evidenced by precipitation in October and November, (3) spreading of the rainy season over 9 months (September–May) for 1985–2010 from previously 7 or 8 months (from October or November onwards, according to the criteria that are defined for the rainy season), (4) increased regularity of rainy season precipitation.

- Proportionally, flow decreased in all seasons from winter to summer and increased dramatically in autumn from just over a quarter (27.3 %) of the flow delivered over the decade 1970–1980 to more than one half (52.5 %) over the period 2000–2010 (Table 3 and Fig. 9b). Flow decreased in summer and the river became dry for much of the summer. Over the last decade, it is striking to see the difference between the average flow rates in fall and spring: the fall rate is almost three times that of spring with almost the same rainfall. This trend is evident over the 40 year period (Fig. 9b).

- These results point towards a change in runoff as defined by the ratio Q/P. Considering the whole basin area, the river discharge at Ain Hamara station averaged over 40 years corresponds to a water depth of 15 mm yr^{-1}, while the average precipitation is 264 mm yr^{-1}. For comparison, on average 85 % of rain in this region evaporates and the remaining 15 % run into surface waters or infiltrate into underground waters layers (Sari, 2009, quoted by Benhamiche et al., 2014). On the Wadi Abd, Q/P averages 5.7 %. We calculated the value of Q/P averaged over 3 consecutive years and over 3 consecutive months (centered) and then took the average per decade (Fig. 12). It appears that the Q/P ratio remains constant during the months from December to April (around 4.4 % in average), it increased slightly in November and May during the decade 2000–2010 and it increased significantly from September to November. In other words, runoff increased, rain decreased slightly and the temperature (and therefore ETP) increased. As a consequence, infiltration will decrease and the level of aquifers be lowered. Moreover, Q/P, which was very high in July and August in 1970s, has nearly halved since 1980s.

- In absolute value, solid discharge has been increasing in all seasons over 4 decades, but more so in the fall than in the other seasons (Table 3 and Fig. 10c). During autumn, it more than doubled from one decade to another (×2.07 in the 1980s vs. 1970s, ×2.17 from 1980s to 1990s, and ×2.88 from 1990s to 2000s). During the other seasons, it doubled or tripled within 30 years, between 1970s and 2000s. The average annual load was multiplied per 1.84 from one decade to another (1.8×10^6 t during the 1970s, 3.34 in 1980s, 6.14 in 1990s and 11.30 in 2000s, see Table 2). While during the 1970s the Wadi Abd had two major periods of roughly equivalent sediment discharge in the fall and spring, suspended sediment mainly occurred in autumn during the 2000s (> 70 %). The Wadi shifted from a regime with two equivalent seasons of sediment production to a major season regime. Autumn produced over 4 times more sediment than spring in 2000s (Ta-

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ble 3, Fig. 9c). This phenomenon does not seem to be due to some exceptional floods because the trend is observable over 4 consecutive decades (Fig. 9c).

7 Discussion

7.1 Interannual variations

7.1.1 Hydrology and climate change over 40 years

Temperature increased rapidly between the 1970s and 1980s (+0.88 °C on average at Chlef). The increases were lower during the following decades (1980s to the 2000s). An increase in temperature of 1.6 °C between 1977–1979 and 2000–2006 was noted by Dahmani and Meddi (2009) for the Wadi Fekan basin in West Algeria and Bakreti et al. (2013) also showed a significant trend of increasing temperature in spring by 0.0183 $^{\circ}\mathrm{C\,yr^{-1}}$ in the Tafna basin in West Algeria over the same period. However, temperature did not increase so fast during the whole 20th century (Fig. 4) and as mentioned by IPCC (2013), "trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends." The longest available time series of temperature in Algeria was measured at Dar El Beida near Algiers. At this station, average temperature increased by 0.62 °C between 1850–1900 (29 yearly values available) and 2003–2012 (Fig. 4), while it increased between 1880 and 2012 by 0.85 °C globally (IPCC, 2013).

A global trend towards an increasing temperature and increasing dryness in Algeria from the 1970s onwards has already been described (Meddi and Meddi, 2009). Over the period 1923–2006 North Algeria experienced an alternation of wet periods (1923–1939, 1947–1973) and dry periods (1939–1946 and from 1974 onwards) (Benhamiche et al., 2014). Over 70 years in the Wadi Fekan, Dahmani and Meddi (2009) showed that the period 1943–1960 was rather wet, that 1960–1975 was average, and that the period 1975 onwards (up to the end of their data set in 2004) was dry and of an exceptional long duration. Using three different statistical tests (Pettitt, Lee Heghinian and Hubert), Meddi and Meddi (2007) shown that a rupture was observed between 1973 and 1980 over most of the rain gauges in Algeria. In North-West Algeria, a rupture was noticed in 1973 in winter rainfall and between 1974 and 1980 in spring rainfall, both of them being responsible of the yearly rainfall deficit (Meddi and Talia, 2008). From the rainfall dataset at the Ain Hamara station between 1968 and 2007, Hallouz et al. (2013) showed that the rupture in annual rainfall occurred in 1976 and calculated a deficit of 19 % between 1968–1976 (304 $\mathrm{mm\,yr^{-1}}$) and 1976–2007 (247 $\mathrm{mm\,yr^{-1}}$). At the stations Ponteba and Rechaiga, near to the Abd basin, the trends of decreasing total precipitation and of increasing mean length of dry spells were amongst the 5 highest in the Maghreb area over the 22 stations considered by Tramblay et al. (2013, see their Fig. 6).

As a consequence of the decrease of rainfall after the 1970s rupture which was observed in most basins of Western Algeria, river discharges were generally seen to decrease as well. Meddi and Hubert (2003) showed that the decrease in river discharge varied between −37 and −70 % from the Eastern Algeria to the Western Algeria. Over the Mecta basin in North-West Algeria, runoff was estimated to be 28–36 % lower in 1976–2002 as compared to 1949–1976 (Meddi et al., 2009). Over the Tafna basin also in North-West Algeria, Ghenim and Megnounif (2013a, b) showed that the decrease of precipitation by 29 % on average over the basin (especially in winter and spring) after the rupture was accompanied by a decrease of 60 % in river flow.

In this context, the Wadi Abd had a different behavior since the river discharge increased. The counter-intuitive increase of runoff with decreasing rainfall has also been observed in Sahel and is referred to as “ the Sahelian paradox ” (see Mahé and Paturel, 2009; Mahé et al., 2012). A closer look at the seasonal variations of the different parameters shows that Q decreased in winter and spring but that Q/P increased in autumn when rainfall increased. Overall Q increased. The decrease of rainfall in spring and its low level in summer may have lead to a change in vegetation cover which would in turn decrease of infiltration. However, although studying the vegetation dynamics of the basin goes beyond the scope of this study, this aspect could be investigated in the future using satellite data, for example.

7.1.2 What is the influence of large-scale circulation indices?

Changes in precipitation are derived from atmospheric-oceanic signals (Milliman et al., 2008; Giuntoli et al., 2013). Low frequency fluctuations related to climate change are modulated with higher frequency interannual fluctuations, such as ENSO (El Niño Southern Oscillation), NAO (North Atlantic Oscillation), AMO (Atlantic Multidecadal Oscillation) or MO (Mediterranean Oscillation). Tramblay et al. (2013) showed that the precipitation amounts and the number of dry days over Maghreb were significantly correlated to the MO and NAO patterns. MO and NAO showed positive trends from the 1970s onwards which could explain the trend towards decreasing frontal conditions over the Mediterranean basin and thus increasing droughts.

Interannual influence by the Austral oscillation ENSO over Algeria was shown to be higher in North-West Algeria over the highest discharges than on the average. The maximum Q seems to be smaller during El Niño and higher during La Niña in North-West Algeria (Ward et al., 2014). Average discharge is less influenced by ENSO than the maximum yearly discharge (Ward et al., 2014). The frequency of extreme rainfall events shows the highest correlation with the Mediterranean Oscillation Index in Algiers and with the Southern Oscillation Index in Oran (Taibi et al., 2014).

In this study, no significant correlation was established between a series of hydrological parameters in the Wadi Abd and the Southern Oscillation Index. The average of AMO per hydrologic year was calculated from its monthly values. AMO has increased from 1970s to the 2000s, with negative values up to 1993–1994, then positive afterwards (except in 1996–1997). Its decadal average was −0.25 in the 1970s, −0.12 in the 1980s, 0.0 in the 1990s and 0.18 in the 2000s. AMO and the discharge variability of the Wadi Abd within the year increased coincidently. The yearly AMO values have a coefficient of determination of 0.226 with the standard deviation of daily river discharges within the year, a proxy for the variability of daily discharge. However, this information does not allow us to conclude that the Atlantic Multidecadal Oscillation is responsible of hydrological changes in the Wadi Abd basin.

7.1.3 Rupture in 1985–1986: change of flow regime

The several weeks of dry river for the first time in 1985–1986 (49 days) can be considered as a threshold effect, which marks the start of a new flow regime. The appearance of a dry regime is a rupture, a fully nonlinear phenomenon. It has strong consequences on water infiltration and groundwater recharge, on seasonality, intensity and type of floods, and in turn, on erosion and sediment transport. 1985 is also a pivotal year for recent climate change as evidenced by the rapid increase in global mean temperature anomaly of air from that year until 1993 (Fig. 1 in Lockwood and Fröhlich, 2007). The hypothesis of a temporary warming caused by dust emitted during the eruption of Mount Pinatubo had been advanced to explain the warming since 1985, but climate scientists later recognized that the temperature anomaly has been increasing since 1993, reaching about 0.6 °C by 2007 compared to the global average temperature calculated for the period 1951–1980 (Lockwood and Fröhlich, 2007).

This threshold is coincident with hydrological ruptures in the Tafna basin in North-West Algeria. Bakreti et al. (2013) analyzed the baseflow and baseflow index of five of its sub-basins between 1976 and 2006 and evidenced ruptures of the baseflow index between 1984 and 1990 depending on the sub-basin, in 1984, 1985 and 1990 in the mountains, and in 1985 and 1986 in the plain. These changes in flow regimes of the Tafna basin were likely caused by ruptures in rainfall late 1970s in the Mounts of Tlemcen and early 1980s in the plains (Ghenim and Megnounif, 2013a).

7.1.4 Shift of the onset of the first summer flood

By observing the daily flow averaged per decade, there is no ambiguity on the average dates of the first flood by decade:

- in 1970–1980, the first flood starts on average 6 September with an average 4 days discharge (6–9 September) of 1.59 $m^3 s^{-1}$, while it was on average 0.58 $m^3 s^{-1}$ over the four previous days,
- in 2000–2010, the first flood in summer starts on 8 August with an average 4 days discharge (8–11 August) of 2.03 $m^3 s^{-1}$, while it was on average 0.03 $m^3 s^{-1}$ from 4 to 7 August.

During the 2000s, the first flood in summer started close to one month before that of the 1970s and the magnitude was 27 % higher. It can be asked if this trend observable over the 40 year period or only between two specific decades. The analysis of mean dates and discharges of the first flood in late dry season gave for the intermediate decades:

- 1980–1990: the first flood started in average on 31 August with a 4 days average discharge (31 August–3 September) of 2.69 $m^3 s^{-1}$, while the average rate over the four previous days was 0.13 $m^3 s^{-1}$
- 1990–2000: the first flood started in average on 22 August with a 4 days average discharge (22–25 August) of 7.67 $m^3 s^{-1}$, while the average rate over the four previous days was 0.33 $m^3 s^{-1}$. The existence of a precursor peak on 17 August, which was not observed in previous decades, was also observed.

It therefore appears that the date of the first flood advanced by about ten days each decade over the previous 40 years. The shift in the onset of the first flood in summer probably has important consequences on flow and erosion rates.

7.2 Relationships between several parameters and sediment yield

7.2.1 Temperature and sediment yield

The curve showing annual suspended load vs. global air temperature anomaly calculated by hydrological year from monthly data provided by NOAA shows a correlation between the sediment yield and ongoing climate change ($r^2 = 0.469$, Fig. 13).

7.2.2 Precipitation and sediment yield

Langbein and Schumm (1958) showed that the sediment load per unit of catchment area is maximum when annual rainfall is between 250 and 350 $\mathrm{mm\,yr^{-1}}$, i.e. in semi-arid areas. On the Wadi Abd, annual rainfall was 310 $\mathrm{mm\,yr^{-1}}$ in the 1970s, fell sharply in the 1980s then slightly increased over the following decades to between 231 and 264 $\mathrm{mm\,yr^{-1}}$. Meanwhile, yearly sediment concentration and suspended sediment discharge have increased. The comparison of their respective variations shows a lack of correlation between precipitation and annual sediment yield ($r^2 < 0.1$ regardless of the type of regression considered). Regarding the relationship between precipitation and erosion, if there are correlations between their spatial variations reported in the literature (though with a strong scatter, see Riebe et al., 2001), our study shows that the temporal variations of precipitation and sediment yield are not correlated in the Wadi Abd. This may be due to the change of flow regime within the study period.

7.2.3 Runoff and sediment yield

Although runoff was noted to have a limited impact on the distribution of sediment yield at regional or global scales by Aalto et al. (2006), Syvitski and Milliman (2007), Vanmaercke et al. (2014), the temporal variability in precipitation, runoff (or discharge) and consecutive vegetation cover was shown to be locally the main impact on riverine sediment load (see the review of Vanmaercke et al. (2014), p. 360). Our results confirm that, on the Wadi Abd, the yearly suspended sediment load was highly correlated with the variability of discharges, and especially to its highest values (Q_{98}), the best correlation being obtained with the standard deviation of daily discharge within the year (Fig. 8). Although the river regime shift clearly changed several parameter evolutions between the two periods, the relationship between yearly sediment load and discharge variability did not change over the study period.

Climate change alters the hydrology of a river basin such as the Wadi Abd. We show that suspended sediment yield was highly correlated with discharge (Q mean or its highest percentiles) and to its intra-annual fluctuation (Fig. 8). We cannot conclude on the exact origin of the regime change but note that it occurred when dry periods started, annual precipitation timing shifted and runoff increased.

7.3 On the use of double-mass curves to determine the climate change and anthropogenic influences

Double-mass curves are often used to determine the impact of developments such as dams on sediment discharge (e.g. Lu et al., 2013). Our findings warn about extrapolations that could be wrongly made to quantify the impact of a development by extending the double mass curves. Indeed, this study shows that the double-mass curve can change its slope (here increasing) when the flow regime change is driven by seasonal temporal variation in precipitation and runoff that isn't linked to any specific anthropogenic activity (such as a dam impoundment) within the basin.

7.4 Physical meaning of rating parameters *a* and *b*

7.4.1 Interannual variation of (a, b)

Since $C = aQ^b$, with $b \neq 0$, $C(1) = a$. a thus represents the sediment concentration when the river discharge is $1\,\mathrm{m^3\,s^{-1}}$, and b reflects the sensitivity of concentration to discharge variation. The general formula $\ln C = \ln(aQ^b)$ provides:

$$\mathrm{d}C/C = b\,\mathrm{d}Q/Q \tag{4a}$$

$$b = \mathrm{d}C/\mathrm{d}Q\,Q/C = 1/a\,\mathrm{d}C/\mathrm{d}Q\,Q^{(1-b)} \tag{4b}$$

thus b varies almost like $1/a$ (Asselman, 2000). Many papers discuss the physical meaning of the rating parameters a and b (see AO2007) and try to connect their values to physiographical characteristics, vegetation cover or hydro-meteorological forcing. A study such as the present one on a single basin avoids physiographical variations and enables the analysis of the dependence of a and b on the hydro-meteorological forcing and, if data are available, on vegetation cover and land use.

Over 40 years the variations of (a, b) averaged over one or several years can be instructive (Fig. 14). In the present study, we only considered the yearly (a, b) values corresponding to yearly $C-Q$ rating curves with $r^2 > 0.21$ or to yearly $Q-Q_s$ rating curves with $r^2 > 0.71$ in our dataset. Based on this criterion, 3 yearly (a, b) values over 40 for the hydrological years 1972/73, 1975/76 and 2009/10 were removed from the present analysis.

At yearly scale, a explains 58 or 66 % of the variance of b depending on the considered relationship, respectively (Fig. 14):

$$b = -0.294 \ln a + 0.912 \tag{5a}$$

$$\ln b = -0.188 a + 0.042. \tag{5b}$$

Relationship (Eq. 5a) is close to the one established for 138 flood episodes between 1973 and 1995 ($b = -0.311 \ln a + 1.066$) (AO2007). The river's regime change is accompanied by a change in the (a, b) pairs of rating curves defined for multi-year periods such that a increases and b decreases (Table 2). Equation (5a) is also very similar to that presented by Iadanza and Napolitano (2006) for the Tiber River after the construction of a dam ($b = -0.3815 \ln a + 0.7794$, $r^2 = 0.992$). Before the construction of this dam, another relationship ($b = -0.4457 \ln a + 0.9615$, $r^2 = 0.991$) corresponded to more than 3 times higher sediment yields. Asselman (2000) suggested to interprete regression lines in a $\ln a - b$ graph as different sediment transport regimes.

On the Wadi Abd, the change in sediment transport regime is not evident from the yearly (a, b) values but it becomes clearly observable when considering a and b values averaged over moving periods of several years. The best correlations were obtained for running averages over 15 years named a_{15} and b_{15} ($N = 25$, from 1970–1985 to 1995–2010, see Fig. 15). The available data set does not allow us to determine if results obtained from averaging over longer periods would perform best.

The time evolution of the moving average pair (a_{15}, b_{15}) clearly shows a first relationship with the values dominated by the pre-1985 regime, and another one for the values predominantly posterior to 1990, with a transitional regime centered on the period 1985–1990 (Fig. 15). They gave:

$$b_{15} = -0.178a_{15} + 1.043(r^2 = 0.960, N = 8) \tag{6}$$

from 1970–1985 to 1977–1991 (average values calculated with mainly pre-1985 data), with a_{15} increasing and b_{15} decreasing, and

$$b_{15} = -0.126a_{15} + 1.021(r^2 = 0.982, N = 12) \tag{7}$$

from 1983–1997 to 1995–2010 (mainly post 1990), with a_{15} increasing and b_{15} decreasing. During the transition period centered over 1985–1990, b_{15} was almost constant (between 0.72 and 0.74) while a_{15} was increasing from 2.01 to 2.34. During the period 1985–1991 the yearly values of b varied very little (between 0.653 and 0.672) while yearly a increased significantly from 1.81 in 1985–1986 to 3.23 in 1990–1991.

The 25 values of moving average (a_{15}, b_{15}) pairs are associated to given river basin and types of transported particules. Their change depends only on the hydrometeorological and vegetation forcings for a given physiography (slope, geology). As the ruptures were coincident, it is possible to analyze the change of (a_{15}, b_{15}) in terms of shift of hydrological regime. The two relationships before and after the transition can be considered as signatures of the dominant hydrological regime.

We can thus conclude that a true change in sediment transport regime occurred on the Wadi Abd basin. Within this change of regime, the rating parameters showed a clear tendency to evolve towards increasing values of a and decreasing values of b (Table 2). A similar trend is generally considered in the literature as typical of an increasing aridity. One example of highly arid river basin was given by Alexandrov et al. (2003) for the case of the ephemeral Nahal Eshtemoa in Israel, where $a = 16.98$ and $b = 0.43$.

Studying the impact of the Three-Gorges dam over the Yantgze River, Wang et al. (2008) showed that a decreased and b increased after dam impoundment and associate this change to a decrease in sediment supply from the basin (with *a*) and an increase of the erosive power of the river (with *b*) which scours the river downstream of the dam. Considering the two main sediment sources (the basin and the river bed) and applying the same reasoning, we could infer that the erosive power of the river decreased while the erosion of the basin increased. This means that in the Wadi Abd climate change would favor the river basin as sediment source to the detriment of the bed.

7.4.2 Parameters that explain *a* (or *b*)

The value of *a* (or *b*, which is deduced from *a*) varies with the hydro-meteorological and vegetation forcing. The annual average liquid flow explains 63.3 % of the variance of *a*. The coefficient of determination between *a* and specific degradation (SD) is low at the annual scale but higher when we consider the moving averages of *a* and SD over 15 years. The specific degradation explained 95.2 % of the variance in the interannual scale (Fig. 16a), much more than the average river flow did ($r^2 = 0.839$, see Fig. 16b).

$$a_{15} = 6.104 \times 10^{-3} \mathrm{SD}_{15} + 1.117 \quad (R^2 = 0.952) \tag{8}$$

b_{15} showed a lower correlation to the specific degradation (Fig. 16c) than a_{15} did.

In summary, our results indicate that the moving average of *a* is strongly correlated to specific degradation over the same moving period of 15 years, and that the moving average of *b* can be deduced from *a* over the same period using a relationship which is given per flow regime, either perennial or intermittent. During the transition to an intermittent regime, *b* remained almost constant while *a* increased. The coincident increase of *a* and specific degradation is consistent with the previous hypothesis of increasing erosion within the basin as a consequence of the regime change.

7.4.3 Validity range of rating curves

The estimate of sediment yield from flow measurements and a rating curve is still acceptable throughout the study period (Fig. 3). However, it should be noted that the pairs (C,Q) become increasingly scattered with time around the best-fit curve. The determination coefficient has decreased from one decade to another over 40 years, from 0.57 to 0.38 (Table 2). As already explained, the rating curve established for the only last decade did not allow to properly estimate the solid discharge, leading to an error of 23 % as compared to the calculation from measurements.

Intermittent flows induce a stronger dependency of river behavior on antecedent wetness (Beven, 2002) and antecedent weathering, i.e. a strong dependency on memory through threshold and hysteresis effects. With increasing memory effects, coincident values of C and Q become less dependent on each other and the rating curves less suitable to model their relation. The study of sediment dynamics in the Wadi Abd will thus likely require in the future a more appropriate method than rating curves, such as the study of each individual flood, like Megnounif et al. (2013) did in the Wadi Sebdou. This finding may have consequences on water management as well. When dealing with rating curves, frequent water discharge must be recorded and measurements of concentration can be sparser. When rating curves cannot be applied, river discharge and sediment concentration should be both frequently and simultaneously measured.

8 Conclusions

Over the last 40 years, in response to climate change which resulted in an increase in temperature of around 1.1 °C between the 1970s and 2000s years, the watershed of Wadi Abd experienced an advance in rainfall during the late warm season, a significant change in the flow regime of the river and an increased variability in inter-annual scale and intra-annual basis. These changes ultimately lead to a dramatic and continuous increase in sediment load over 4 decades (in average 84 % more every decade as compared to the previous one).

The main result of our analysis is the shift of the onset of the first summer flood that occurred 1 month earlier in the 2000s than in the 1970s. This shift is likely responsible for the cascading effects on the hydrological regime of the Wadi Abd. In particular, earlier floods during the warmer season have higher evaporation which limits the groundwater storage. A parallel study of seasonal changes in vegetation cover is needed to provide additional information.

The increase in erosion of the watershed (coefficient *a*) is accompanied by a decrease in the coefficient *b* that seems to be associated with a decrease in the erosive power of the river. But this interpretation is still questionable since the sediment fluxes do not reflect erosion processes only, but also sediment storage (Trimble, 1999). The traditional rating curves approach which was applicable when the river was perennial is now less adapted to model the behavior of the river (Table 2). This could be explained by a more pronounced hysteresis phenomenon, which is consistent with the change of hydrological regime in the dry season thereby limiting the utility of rating curves to model $C-Q$ relationships. Indeed, system memory related to hysteresis phenomena cannot be accounted for by instant models such as rating curves. Other methods such as that proposed by Megnounif et al. (2013) are probably better adapted to understand future sediment dynamics of the Wadi Abd.

This analysis only includes hydrological parameters. Management programs that were conducted to fight erosion in Algeria from 1960s until 1990s by reforesting and setting up banks over cultivated marnes and clay areas proved to be little or no efficiency (Touaibia, 2010). Human activities may have influenced the hydrological regime change and increased erosion, in particular through firewood cutting during economically difficult periods (1990s), however the rupture was shown to occur earlier. The lack of data on land use and land cover changes over 40 years does not allow us to isolate the factors directly related to climate change from those related to other anthropogenic activities, but this question was not in the scope of the paper. The small population and the low coverage of cultivated areas and vegetation in the basin make us think in this system the effects of climate change dominate anthropogenic effects.

It is important to emphasize that it is impossible to define long-term hydrological averages in the context of a changing flow regime. Our analysis is based on the shift from a perennial regime to an intermittent one. The example of the Wadi Abd shows that the difficulty is challenging with regard to sediment transport in suspension, since changes of flux cannot be counted as a fraction but can reach an order of magnitude.

Changes in flow regime in relation to climate change can be investigated using climate models. Das et al. (2013) using 16 climate projections showed that more intense floods of a return period of 2–50 years should occur in the Sierra Nevada, regardless of the rainfall variation. The recent changes in the Wadi Abd show that extreme events with increasing variability already occur in the basin. Over Algeria, an increase of 1–2 °C in temperature could induce a reduction of 10 % in precipitation before the end of the 21st century (Benhamiche et al., 2014) with unknown consequences on erosion and sediment transport. Lu et al. (2013) calculated the impact on sediment loads of every 1 % change in precipitation or river discharge in large Chinese rivers. Such a calculation has no meaning in our basin since the rainfall and discharge were not monotonic (severe decrease in the 1970s then slight increase during 30 years) while the sediment loads have always increased. The difficulty of forecasting climate change-driven impacts on sediment yield due of non linear effects has been underlined by geomorphologists (see Goudie, 2006; Jerolmack and Paola, 2010; Coulthard et al., 2012; Knight and Harrison, 2013). The present study illustrates that the change of flow regime induce a fully non linear effect between river discharge and sediment yield. This needs be considered in forecasts especially in small river basins in semi-arid areas.

Changes in erosion and sediment transport under new climate constraints will induce changes on the middle to long term that decision-makers must integrate into water resources management, habitat status, agricultural adaptation (O'Neal et al., 2005), landscape evolution (Temme and Veldkamp, 2009) as well as in many other environmental adaptations (Ouillon, 1998). We thus encourage the local adaptation of sampling strategies and measurements to take into account changing in flow regimes. Furthermore, due to the uncertaincy of water resources and erosion in Maghreb (Taabni and El Jihad, 2012) and in the Mediterranean basin (Nunes et al., 2008), we also encourage the development of studies on long-term sediment transport in North African basins, in connection with changes in forcing factors.

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Table 1. General statistics of the yearly averages of hydrologic parameters of the Wadi Abd at Ain Hamara gauging station over 1970–2010. (Note: T at Chlef was estimated from measurements at Dar El Beida and Miliana for 20 months over 480.)

Statistic value	T (Chlef) °C	P mm yr^{-1}	Q m^3 s^{-1}	Q_w m^3 s^{-1}	M 10^3 t yr^{-1}	SPM* g L^{-1}
Mean	19.09	264	1.18	1.29	564	12.3
Min	17.52	165	0.37	0.46	33.1	2.56
(Year)	1971–1972	1999–2000	1992–1993	1983–1984	1992–1993	1975–1976
Max	20.32	506	2.19	2.98	3266	50.25
(Year)	1989–1990	1995–1996	1994–1995	1994–1995	2007–2008	2007–2008
standard deviation	0.69	71.2	0.52	0.59	696	10.6
CV (%)		27.0	44.4	45.6	123.3	86.0

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Recent changes in climate, hydrology and sediment load in the Wadi Abd, Algeria (1970–2010)
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Table 2. General statistics of the averages of hydrologic parameters of the Wadi Abd at Ain Hamara gauging station per decade and significant period over 1970–2010. (Note: T at Chlef was estimated from measurements at Dar El Beida and/or Miliana for 20 months with missing values over 480. Full 4-decades + two periods 1970–85 and 1985–2010 are in bold.)

Period	T at Chlef	P, yearly precipitation		NDD, average yearly number	Q, yearly discharge		Q_w, yearly discarge of wet days		Q_s, yearly sediment load		Q_{98}, average of yearly values	
	Average (°C)	Average (mm)	CV (%)	of dry days ($Q = 0$)	Average ($m^3 s^{-1}$)	CV (%)	Average ($m^3 s^{-1}$)	CV (%)	Average ($10^3 t yr^{-1}$)	CV (%)	Average ($m^3 s^{-1}$)	CV (%)
1970–2010	**19.09**	**264.1**	**27.0**	**28.3**	**1.18**	**44.4**	**1.29**	**45.7**	**564**	**123.3**	**9.18**	**78.6**
1970–1980	18.32	310.5	19.4	1.2	1.16	32.9	1.16	32.9	180	78.8	4.37	66.9
1980–1990	19.19	231.2	16.8	24.1	0.98	36.8	1.07	41.5	334	91.7	7.39	68.0
1990–2000	19.37	250.4	40.5	59.9	1.13	55.1	1.34	55.2	614	98.3	11.03	88.5
2000–2010	19.49	264.2	19.7	28.1	1.45	43.3	1.57	42.2	1130	90.3	13.94	44.5
1970–1985	**18.51**	**284.3**	**23.1**	**0.8**	**1.02**	**37.8**	**1.02**	**38.2**	**159**	**78.9**	**4.13**	**58.8**
1985–2010	**19.47**	**252.0**	**29.0**	**44.8**	**1.28**	**45.1**	**1.45**	**43.7**	**808**	**97.0**	**12.21**	**61.1**

Table 2. Continued.

Period	SD, average specific degradation ($t\,km^{-2}\,yr^{-1}$)	SPM*		Rating curve parameters			
		Average ($g\,L^{-1}$)	CV (%)	*a*	*b*	R^2	*N*
1970–2010	**227.6**	**12.3**	**86.0**	**2.270**	**0.647**	**0.431**	**1213**
1970–1980	72.7	4.54	47.9	1.021	0.890	0.573	240
1980–1990	134.5	9.93	57.0	2.049	0.649	0.449	316
1990–2000	247.5	14.36	69.2	2.753	0.659	0.418	343
2000–2010	455.6	20.55	68.7	4.440	0.412	0.384	324
1970–1985	**64.2**	**5.16**	**58.9**	**1.213**	**0.818**	**0.519**	**346**
1985–2010	**325.6**	**16.65**	**67.4**	**2.974**	**0.576**	**0.415**	**867**

Table 3. Variation of precipitation, water discharge and sediment delivery averaged per season over each decade.

	Precipitation (mm)				Water discharge ($m^3 s^{-1}$)				Sediment delivery (10^3 t)			
	autumn	winter	spring	summer	autumn	winter	spring	summer	autumn	winter	spring	summer
1970–1980	68.5	102.6	128.2	11.2	3.79	4.15	4.22	1.75	62.2	43.7	66.1	8.4
1980–1990	56.0	94.4	70.7	10.1	3.45	3.86	3.25	1.19	128.8	61.0	97.2	46.8
1990–2000	67.0	81.1	86.9	15.5	5.58	2.98	3.33	1.62	279.1	57.8	130.9	146.0
2000–2010	78.6	98.4	77.7	9.5	9.13	4.05	3.18	1.05	804.9	94.4	195.3	35.4
	Precipitation (%)				Water discharge (%)				Sediment delivery (%)			
	autumn	winter	spring	summer	autumn	winter	spring	summer	autumn	winter	spring	summer
1970–1980	22.1	33.0	41.3	3.6	27.3	29.8	30.3	12.6	34.5	24.2	36.6	4.7
1980–1990	24.2	40.8	30.6	4.4	29.4	32.8	27.7	10.1	38.6	18.3	29.1	14.0
1990–2000	26.7	32.4	34.7	6.2	41.3	22.1	24.6	12.0	45.5	9.4	21.3	23.8
2000–2010	29.7	37.3	29.4	3.6	52.5	23.2	18.2	6.1	71.2	8.4	17.3	3.1

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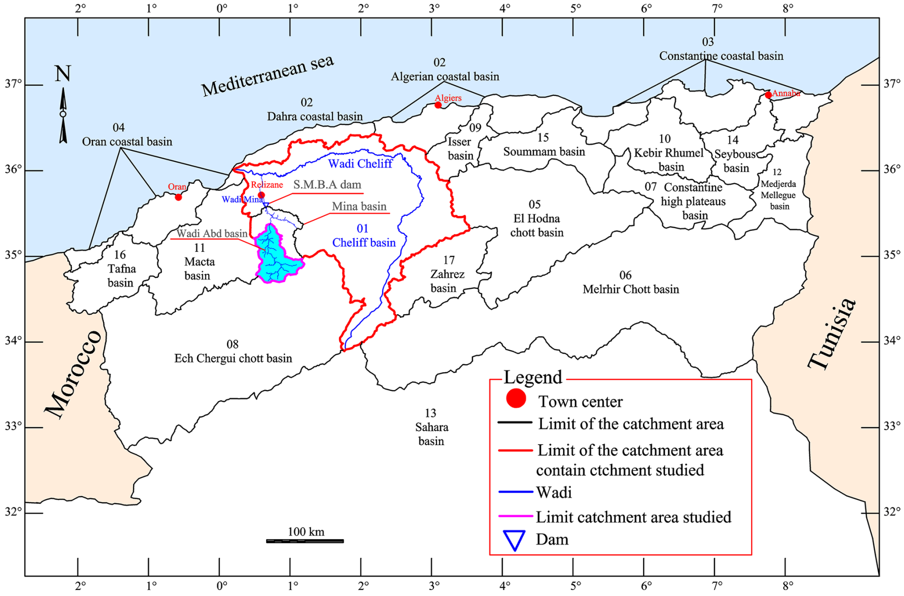

Figure 1. Location of the Wadi Abd sub-basin within the Mina and Cheliff basins, and the other main basins of Algeria.

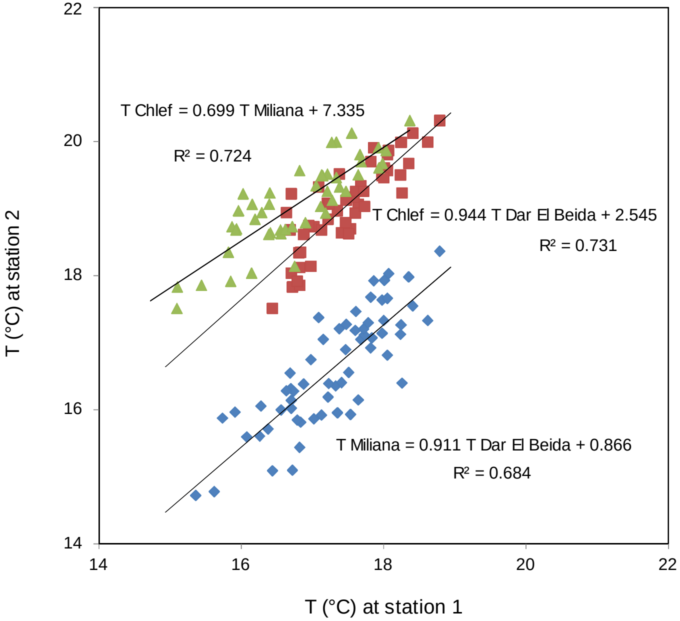

Figure 2. Relationships between mean yearly temperatures at the three stations of Dar El Beida, Miliana and Chlef (from CRUTEM4).

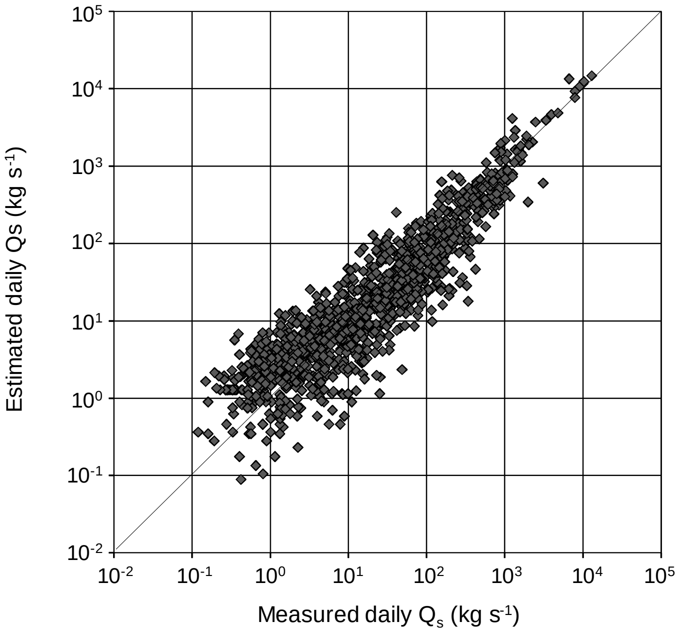

Figure 3. Comparison between estimates of Q_s obtained from Q and the global rating curve, and measured Q_s.

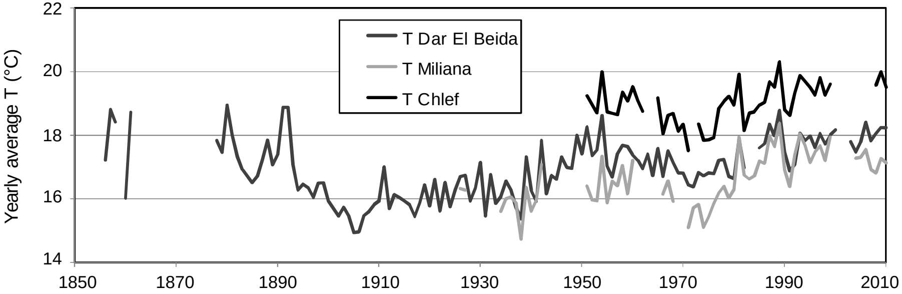

Figure 4. Interannual variations of mean yearly temperature (calculated from September to August monthly temperatures) at three stations in northern Algeria: Dar El Beida, Miliana, Chlef (from measurements of CRUTEM4 only, extrapolated values are not shown).

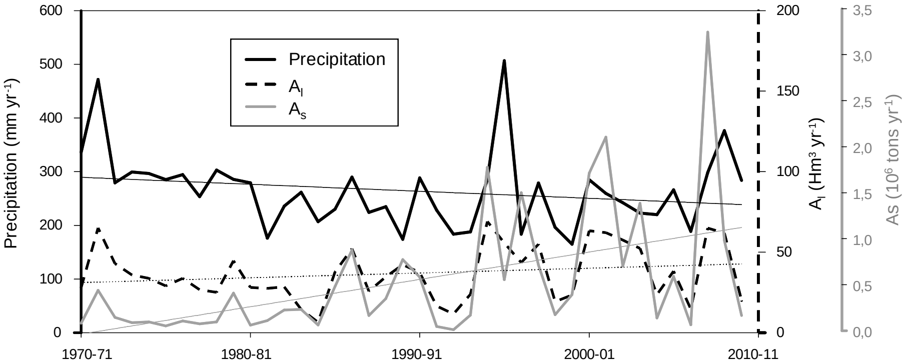

Figure 5. Interannual variations of annual precipitation, water discharge and sediment delivery at Ain Hamara station.

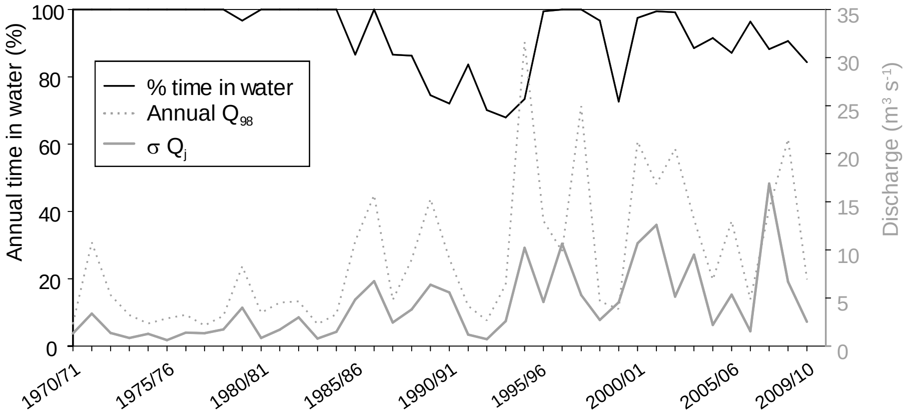

Figure 6. Variation of hydrological regime with annual % of time of running water, Q_{98} (amongst daily discharges, per year) and annual standard deviation of daily river discharge.

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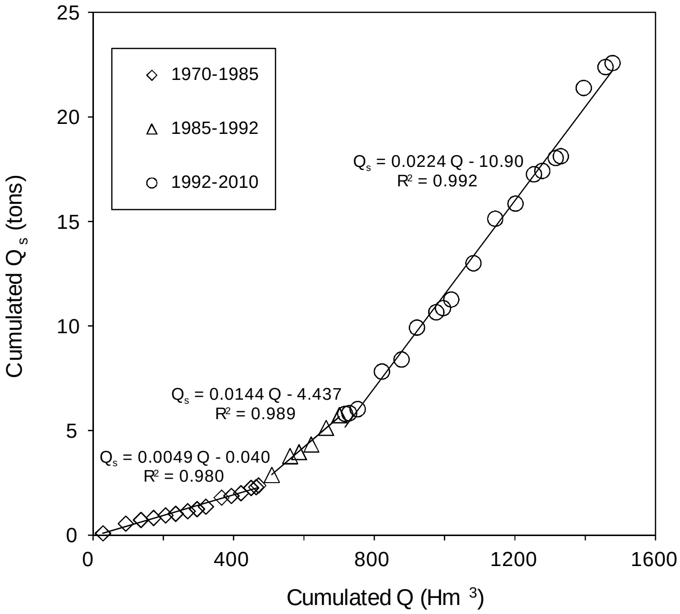

Figure 7. Double mass plot of sediment delivery vs. water flow.

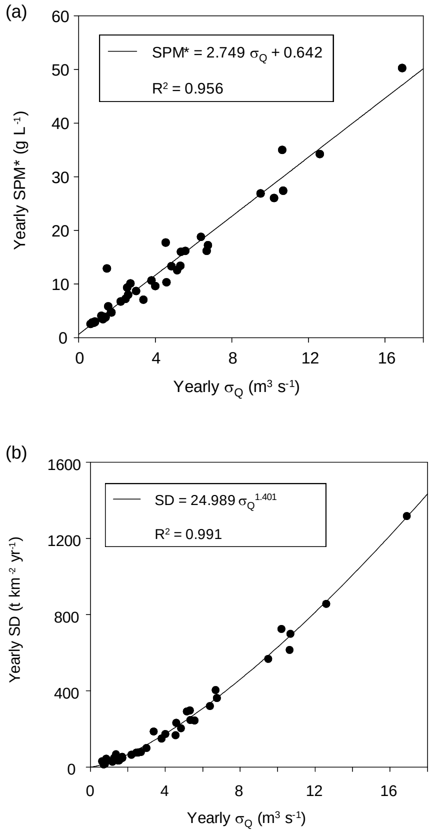

Figure 8. Yearly average of related sediment-delivery parameters vs. intra-annual variability of daily river discharge, characterized by their annual standard deviation. **(a)** SPM*, **(b)** specific degradation.

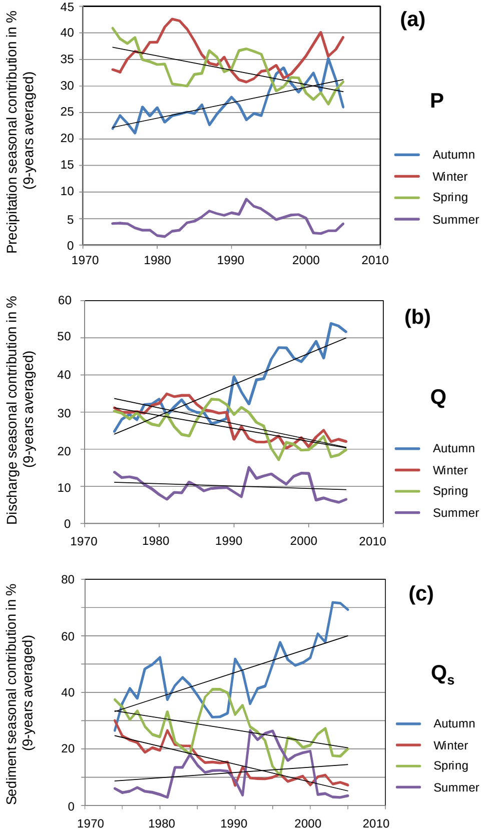

Figure 9. Trends of the seasonal indexes of precipitation **(a)**, discharge **(b)** and **(c)** sediment discharge in the Wadi Abd basin.

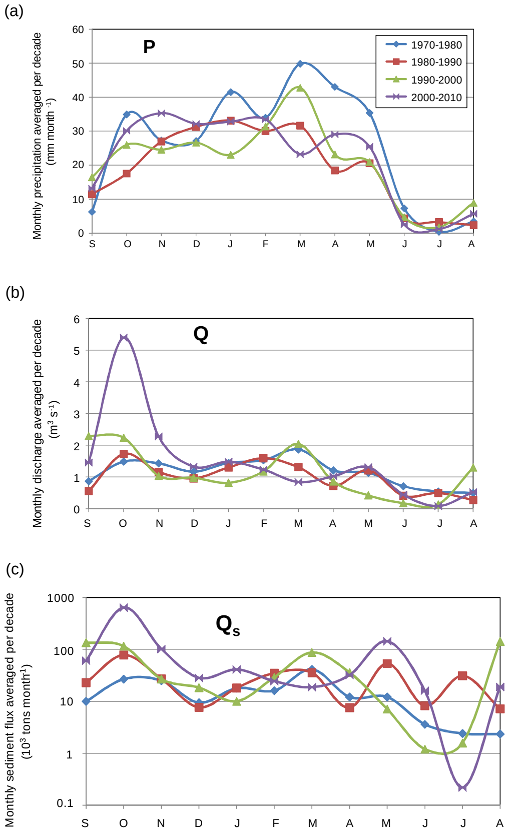

Figure 10. Monthly values of precipitation **(a)**, Q **(b)** and Q_s **(c)** averaged over decades in the Wadi Abd basin.

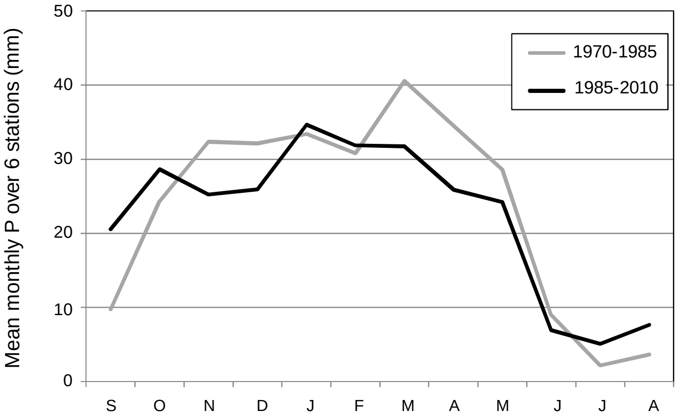

Figure 11. Monthly values of precipitation averaged over 6 stations, for the two periods 1970–1985 and 1985–2010.

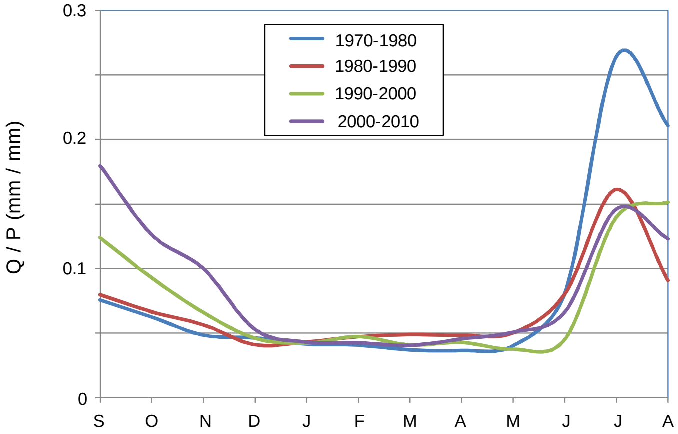

Figure 12. Monthly values of the ratio Q/P averaged over decades.

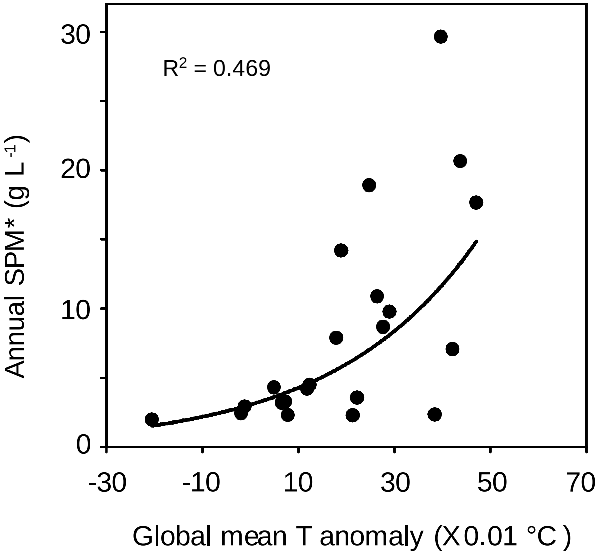

Figure 13. Variations of SPM* against the global mean temperature anomaly (from GSS).

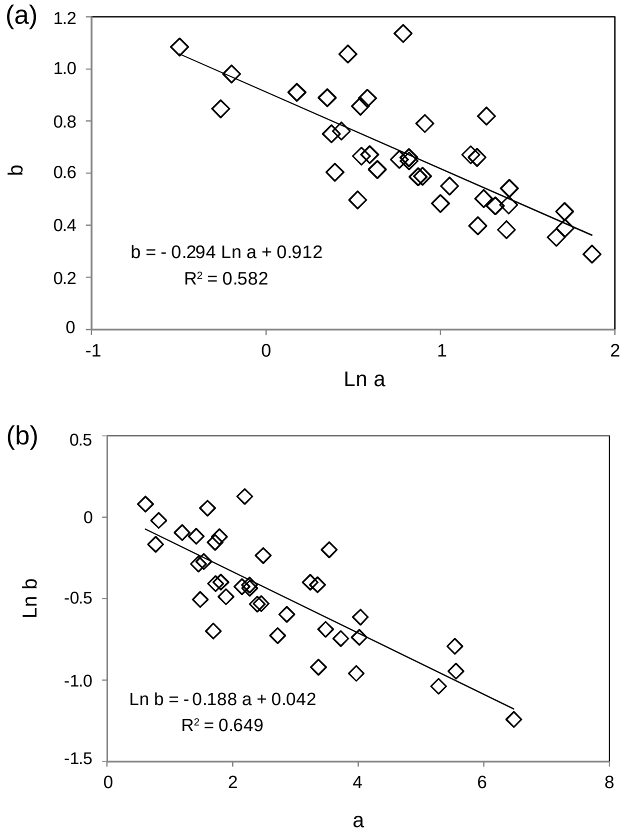

Figure 14. Relationship between yearly values of the rating curve parameters **(a, b)**.

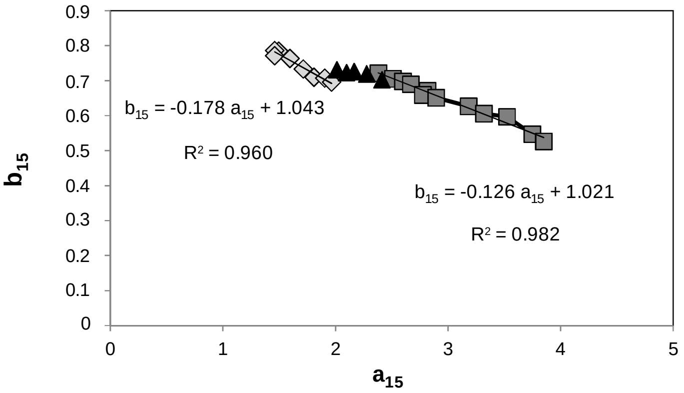

Figure 15. Relationship between the rating curves parameters averaged over 15 years.

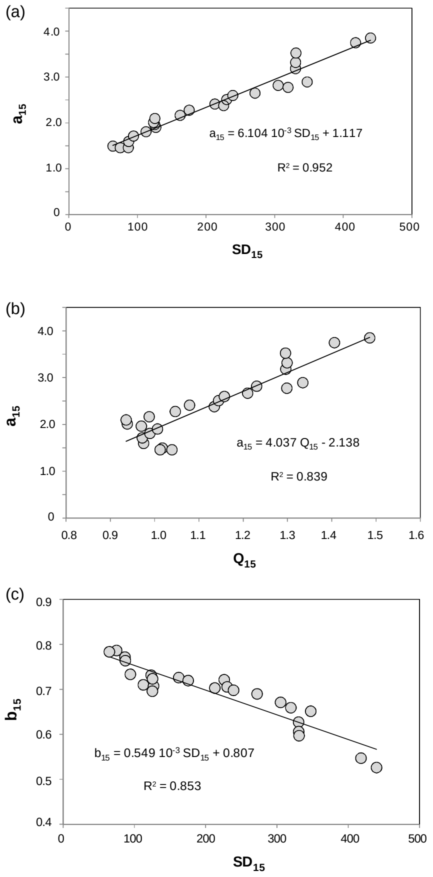

Figure 16. Relationship between the rating curve parameters averaged over 15 years and the averaged values of specific degradation or river discharge over 15 years.