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Hydro-sedimentary flow modelling in some catchments Constantine highlands, case of Wadis Soultez and Reboa (Algeria)

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Abstract

Erosion is a major phenomenon that causes damage not only to soil and agriculture, but also to the quality of the water amounting to tonnes of matter annually transported on the earth's surface. This fact has attracted the interest of researchers to understand its mechanism and explain its causes and consequences. This work is a comparative study of water erosion in the two semi-arid catchments of Wadi Soultez and Wadi Reboa; located in the North-East of Algeria. The approach adopted for the quantification of sediment transport consists on researching the best regressive model to represent the statistical relation between the sediment yield and the measured water discharge at different scales: annual, seasonal and monthly. The available data cover 27 years from 1985–2012. The results show that the power model has given the best correlation coefficient. Results have indicated that Wadi Reboa transported an average of 14.66 hm^3 of water and 0.25 million tonnes of sediments annually. While Wadi Soultez has transported 4.2 hm^3 of water and 0.11 million tonnes of sediments annually. At a seasonal scale, sediment amounts have showed significant water erosion in autumn with around 44% and secondarily in the spring with 29% in Wadi Soultez. Unlike Wadi Reboa, sediment transport represents 32% and 46% in autumn and spring respectively. Based on the obtained sediment amounts; it is found that the physical factors: such as steep reliefs, vulnerable lithological nature of rocks and poor vegetal cover, have significantly contributed in accelerating soil erosion.

Key words: *accelerating, regressive model, sediment transport, Wadi Reboa, Wadi Soultez, water discharge, water erosion*

INTRODUCTION

The sediment transport is a complex phenomenon by its intermittent nature, randomness and by its spatio-temporal discontinuity [BERGHOUT, MEDDI 2016]. It constitutes a major constraint for development by decreasing soil productivity and storage capacity of dams and by degrading state of ancillary structures.

Many river systems in the Maghreb and especially in Algerian regions continue to experience severe environmental soil erosion. This has resulted into enhanced sediment transport increase in the catchments, thereby causing a range of problems from considerable loss of soil fertility to accelerated river erosion. In the case of Wadis Soultez and Reboa, the declining catchment resources have put considerable pressure on the agricultural land and reservoir to support households.

Considering the principles of river material extraction and transported sediments by river flow in design of river structures, study of various methods to predict river sediment transport rate seems to be necessary. Various sediment transport models have been used to predict sediment loads, and the most widely used ones have been the construction of a sediment rating curve, which combines suspended sediment concentrations with water discharges (e.g. JANSSON [1997], KHANCHOUL *et al.* [2007]).

Studies conducted in the Maghreb have shown erosion varying significantly from one catchment to another; such as the work of SNOUSSI *et al.* [1990] who have evaluated, when studying the case of three wadis in Morocco, the sediment yield about 750 t·km^{-2}·yr^{-1}. SIBARI *et al.* [2001] have estimated the average annual sediment yield contribution of the Moroccan catchment of Wadi Inaouène at 2142 t·km^{-2}·yr^{-1}. BERGAOUI *et al.* [1998] have attributed a sediment yield of 318 t·km^{-2}·yr^{-1} to the micro-catchment of Tebaga, Tunisia. PROBST and AMIOTTE SUCHET [1992] have estimated the mean annual sediment yield equal to 7200 t·km^{-2}·yr^{-1} in Wadi Agrioun (Algeria) for the period 1972 to 1979. BOUROUBA [1998] has attributed a value of 113 t·km^{-2}·yr^{-1} to the High Wadi Madjerdah catchment located in the eastern part of Algeria.

Assessments of methods for estimating loads in reservoirs have been recently carried out by KHANCHOUL *et al.* [2012] and TEBBI *et al.* [2012] who have predicted sediment inflow in Mexa and Foum El Kherza reservoirs using hydrological data. The importance of the erosion phenomenon has led other researchers to focus on the estimation of sediment transport and some examples are presented in Table 1.

Table 1. Magnitude of water erosion in some Algerian catchments

Catchment	Period	*S*, km^2	*P*, mm	*SY*, t·km^{-2}·yr^{-1}	Source
Wadi Mouilah	1977–1993	2650	300.90	126.40	TERFOUS *et al.* [2001]
Wadi Mouilah	1977–1995	2650	297	165	GHENIM *et al.* [2008]
Wadi Haddad	1973–1995	470	200–379	287	ACHITE, MEDDI [2004]
Wadi Abd	1973–1995	2480	174–303	136	ACHITE, OUILLON [2007]
Wadi Soubella	1974–1989	183.5	288.50	126	ACHITE, OUILLON [2007]
Wadi Saf Saf	1976–1997	322	377.52	461	KHANCHOUL *et al.* [2007]
Wadi Kebir Ouest	1976–1997	1130	394.12	247	KHANCHOUL *et al.* [2007]
Wadi Mellah	1975–1999	550	707	562	KHANCHOUL *et al.* [2009]
Wadi Mekerra	1950–2001	1890	350–450	111	CHERIF *et al.* [2009]
Wadi El Hammam	1973–2006	8348	280	256	EL-MAHI *et al.* [2012]
Wadi Elham	1968–2006	5604	185	530	HASBAIA *et al.* [2012]

Source: own elaboration acc. to literature datas.

These examples have shown the level of erosion in the Maghreb in general; particularly in semi-arid areas where the climate tends to accelerate and amplify this phenomenon [BENBLIDIA *et al.* 2001].

This study has been conducted on the two basins of Wadi Soultez and Wadi Reboa, which are part of the semi-arid bioclimatic stage where water erosion appears more problematic. This study, which has investigated the estimation of the sediment yield, is based on the measurement data of instantaneous water discharges and suspended sediment concentrations over a period of 27 years.

The purpose of this study is to (i) develop a method for the estimation of sediment loads using relationships between suspended sediment concentrations (g·dm^{-3}) and water discharges (m^3·s^{-1}) in Wadis Soultez and Reboa, (ii) to focus on the temporal variability of sediment yield and runoff. The role of the geomorphic factors on the landscape degradation is going to be discussed.

STUDY AREA

Belonging to the catchment of Wadi Chemorah (755 km²), the two sub-catchments of Wadi Reboa and Wadi Soultez are located in the Aures region to the northeast of Algeria (Fig. 1). They spread over an area of 327 km² and 207 km² respectively. The wadis of the two sub-catchments flow into the catchment of Koudiet-Medouar Dam with the capacity of 20·10^6 m^3 regularized since 2003 [ANBT 2005].

CLIMATE

The semi-arid Mediterranean climate is wet and cold in winter and hot and dry in summer. It is characterized by very irregular precipitations that come often intense with an average interannual rainfall of 330 mm·yr^{-1} in Wadi Soultez catchment and an average of 458 mm·yr^{-1} in Wadi Reboa catchment for the period of 27 years (from 1985 to 2012). Although sporadic

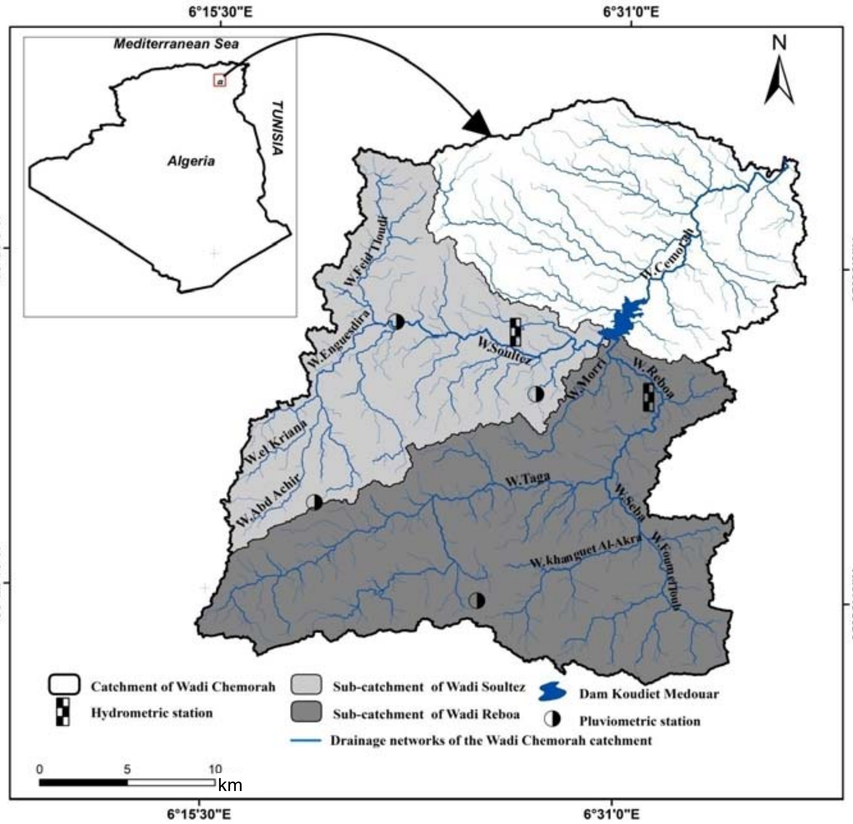


Fig. 1. Location map of Wadi Reboa and Wadi Soultez catchments; source: own elaboration

rainfall events occurred almost throughout the year, the rainy season in the area normally lasted for about four months (September to November and February). Annual temperatures in the area vary between 8.26 and 22.8°C (from 1985 to 2012) with an average of 15.6°C.

MORPHOMETRY

In the Aures region of Algeria, a series of mountains ranging long the southern boundary of Wadi Reboa catchment and reach up to 2294 m in elevation (Djebels El Mahmel and Djebels Aurés). Depression of these Mountains widens and narrows towards the north of the catchment forming a flat area with a minimum altitude of 981 m (Fig. 2). This figure has been realized by using Digital Elevation Model (DEM) at 50 m of resolution. Moreover, the Aurès Mountains form the southern boundary of Wadi Soultez catchment. These mountains can go up 1938 m in elevation (Djebel Askar). Their depression lengthens and widens from the north towards the east.

Reboa is composed with the junction of Wadi Taga; issuing from the Aures Mountains (Djebel Lizourés) running from SW towards NE and Wadi Seba which results from the confluence of two wadis: Wadi Khanguetel-Akra and Wadi Foum Toub. Wadi Reboa suddenly changes direction (sandstone rock) to the northwest where it receives Wadi Morri on its left bank and then resumes its SW–NE direction to meet Wadi Soultez after 3 km (Fig. 1).

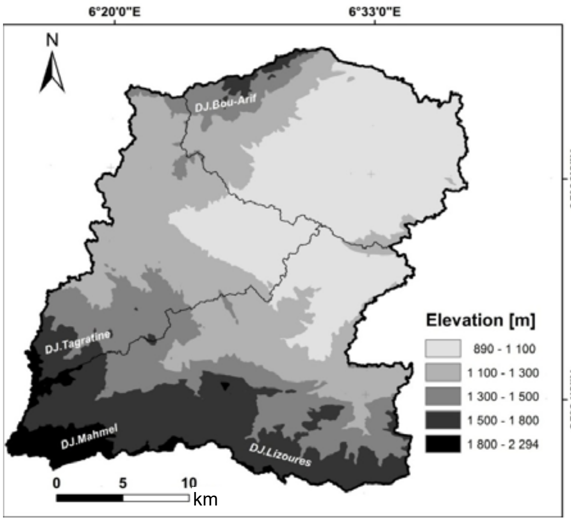


Fig. 2. Elevation map of Wadi Reboa and Wadi Soultez catchments; source: own elaboration

Wadi Soultez is also the result of two wadis junction: Feid Tloudi which originates from the northwest of Tagratine Mountain and Wadi and Enguesdira that arises from the confluence of Wadi El-Kriane and Wadi Abdel Achir that unite in the Tagratine before meeting Wadi Reboa (Fig. 1).

According to Table 2, Wadi Reboa catchment has a 2.73 km·km^{-2} drainage density which is lower especially in the mountains and high reliefs (Djebel Lizourés, Djebel Madjeba and Temagoult) where the soil is permeable. Wadi Soultez catchment's density is 2.84

Table 2. Morphometric characteristics of the study catchments

Morphometric parameters	Wadi Soultez	Wadi Reboa
Area, km^2	207	328
Perimeter, km	108	128
Minimum elevation, m	976	975
Maximum elevation, m	1 913	2 290
Average elevation, m	1 242	1 417
Drainage density, km·km^{-2}	2.84	2.73
Concentration time, h	6.50	6.00
Compactness coefficient	2.12	1.99
Talweg frequencies, km^{-2}	3.36	3.42
Orographic coefficient	1 605	1 907
Average slope, %	9.00	15.00

Source: own elaboration.

km·km^{-2}, which is higher than Wadi Reboa catchment especially at the elevations of Djebel Tgratine characterized by steep slopes. The rest of the catchment is known with smooth slopes and a less dense drainage network. Comparing the orographic coefficients of the two basins, we have noticed that Wadi Reboa's coefficient has higher reliefs with steeper slopes compared to Wadi Soultez catchment (Fig. 2).

LITHOLOGY

The lithology of the study catchments has been done using geological maps of 1:50,000 in scale. The lithological analysis of the two basins has revealed the existence of several rocks whose surface formations can be distinguished as quaternary formations which are divided in the form of polygenic glaze generating gentle slope surfaces at the plain but highly fragmented, showing gully erosion and causing pebble deposits. They are very limited in areas covered with vegetation.

The sandstone and clay of Miocene age outcrop from the center to the east of Wadi Soultez catchment and scatter towards the edges of Wadi Reboa catchment by hills of less than 1600 m high. These rocks include the reliefs of Djebel Amrane, Timagoult, Koudiat Safia el Djebel Faoun which are home to large landslides. Moreover, Cretaceous clays are found to the northeast of the two basins on the foothills along with sandstones. They form hills stretching between 1000 m to 1400 m and represent the most ploughed lands of the area. These are homes to gully erosion phenomenon.

The formations of average resistance to degradation are marl, limestone and Miocene conglomerates found at the high hills and high mountains with slopes of >25%. These rocks are found in northern Djebel Asker. For the calcareous marl of Cretaceous age, the rocks represent the major part of Djebel Lizourés reliefs.

The limestone of Eocene age outcrops on the north side of Wadi Soultez catchment and at the center of Wadi Reboa catchment at Djebel El Mahmel. These less spread formations have a mechanical disintegration and chemical weathering in producing clay soils.

Table 3. Lithology of the Wadi Soultez (BV1) and Wadi Reboa (BV2) catchments

Types	Age	BV1		BV2	
		km^2	%	km^2	%
Quaternary formation	Quaternary	115	56	110	34
Sandstone and clay	Tortonian Miocene	45	22	58	18
Clay	Tortonian Miocene	18	9	24	7
Marl, conglomerate and limestone	Tortonian Miocene	4	2	5	2
Marly limestone	Higher Cretaceous	23	11	114	35
Limestone	Lower Eocene	2	1	17	5

Source: own elaboration.

SLOPES AND VEGETATION COVER

Both slopes and vegetation cover have a significantly complex and contradictory role affecting the variation of erosion intensity. The slopes distribution obtained by the geographic information system (GIS) in the two catchments is shown in Figure 4. The use of DEM and Arcgis 10.1 have permitted the creation of the slope map; while the land use map has been realized using Google Earth Professional images at high resolution with Arcgis, aerial photographs and terrain verification.

Wadi Soultez catchment has shown a significant distribution of slopes (from 3 to 10%), which have spread over 41% of the catchment's surface; while the steep slopes (>25%) have been rare and have covered only 6%. However, Wadi Reboa catchment has much steeper slopes with values ranging between 15% and 25% and representing 30% of the total area. In addition 20% of this area is composed of high relief with slopes higher than 25%. The low slopes found in plains (0–3%) are rare and have not exceeded 8%, unlike Soultez catchment where the plain has been extended over 25% of the surface.

Table 4. Slope classes of the Wadi Soultez and Wadi Reboa catchments

Slope, %	Wadi Soultez		Wadi Reboa	
	km^2	%	km^2	%
0–3	51.85	25.04	25.71	7.84
3–10	84.33	40.76	89.50	27.29
10–15	31.42	15.17	50.67	15.45
15–25	26.65	12.87	97.34	29.67
>25	12.75	6.16	64.78	19.75

Source: own elaboration.

The predominant land use in the Wadi Soultez and Wadi Reboa catchments is for agricultural land and forests. In Soultez catchment, 50% of the catchment area is cultivated with wheat and barley (Tab. 5 and Fig. 5). More than 60% of Wadi Reboa catchment lands are agricultural and known by cereal growing and few villages are found. However, no villages are found in Wadi Soultez catchment. Forests cover 42%

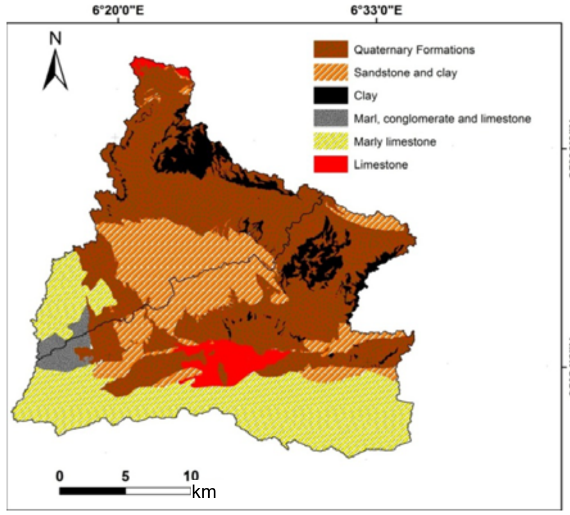


Fig. 3. Lithology map of Wadi Reboa and Wadi Soultez catchments; source: own elaboration

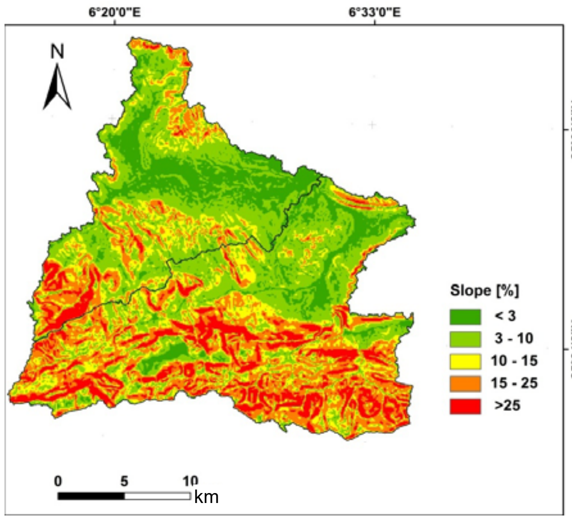


Fig. 4. Slope map of the Wadi Reboa and Wadi Soultez catchments; source: own elaboration

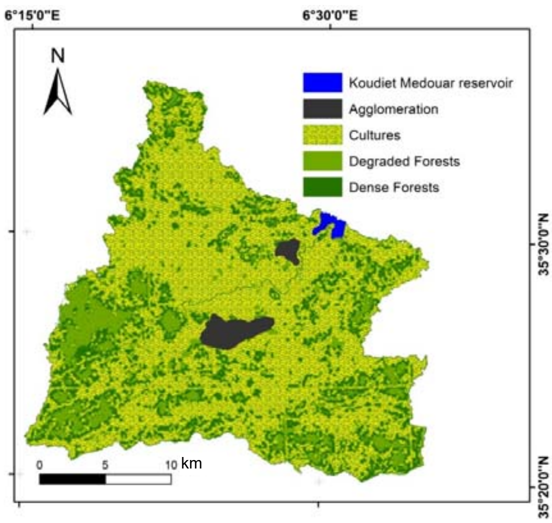


Fig. 5. Land use map of Wadi Reboa and Wadi Soultez catchments; source: own elaboration

Table 5. Distribution of the vegetation cover for the Wadi Soultez and Wadi Reboa catchments

Type	Wadi Soultez		Wadi Reboa	
	km^2	%	km^2	%
Koudiet Medouar reservoir	1.20	0.60	1.10	0.30
Agglomeration	2.50	1.20	10	3
Degraded Forests	52.30	25.30	82.90	25.30
Dense Forests	20	9.70	37	11.30
Cultures	131	63.30	197	60.10

Source: own elaboration.

of Wadi Soultez catchment (Fig. 5); they are found mainly on poorly developed soils of sandstone and marl limestone on slopes higher than 15%.

Wadi Soultez catchment area has been damaged by livestock and fires during summer season, and overgrazing has been observed in pastures and open shrub lands while in Wadi Soultez region, dense forests have been rare in the Wadi Reboa catchment because of the climatic system of the area and the frequent fires in summer. The forest areas were generally more open with bare soils exposed to erosion. This sub-catchment, similarly to the main catchment was characterized by overgrazing, degraded forest cover and undulating topography coupled with erratic and intense rainstorms.

DATA AND METHOD

The data used in this study came from the National Agency of Water Resources [KHANCHOUL 2001]. They were mainly measured in hydrometric stations used by ANRH upstream of Koudiet Medouar Dam at the hydrometric station Timgad (coordinate geographic; the longitude 6°27'29" E and the latitude 35°30'25" N) in Wadi Soultez and Reboa hydrometric station (coordinate geographic; the longitude 6°31'30" E and the latitude 35°29'43" N) in Wadi Reboa over a period of 27 years (1985–2012).

Instantaneous water discharges, estimated from the rating curve $Q = f(H)$ using the water level read on a gauging ruler with a float gage, were converted into water discharge rates. Sediment samples were taken in the edge using one-litter bottles in Wadi Soultez and Reboa according to a measurement protocol by the ANRH department.

Water samples taken in different flow conditions have been filtered in a Laurent type filter (ø = 32 cm). The sludge contained therein is weighed after drying in a special oven for 30 min at a temperature of 110°C. This method was conducted to determine the sediment concentrations in a standard procedure established in the national territory and by many world agencies [ACHITE, OUILLON 2007; KHANCHOUL *et al.* 2007].

For a better representation of the erosive dynamics of the two studied rivers, a regression analysis was performed between instantaneous sediment concentrations C ($g \cdot dm^{-3}$) and water discharge Q ($m^3 \cdot s^{-1}$). Among the trend curves used generally to represent the relationship $C = f(Q)$: (power: $y = ax^b$; exponential: $y = ae^{bx}$). In this study, we opted a power type function giving the best determination coefficient R^2 which is written as follows:

$$C = aQ^b \quad (1)$$

where: C = the measured suspended sediment concentration (g·dm^{-3}), Q = the water discharge (m^3·s^{-1}), a and b = the regression constants.

RELATIONSHIPS BETWEEN SEDIMENT CONCENTRATION AND WATER DISCHARGE

Instantaneous values for which a reasonable and representative number of samples were carried out. They have allowed a good reconstruction of sediment rating curves. Selected value pairs are shown on a log-log scale (Fig. 6).

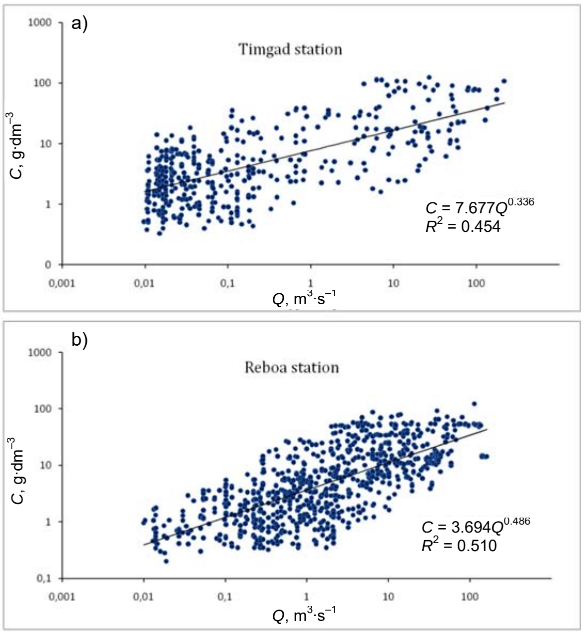


Fig. 6. Suspended sediment concentration C versus water discharge Q (1985–2012) in: a) Wadi Reboa, b) Wadi Soultez; source: own elaboration

The relationship $C = f(Q)$ was used on the basis of collected instantaneous water discharges and sediment concentrations using 427 pairs of measurements for Wadi Soultez and 812 for Wadi Reboa. The models have not shown strong coefficients of correlation (0.45–0.51). They have revealed the wide divergence between the models based on measured and estimated concentration data for both stations of Timgad and Reboa (Fig. 6). To adjust the regression relationships, the water discharge class method has been used by dividing flows into classes and calculating the arithmetic means of the concentration values (C) for each discharge class [COHN *et al.* 1992; DUAN 1983; JANSSON 1985; 1997; NEYMAN, SCOTT 1960]. The scatter plots have shown a trend with a changing of the direction of the regression line and by applying the division of datasets into two regression lines; we could have an improvement of the coefficients of correlation (R). This method was applied in Algeria by various authors such as KHANCHOUL *et al.* [2007], ACHITE and OUILLON [2007], YAHIAOUI *et al.* [2011].

However in all regression models, there was a bias responsible for the error [DUAN 1983; JANSSON 1985; 1996; NEWMAN 1960; WALLING *et al.* 1988]. To overcome this bias, MILLER [1984] has proposed a statistical technique (logarithmic retransformation) which has allowed developing a logarithmic correction factor CF, determined by the following formula:

$$CF = \exp(0.5\delta^2)\delta^2 = \frac{1}{(N-1)\sum\left(\ln C_{obs} - \ln C_{cal}\right)^2} \quad (2)$$

where: CF = correction factor, δ = standard error, N = size of the series, C_{obs} = observed concentration, C_{cal} = concentration calculated by regression.

After applying the correction coefficient, we used the equation:

$$C = CF \cdot aQ^b \quad (3)$$

The sediment discharge (Q_s) was calculated by the following equation:

$$Qs = QC \quad (4)$$

where: Q_s = sediment discharge (kg·s^{-1}), Q = water discharge (m^3·s^{-1}), C = measured suspended sediment concentration (g·dm^{-3}).

The correction factor was successfully applied in several works to improve the estimation of sediment discharge (Q_s). According to ASSELMAN [2000] the use of the power function after the logarithmic retransformation tends to underestimate the sediment load from 10% to 50%. Ferguson found an improvement of less than 10% in studies on Rhine catchment.

In most cases the relationship between concentration or load and water discharge will exhibit considerable scatter. It is difficult to isolate the precise causes of scatter on a rating plot, because of the interrelated nature of the controls and because the rating plot is essentially a univariate expression of a complex multivariate system [WALLLING 1988]. If due consideration is given to the problems associated with combining the flow record and the sediment rating curve, an indication of the inherent inaccuracy of using a sediment rating curve to summarize the sediment transport characteristics of a river could be obtained by comparing estimated loads with loads predicted. Therefore, the observed and predicted sediment discharges have been compared with the load values obtained from the continuous concentration record and errors have been expressed as a percentage of these measured values as:

$$Error = \left[\frac{\text{estim. sediment discharge value}}{\text{meas. sediment discharge value}} - 1 \right] \cdot 100\% \quad (5)$$

Then the responses of each catchment might be studied by quantifying sediment transport at an annual and seasonal scale.

CALCULATION OF SEDIMENT LOAD

Sediment load (*SL*) in the outlets of the two Wadis Soultez and Reboa was calculated by the following formula:

$$SL = \sum QCT \cdot 10^{-3} \quad (6)$$

where: SL = sediment load (t), Q = water discharge ($m^3 \cdot s^{-1}$), C = suspended sediment concentration ($g \cdot dm^{-3}$), T = the duration between concentration values, measured or computed (s).

Consequently, the computation of the sediment yield was calculated by the following formula:

$$SY = \sum \frac{SL}{A \cdot N} \quad (7)$$

where: SY = average annual sediment yield ($t \cdot km^{-2} \cdot yr^{-1}$), SL = the annual sediment load (t), A = the area of the catchment (km^2), N = the number of years.

RESULTS AND DISCUSSION

Regarding the data of the two hydrometric stations under study (Timgad and Reboa), an analysis of water discharges and sediment concentrations was performed to explain the hydro-sedimentary response on an annual and seasonal scale during three seasons, autumn, winter and spring for the period 1985–2012.

The graphs in Figure 7 and 8 have illustrated the relationships $C = f(Q)$ for annual and seasonal data.

The results of instantaneous sediment concentration – instantaneous water discharge models have been significant, where the coefficients of correlation have ranged between 0.62 and 0.83 for the Timgad catchment and between 0.70 and 0.87 in Reboa basin. The relationships have given best goodness of fit using the mean water discharge class technique. According to the water discharge class method; these regressions have given acceptable results (Tab. 6 and 7).

In Tables 6 and 7, the best regression models for the two catchments were found by considering the annual series. It was improved by using the factor correction where the calculated error has overestimated value by 4.21% and 8.80% respectively. The error rate obtained was small; it was of the same order as that obtained by JANSSON [1996]. However, the sub-series that represent the seasons (autumn, winter and spring) have given an overestimation of 14.08% and 27.80% for both Wadi Timgad and Reboa catchments respectively, and that despite the correction made using the correction factor (Tab. 6 and 7). Moreover, the fall season in Wadi Soultez might be considered as the period whose overestimation in sediment discharge was the highest with almost 42%.

ANNUAL VARIATION OF SEDIMENT LOAD

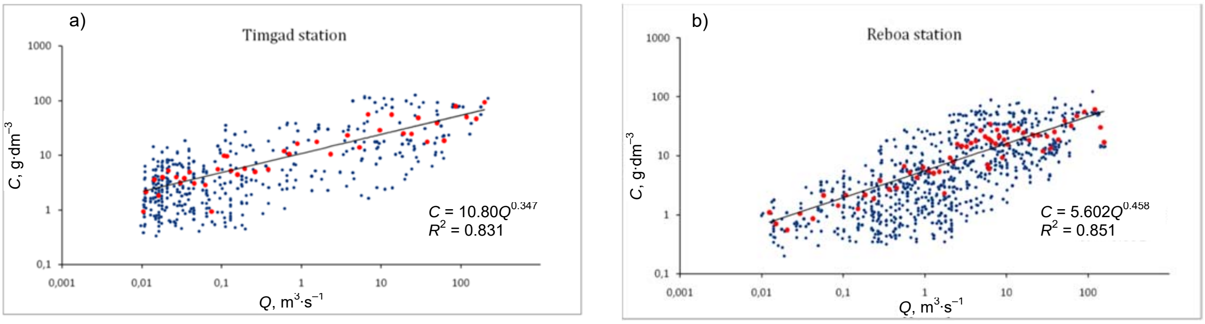
The years which were the most productive in sediments for a period of 27 years starting from 1985 to 2012 are represented in Figure 9. It has illustrated water discharge and sediment yield for both study catchments. An unequal contribution was observed during years regarding the amount of sediment yield, and the highest annual water volume and sediment load amounts have been noticed during 1989/1990, 1999/2000, 2008/2009 and 2011/2012 in Wadi Reboa catchment. These four years have contributed 57% of the total sediment load. Meanwhile, the three years of 1989/1990, 2004/2005 and 2007/2008 observed in Wadi Soultez catchment have a contribution of 48%. The results of sediment loads in both catchments have shown a discordance of sediment supply relative to years. This is due the irregularity in rainfall distribution from one basin to another.

The average annual contribution of sediments recorded in the outlet of Wadi Soultez catchment was estimated to be $114.69 \cdot 10^3$ tonnes, which corresponded to a mean annual sediment yield of 575 $t \cdot km^{-2} \cdot yr^{-1}$. This value was low compared to the value in the Wadi Reboa catchment whose amount was equal to $222.50 \cdot 10^3$ tonnes, corresponding to a mean annual sediment yield of 678 $t \cdot km^{-2} \cdot yr^{-1}$. The later basin is distinguished by a fairly higher sediment supply which is due to its specific geomorphic conditions that are favourable to accelerate soil erosion such as more extended weak rocks, rainfall and topography.

Concerning the annual variation of the sediments loads, it is seen from the graphs that both catchments present high variability or dispersion of their values. By computing the coefficient of variation (*CV*) which is the standard deviation divided by the mean, we have remarked that the Timgad catchment has the highest variation with a *CV* equal to 173% compared to the Reboa basin with a *CV* equal to 134%. Contrary to the Reboa catchment, the Timgad one has shown a deviation of the sediment loads and water volumes to the right, which means that the high sediment production has started from the year 2000. We have here the mass of the distribution is concentrated on the right of the figure; the distribution is skewed to the left.

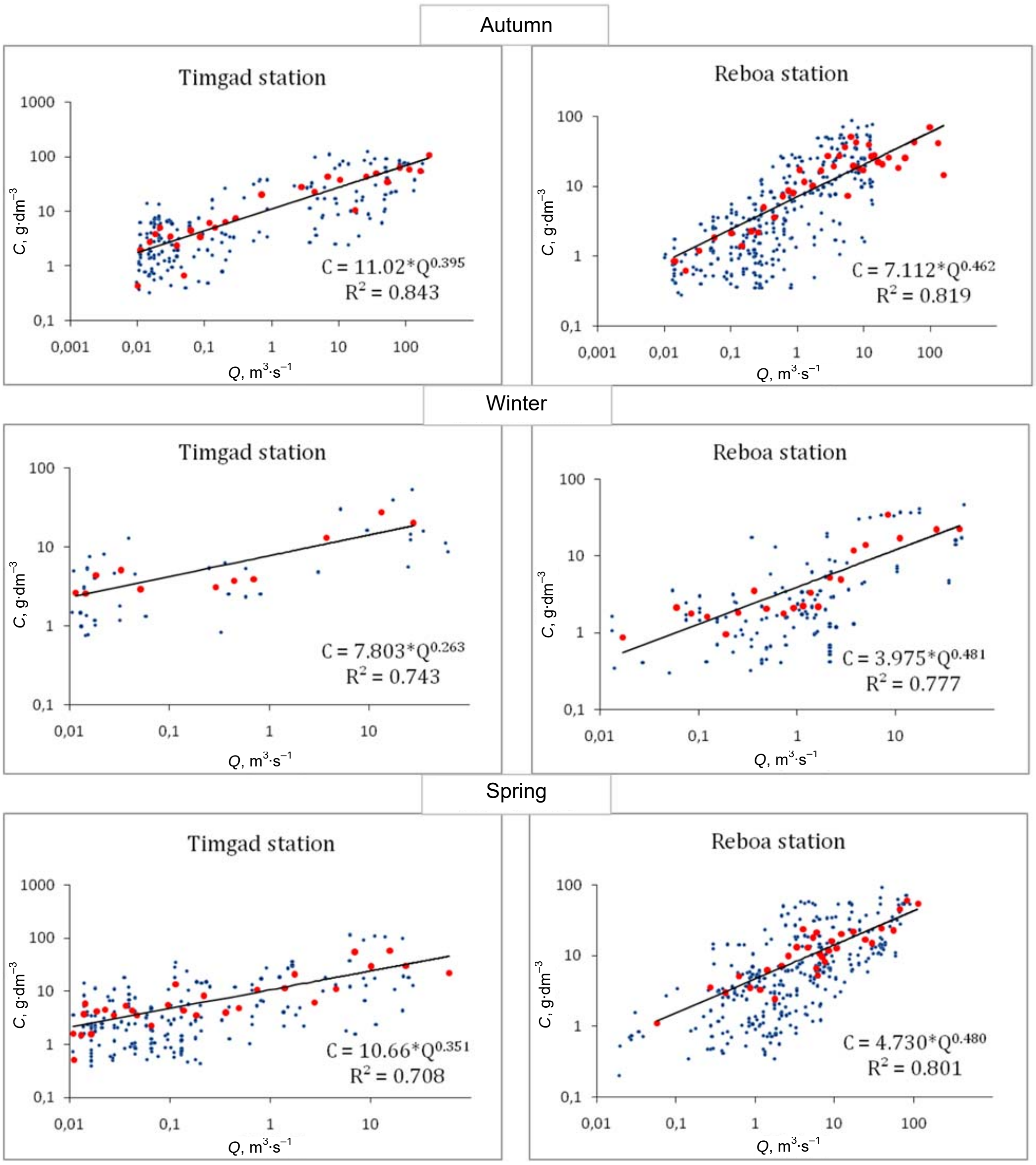
SEASONAL VARIATION OF SEDIMENT LOAD

The sediment load was noted to be highly variable from one season to another. During the study period, it was noted that the monthly values of the transported sediments in the two Wadis were very high during the autumn and spring seasons. In fact, these high monthly values were more abundant in autumn in the Wadi Reboa catchment, whose sediment load in September represented almost 32% of the annual sed-



• the pair of water discharges and sediment concentrations values before using the class method
• the pair of water discharges and sediment concentrations values after using the class method

Fig. 7. Sediment concentration versus water discharge according to water discharge classes (1985–2012) in: a) Wadi Reboa, b) Wadi Soultez; source: own study



• the pair of water discharges and sediment concentrations values before using the class method
• the pair of water discharges and sediment concentrations values after using the class method

Fig. 8. Seasonal models of sediment concentration versus water discharge according to water discharge classes (1985–2012) in wadis Reboa and Soultez; source: own study

Table 6. Seasonal models of suspended sediment concentration versus water discharge in Wadi Reboa catchment

Specification	Periods	Number of data	δ^2	*CF*	R^2	Corrected equation	Sediment discharge $kg \cdot s^{-1} \cdot 10^3$ observed	Sediment discharge $kg \cdot s^{-1} \cdot 10^3$ calculated	Error %	Total error %
All data	annual	427	–	–	0.83	$C = 10.80Q^{0.347}$	149.18	142.89	4.21	4.21
Sub-series	autumn	186	–	–	0.84	$C = 11.02Q^{0.395}$	133.09	154.29	15.93	14.08
	winter	42	–	–	0.74	$C = 7.80Q^{0.263}$	4.98	5.82	16.90	
	spring	199	0.34	1.19	0.75	$C = 10.66Q^{0.351}$	11.11	11.98	7.85	

Source: own study.

Table 7. Seasonal models of suspended sediment concentration versus water discharge in Wadi Soultez catchment

Specification	Periods	Number of data	δ^2	*CF*	R^2	Corrected equation	Sediment discharge $kg \cdot s^{-1} \cdot 10^3$ observed	Sediment discharge $kg \cdot s^{-1} \cdot 10^3$ calculated	Error %	Total error %
All data	annual	812	–	–	0.83	$C = 5.602Q^{0.458}$	243.69	265.14	8.80	8.80
Sub-series	autumn	381	–	–	0.82	$C = 7.112Q^{0.462}$	151.35	214.29	41.58	27.80
	winter	125	0.27	1.15	0.78	$C = 3.975Q^{0.481}$	9.34	10.58	13.32	
	spring	306	0.17	1.09	0.81	$C = 4.730Q^{0.480}$	83.00	87.07	4.91	

Source: own study.

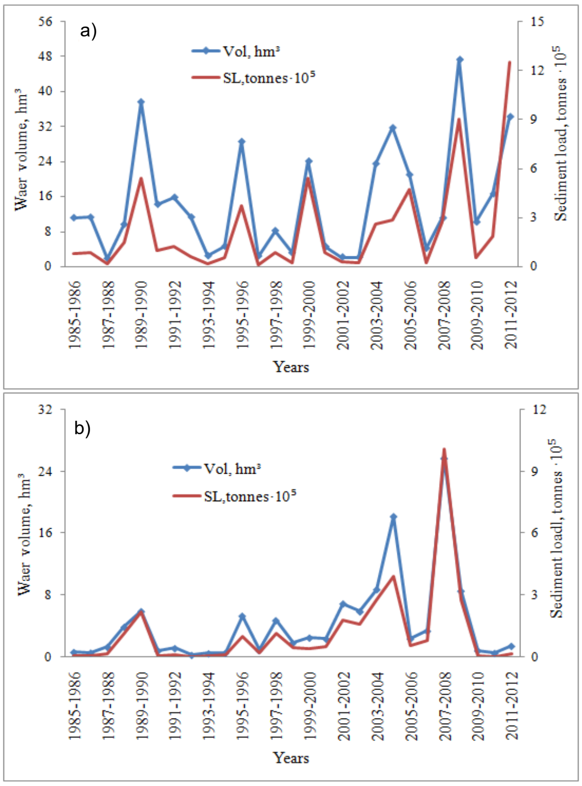


Fig. 9. Annual variation of water volumes and sediment loads in the study catchments: a) Wadi Reboa, b) Wadi Soultez; source: own study

iment load; while in the Wadi Soultez catchment 25% of the annual sediment load was found during the month of October. The floods of both catchments were mainly characterized by three types of hysteresis: simultaneous, positive and negative loops.

The autumn rainfall in semi-arid areas are often of high intensity generating higher floods than that of winter with a mean monthly runoff coefficient ranging from 10 to 20% in the Wadi Reboa catchment and from 4 to 15% in Wadi Soultez catchment.

Moreover, in September the mean sediment yield was estimated at 183 $t \cdot km^{-2}$ with a concentration of 28.71 $g \cdot dm^{-3}$ in the Wadi Soultez catchment, whereas it was at 150 $t \cdot km^{-2}$ with a concentration of 32.96 $g \cdot dm^{-3}$ in October in the Wadi Reboa catchment. This could be explained by the fact that after a long dry season (summer), the first autumn rains might meet a dry and hard soil, which could be easily eroded. Torrential rains have generated rain splash process on unprotected soils. This situation has allowed the storm events to leach the soil by ripping out large amounts of fine matters, which would be then moved in suspension by the streams. Also, runoff was very high in the Wadi Reboa catchment that occurred on more steep slopes.

In the winter season, sediment transport was lower compared to the autumn season. Nevertheless, the sediment yield remained higher in the Wadi Reboa catchment (90 $t \cdot km^{-2}$) than in the Wadi Soultez catchment with only 57 $t \cdot km^{-2}$ (Fig. 10, Tab. 8). These

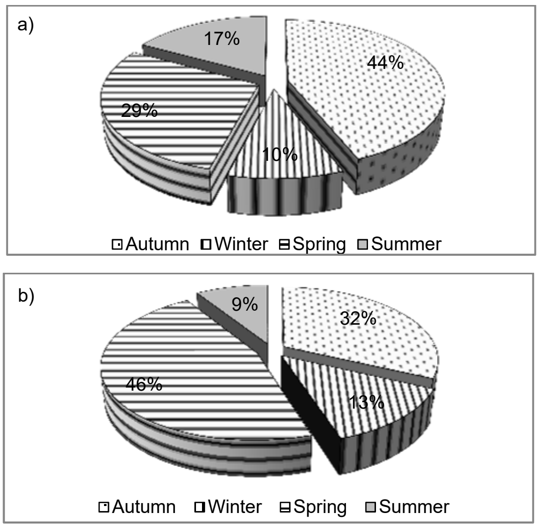


Fig. 10. Seasonal distribution of sediment yield in catchments (period from 1985 to 2012): a) Wadi Reboa, b) Wadi Soultez; source: own study

Table 8. Seasonal distribution of water volume, sediment yield and of sediment yield, runoff coefficient, mean concentration in Wadi Reboa, Reboa Hydrometric Station and Wadi Soultez, Timgad Hydrometric Station; period from 1985–1986 to 2010–2012

Catchment	Parameter	Seasons				
		autumn	winter	spring	summer	year
Wadi Reboa	runoff coefficient, %	11.49	8.38	19.14	9.74	12.19
	water volume, hm^3	2.75	2.82	6.88	1.55	14.00
	sediment yield, $t \cdot 10^5$	0.65	0.32	1.18	0.10	2.25
	mean concentration, $g \cdot dm^{-3}$	23.80	11.18	27.43	9.59	18.00
	sediment yield, $t \cdot km^{-2} \cdot yr^{-1}$	218.62	89.56	313.72	56.47	678.34
Wadi Soultez	runoff coefficient, %	9.14	4.23	6.44	5.53	6.34
	water volume, hm^3	1.69	0.82	1.25	0.63	4.39
	sediment yield, $t \cdot 10^5$	0.52	0.15	0.33	0.25	1.25
	mean concentration, $g \cdot dm^{-3}$	15.01	6.31	14.54	11.82	12.78
	sediment yield, $t \cdot km^{-2} \cdot yr^{-1}$	249.78	57.13	166.56	101.13	575.60

Source: own study.

low values are due mainly to the small amounts of rainfall in the two catchments during this season.

In the spring season, from March to May, it was observed that the mean sediment yield was 2 times higher in the Wadi Reboa catchment 314 $t \cdot km^{-2}$ than in the Wadi Soultez catchment 167 $t \cdot km^{-2}$. These high sediment values were observed mainly in May for the two catchments. Suspended sediment concentrations varied between 20 and 37 $g \cdot dm^{-3} \cdot s^{-1}$ in the first catchment and between 12 and 20 $g \cdot dm^{-3} \cdot s^{-1}$. In the Wadi Reboa catchment, high concentrations during the spring could be explained by many factors that have favoured the erosion process, such as steep slopes and poor vegetation cover like cultures. The most representative floods of this season were illustrated in the flood of 8 April 1990.

This flood was a major event in terms of sediment transport in the Wadi Reboa catchment which has occurred after the high winter flood. The total rainfall of 64 mm has produced runoff of 39 mm. The morphological impact of this flood event was certainly influenced by the saturation of the highly erodible soils poorly covered by vegetation. The high peak of water discharge (17 $m^3 \cdot s^{-1}$) obtained after seven hours and half did not coincide with the peak of the sediment concentration (42 $g \cdot dm^{-3}$). This should be a positive hysteresis where the sediment concentration peak came before the water discharge peak (Fig. 11a). There was more sediment ready to be transported by runoff over slopes or because of bank erosion. The suspended sediment load of this flood has been estimated to $22 \cdot 10^3$ tonnes. This high concentration might be produced on saturated soils giving unusual high overland flow. The nature of these soils was distinguished by loamy and clayey material that was easily eroded.

For the same flood in Wadi Soultez catchment, we noticed a decrease in the intensity and magnitude of this storm event. First of all, the rainfall and runoff were half the values compared to the Reboa basin; there were 49.20 mm and 45 mm respectively. Second, the flood was characterized by a simultaneous increase in sediment concentration and water discharge. The sediment concentration and water discharge peaks were equal to 5 $m^3 \cdot s^{-1}$ and 36 $g \cdot dm^{-3}$ (Fig. 11b). It is believed that this smaller amount sediment load of 5.76 tonnes in Wadi Soultez could be caused by less supply of sediments due to a more vegetation cover and less steep slopes and unfavourable climatic conditions.

In the summer season, the climatic conditions are unfavorable for sediment transport since rainfall are often non-existent or too low to generate a runoff able to erode and transport significant quantities of sedi-

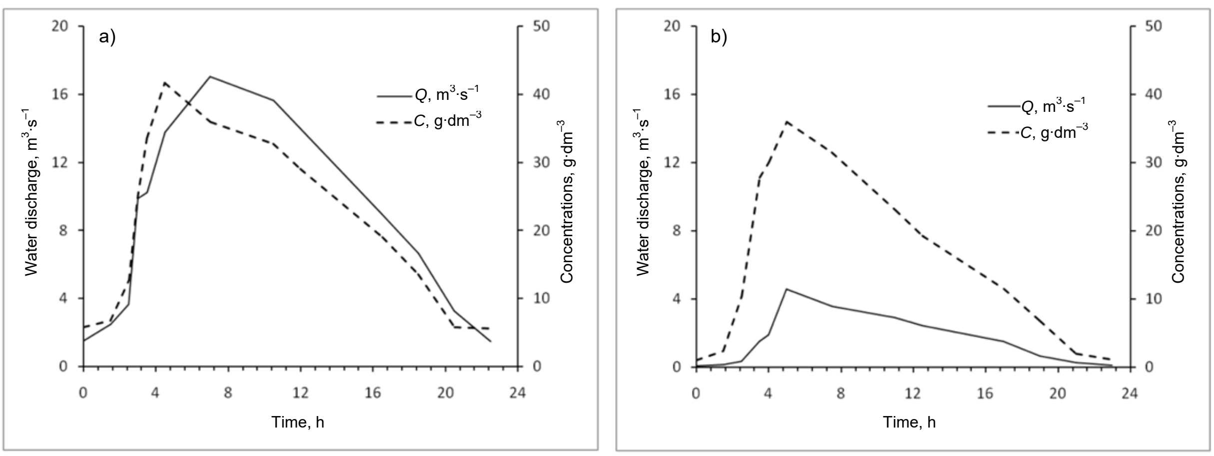


Fig. 11. Floods of 8 April 1990 in: a) Wadi Reboa catchment, b) Wadi Soultez catchment; source: own study

ments. This season was characterised by a sediment yield of 56.5 t·km^{-2} in the Wadi Soultez catchment and 101 t·km^{-2} in the Wadi Reboa basin (Tab. 8). The latter has a higher runoff coefficient of 15% in July compared to the Wadi Soultez catchment which has a coefficient of only 9%. This should be certainly related to the fact that torrential rains are less frequent in the Wadi Soultez catchment than in the Wadi Reboa one.

Overall, it should be noticed that a significant relationship might exist between the runoff coefficient and sediment yield whose topographic and lithological factors could promote soil erosion that might vary according to the presence or absence of vegetation cover and cultural practices.

CONCLUSIONS

The suspended sediment transport was calculated for Wadi Reboa with a catchment area of 328 km^2 and for Wadi Soultez with an area of 207 km^2. The valorisation of water discharge and the sediment concentration data have been made possible by the application of a power-type statistical model along with the application of the mean water discharge class technique.

The sediment rating curve method has provided a mean to estimate sediment loads in the two study catchments. The amounts of suspended sediments recorded during the period between 1985 and 2012 have been evaluated to 32·10^5 tonnes or 575 t·km^{-2}·yr^{-1} and 60·10^5 tonnes or 678 t·km^{-2}·yr^{-1} in Wadi Soultez and Wadi Reboa respectively. The difference in values is providing information on the intensity of soil erosion in each basin and therefore the disparity has resulted mainly from the geomorphic conditions such as lithology, slopes and vegetation cover.

Interannual variability is even more intensely influenced by the hydroclimatic parameters, which involves a higher suspended sediment transport, due to the high rainfall intensities in autumn and spring which can generate heavy floods. The Wadi Reboa catchment is characterized by more aggressive flow conditions.

During the 27-years study period, four years contributed to 57% of the sediment transport in the Wadi Reboa catchment. On the contrary, the contribution in sediment production in the Wadi Soultez catchment was a little inferior; it was only 48% in four years.

Suspended sediment yield was highest in the fall and spring seasons. The differences in erosion between the two catchments were especially more or less great during the spring. During the high magnitude of storm events in both previous seasons, the basins have highly peaked discharge and concentration graphs with a slight advantage for the Reboa basin, which implies surface runoff with high erosion because of extended cultivated overgrazing areas on slopes greater than 10% on clayey soils.

Hopefully, these finding will help soil conservationists in these two basins to prevent the risk of sedimentation in the Koudiet Medouar reservoir.

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Modelowanie hydrologicznego przepływu i transportu osadu w wybranych zlewniach wyżyny Konstantyny, przykład epizodycznych rzek Soultez i Reboa (Algieria)

STRESZCZENIE

Erozja jest głównym czynnikiem, który nie tylko przynosi szkody w rolnictwie (ubytki gleb), ale także obniża jakość wód powierzchniowych wskutek transportu wielkiej ilości materii niesionych rocznie w skali całego świata. Zjawisko to przykuwało uwagę badaczy, którzy pragnęli poznać mechanizm erozji oraz jej przyczyny i skutki. Przedstawiona praca jest porównawczym studium erozji wodnej półpustynnych zlewni dwóch epizodycznych rzek – Soultez i Reboa w północnowschodniej Algierii. Podejście do ilościowego ujęcia transportu osadów polegało na znalezieniu najlepszego modelu regresji między transportem osadu a mierzonym odpływem wody w skali rocznej, sezonowej i miesięcznej. Dostępne dane obejmują 27 lat – od 1985 do 2012. Najlepszy współczynnik korelacji uzyskano, stosując model potęgowy. Wyniki wskazują, że Reboa transportowała średnio 14,66 hm^3 wody i 0,25 mln t osadu rocznie, podczas gdy transport rzeki Soultez wynosił 4,2 hm^3 wody i 0,11 mln t osadu rocznie. W ciągu roku największe ilości osadu rzeka Soultez transportowała jesienią (44%) i wiosną (29%), natomiast największy transport osadu w rzece Reboa odnotowano wiosną (46%), a mniejszy jesienią (32%). Na podstawie uzyskanych danych o transporcie osadów stwierdzono, że czynniki fizyczne, takie jak głęboka rzeźba terenu, litologiczny charakter skał podatnych na erozję i uboga pokrywa roślinna przyczyniają się znacząco do zwiększonej erozji gleb.

Słowa kluczowe: *erozja wodna, model regresji, natężenie przepływu, odpływ wody, rzeka Reboa, rzeka Soultez, transport osadów*