

## ANALYSIS OF HYDRO-SEDIMENTARY PROCESSES IN THE EL-MALAH EAST RIVER BASIN UPSTREAM OF THE BENI SLIMANE GAUGING STATION (N ALGERIA)

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### ABSTRACT

Predicting suspended sediment load is essential to identify its intensity and define necessary actions for its reduction. Mathematical models simulating suspended sediment load are an interesting tool for this purpose. The methodological approach adopted in this article consists in looking for a regressive model that can better explain the suspended sediment discharge through flow discharge by studying this relationship at different temporal scales. The work comprises analyzing and quantifying the suspended sediment intakes conveyed by the El-Malah East river at the Beni Slimane gauging station towards the Koudiat Acerdoune reservoir. The available data covers the period from 1973/74 to 1988/1989 for instantaneous measurements of liquid flow discharge  $Q_l$  – Suspended sediment concentration  $C$  and the period from 1985/86 to 1996/97 for daily mean flow discharges and daily mean precipitations. Only power relations obtained on a seasonal scale giving the best coefficient of determination have been selected for the quantification of suspended sediment load conveyed by El-Malah river at Beni Slimane hydrometric station in the period of availability of daily mean flow discharges (1985/86 to 1996/97). The optimization of suspended sediment rating curves has been validated by comparison of the estimated values with the observed data and by fitting Normal distribution to residues datasets. The use of these models has highlighted an intra-annual distribution of the suspended sediment contributions conveyed by the El-Malah East river at Beni Slimane hydrometric station estimated at 0.088 Mt per year, representing a specific degradation of about 325 t.km-2y-1 (423 t.km-2y-1 of suspended and bed loads). The results have also shown that the highest liquid intake occurs in spring (45.72 %), winter (32.36 %) and autumn (11.93 %) seasons. This distribution, as well as the distribution of the monthly rainfalls, allowed the conclusion that the runoff period does not always correspond to the rainy period. The highest precipitation occurs in winter (38.74 %), spring (32.25 %) and autumn (21.53 %) seasons. The intra-annual distribution of suspended sediment contributions showed that winter and autumn participate in each one with 28.31 and 27.03% of the total suspended sediment load annually, while summer and spring participate with 23.28 and 21.38 %, respectively. The obtained results can be verified and improved by increasing the size of the available series. They provide appreciable elements of comparison for others basins of the same order, located in semi-arid and arid regions and subjected to similar phenomena. They also allow river basin managers and policymakers to consider necessary actions to fight against land erosion, preserve human activities, increase the life of the Koudiet Acerdoune dam 60 km downstream from the watershed outlet, facilitate decision-making and planning, and ensure effective management.

**Keywords:** Rating curve; Regression; Residues; Surface degradation; Surface runoff; Suspended sediment load.

## 1 INTRODUCTION

Water has currently become a rare and precious commodity less and less accessible in several regions of the world, and water reserves have continued to decline for the last fifty years, especially in arid and semi-arid countries where drinking water, industry, and irrigation can only be provided by storing the surface flow [1].

Water resources are in free fall and seriously threatened by soil degradation and continuous dam siltation while demand increases dramatically. In many countries of the world, sediment transport in hydrographic networks of watersheds and their deposition in the reservoirs pose severe problems and damages for management, flood control, hydropower production, and downstream river morphology [2–6], whose resolution is complex and very expensive. Not only the useful capacity is gradually reduced as the sediments are deposited in the reservoir but also the removal of sediment is a delicate and difficult operation, very often requiring the dam to be out of service, which is practically impossible in arid and semi-arid countries. In both cases, significant environmental damages are generated, and serious threats to the project economy are caused [7].

Although soil erosion by rain and runoff is a natural phenomenon widespread in different countries of the world, it is considered a serious environmental issue. It continues to take considerable proportions, in particular on slopes, because of the torrentiality of rains, the high vulnerability of lands (tender rocks, fragile soils, steep slopes and often degraded vegetation cover), and the unfavourable impact of agricultural activities.

In Africa, it is estimated that 500Mha (million hectares) have undergone degradation since 1950, relating to 65 % of the agricultural land in the region. Land degradation concerns some 300 Mha in Latin America, 95 Mha in North America and 157 Mha in Europe [8]. In recent years, losses in cultivable land have increased until reaching 7 to 10Mha per year, mainly due to erosion. At this rate, it would take three centuries to destroy all cultivable land [9].

In Algeria, water erosion threatens 45 % of Tellian areas [10]. Erosion manifests itself by forming channels and gullies throughout the watershed with the outcrop of the mother rock and evolution into badlands [11]. The intensity of water erosion varies from one area to another. The western part of the country is the most eroded, followed by the centre and the East. Algeria is, therefore, one of the most threatened countries in the world by erosion, solid transport and dam siltation. We estimate practically more than 20 Mha of the land is affected by erosion, particularly in mountainous areas where more than 90 % of dams are located [12].

Erosion, solid transport, and siltation of dams are, therefore, serious environmental problems worldwide. However, they are much more worrying in some regions of the world, such as in the Maghreb and particularly in Algeria [13] where a laudable effort has been undertaken since 1945 to fight against erosion, practised until 1990, but often with failures. We can cite the example of the benches made during the colonial period and after independence on more than 66,000 hectares of cultivated land, precisely on marl and clays, which are currently in advanced degradation. The reforestation of 800,000 hectares (green dam) and 350,000 hectares, arranged in benches between 1962 and 1973, did not improve the situation [14]. Since 1978, the construction of benches has been suspended due to criticisms of researchers, rejection of peasants, and especially economic difficulties.

Despite decades of anti-erosive control, the soils continue to deteriorate, and the dams are filled with sediments. The nature and morphology of sloping terrain, the fragility of vegetation cover, the lack of afforestation, and the upstream dam urbanization generate strong erosion that reduces the storage capacity of dams from 0.5 to 1 % each year [15, 16], following the siltation, due to the transport and deposit of sediments by the surface runoff. Before new dam projects were accounted for, researchers estimated that more than a quarter of the global reservoir storage capacity would be lost by 2050 [17, 18]. This capacity loss in our existing reservoirs threatens the sustainability of global water supplies as the demand for water storage increases and the availability of feasible and economically justifiable sites for new reservoirs decreases [6].

The severity of the phenomenon incites water managers to provide more effort and actions against erosion and solid transport and challenges many researchers all over the world to be interested in it, to understand its mechanism and to quantify the transported quantities.

Several sediment load estimation methods have been used. One of these methods, widely used when the measurements are rare or non-existent, uses empirical models. They are referred to as solid transport rating curves and are generally based on the power relationship linking the suspended sediment concentration to liquid

flow [19–27]. The work consists of i) analysing data of suspended sediment concentrations measured on the El-Malah East river at the Beni Slimane gauging station (Algeria); ii) highlighting relationships between suspended sediment concentrations (or sediment discharges) and liquid flows; iii) identifying interannual, intraannual and seasonal variations of suspended sediment contributions, conveyed by the El-Malah East river at the Beni Slimane hydrometric station during the period of availability of daily mean flow discharges (1985/86 at 1996/97,  $365 \times 12$ ; continuously without any gap); and iv) determining the interannual and intraannual variations of surface degradation of the basin and analysing the intraannual distribution of rainfall, surface runoff, and suspended sediment intakes conveyed by the El-Malah East river at the Beni Slimane station.

## 2 REGION STUDY

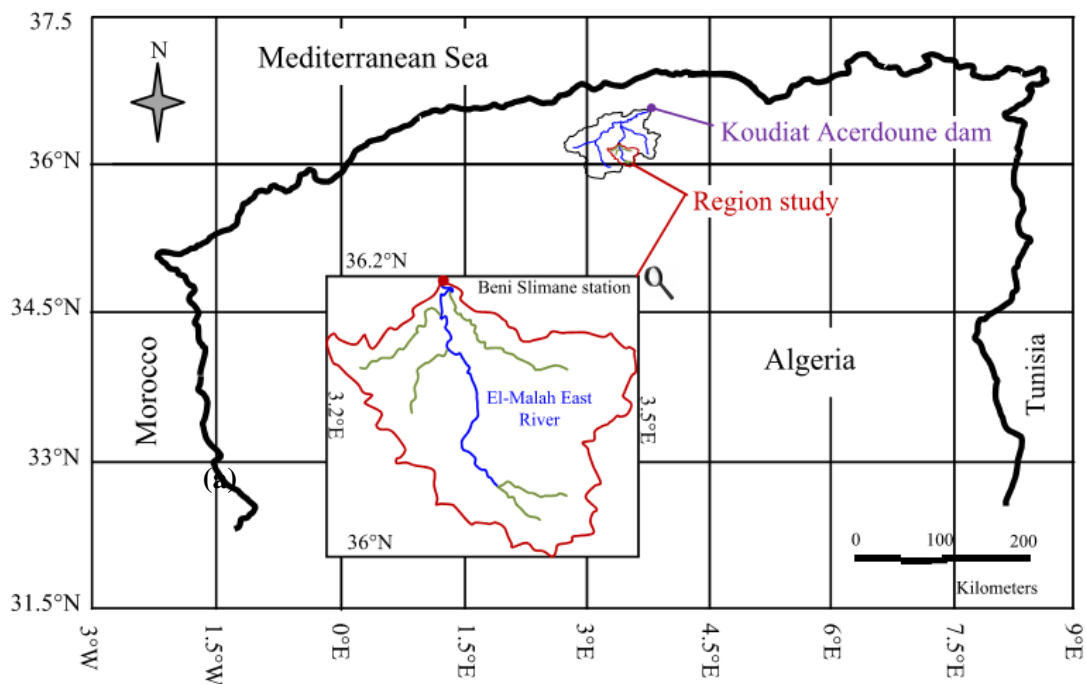
The research is focused on the El-Malah East river basin upstream of Beni Slimane gauging station in northern Algeria at about 120 km from Algiers between  $3.20^\circ$  and  $3.50^\circ$  E and between  $36^\circ$  and  $36.20^\circ$  N (Figures 1a and 1b). The El-Malah East river watershed is a part of the large Isser basin that overlaps on three Wilayas (Media, Bouira and Boumerdes) and drains an area of 2785 km<sup>2</sup> at the Koudiat Acerdoune dam. The watershed of the El-Malah East river drains at Beni Slimane gauging station, an area of 273 km<sup>2</sup> within a perimeter of 71 km. The El-Malah East river is one of the main tributaries of Wadi Isser (Isser river), travelling a distance of about 26 Km between the continental divide and the Beni Slimane station with a SE-NW direction. The National Agency of Water Resources (NAWR) of Algiers operates several pluviometric stations with a daily survey in the El-Malah East river basin and its surroundings, many of which have been in service for only a few years. Only five of them operate by presenting a long and common period (1986/1986 to 1996/1997).

The basin is characterized by altitudes ranging from 600 to 1371 m with an average altitude of 940m, an overall slope index of 31.86 m/km and a specific elevation (overall slope  $\times$  square root of square root the surface) of 526 m, emphasizing an accidental relief that can be qualified as strong according to the Orstom classification [28]. The El-Malah East river, whose average slope is 29.654 m/km, forms a fairly dense hydrographic network; the drainage density and the torrentiality coefficient (number of the river/surface of the basin) are 2.4 km. km<sup>-2</sup> and 17.5 km<sup>-2</sup>, respectively.

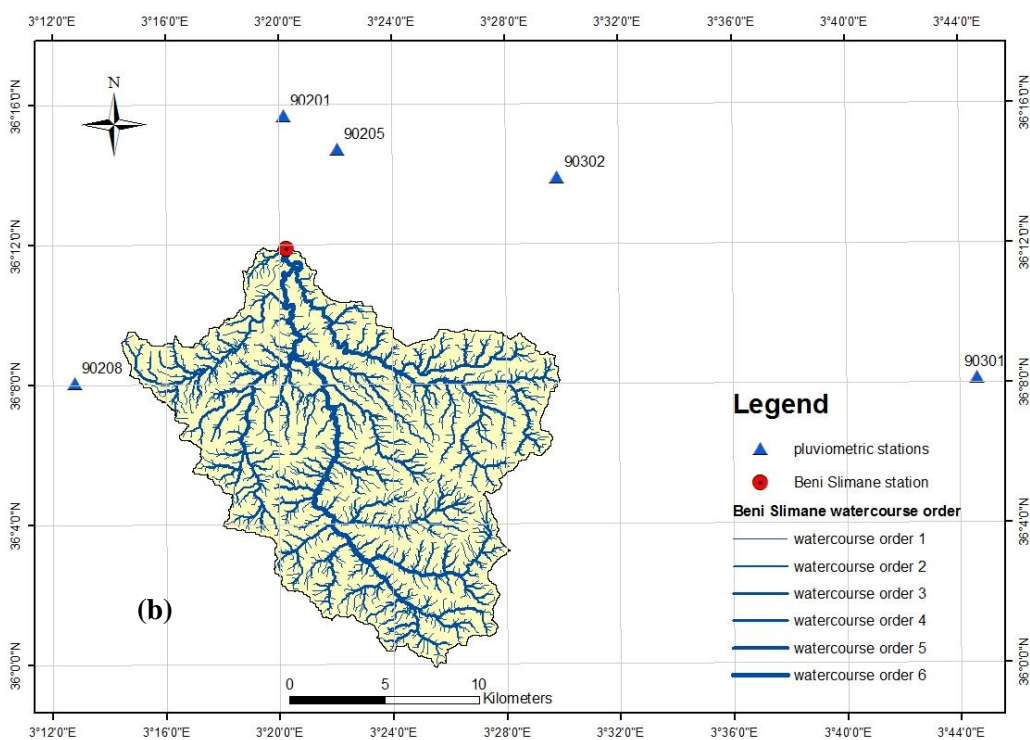
Slopes less than 12 % represent 29.62 % of the total basin's area, distributed in the centre area. Slopes ranging from 12 to 23 %, 23 to 34 %, and 34 to 49 % represent 36.71 %, 21.18 % and 10.26 % of the basin's total area, respectively. Steep slopes greater than 49 % represent a minority of the overall basin's slopes, estimated at 2.23 % and occupy mainly the marl and marl-limestone portion located to the north of the basin (Figure 1c). For the El-Malah East river watershed, the average slope is around 53 m/km, which promotes surface flow and, therefore, erosion and solid transport. The morphometric characteristics of the El-Malah East river basin at the Beni Slimane hydrometric station are given in Table 1.

From a geological point of view, the watershed is made up of marly and marly-limestone formations belonging to the lower, medium and upper Cretaceous; approximately 57 % of shale with limestone (in the south and the centre of the basin), 27 % of schist with sandstone (in the north of the basin), 13 % of red sandstone and conglomerates (in the centre and east of the basin) and 3 % of limestone (in the southern end of the basin). The watershed is also characterized by a degraded vegetation cover promoting surface flow and solid transport.

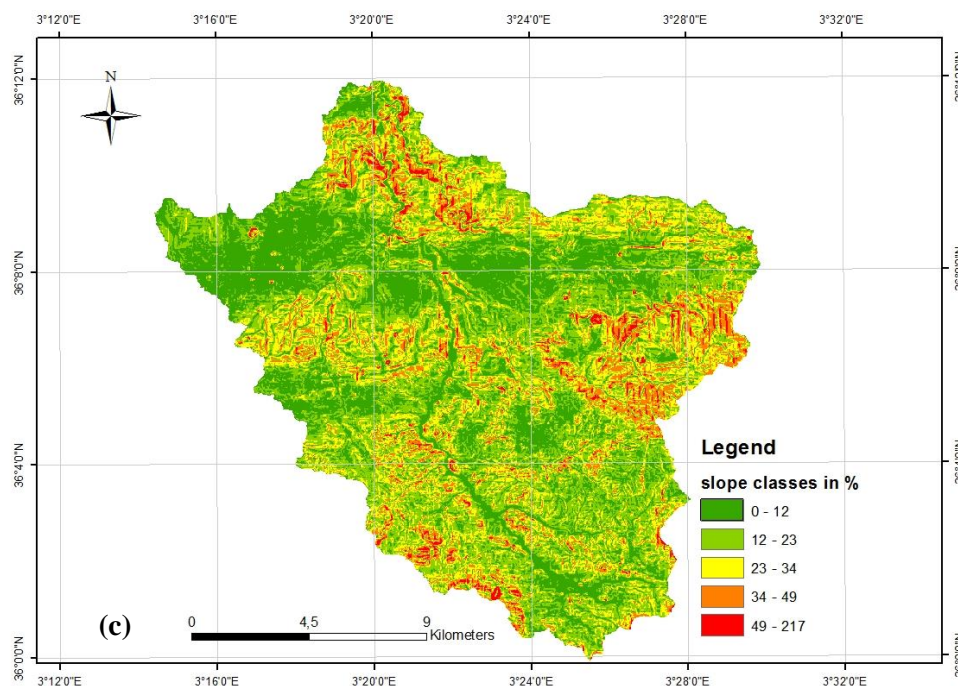
The climate over the watershed is Mediterranean semi-arid to arid, characterized by dry and hot summers and cold and humid winters. The rainfall regime is very irregular, and the basin receives between 271 and 526 mm with an annual average of 392 mm. The hydrological regime of the El-Malah East river depends essentially on the rainfall regime and is characterized by a great temporal variability illustrated by remarkable values of the coefficient of variation CV (0.71 for the annual mean discharges and 0.42 for the annual maximum discharges). The annual distribution of rainfall (CV = 0.21) and surface runoff elevation "effective rainfall" (CV = 0.71) in the El-Malah East river basin indicates that the liquid flows do not always evolve in the same way as the rains (Figure 2).



**Figure 1a.** Geographical location of the El-Malah East river basin



**Figure 1b.** Hydrological network of the El-Malah East river basin

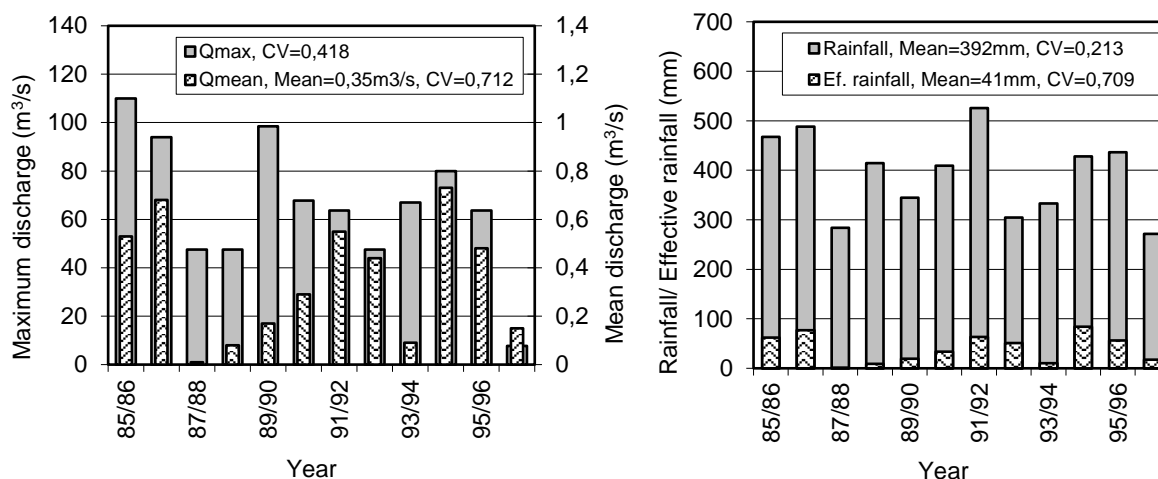


**Figure 1c.** Slopes of the El-Malah East river basin

Two climatic periods characterize the hydrological year of the study region: a period corresponding to the dry months: June, July and August (29 mm = 7.47 %) and another from September to May, corresponding to the rainiest months of the year (85 mm = 21.53% in autumn, 152 mm = 38.74% in winter and 126 mm = 32.25 % in spring). The annual average flow rate conveyed by El-Malah Est river during the period (1985/86 to 1996/97) at Beni Slimane hydrometric station is  $0.00128\text{m}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$ .

**Table 1.** Characteristics of the El-Malah East river watershed at the Beni Slimane gauging station

Characteristics	Parameters	Unit	Symbol	Value
Lambert coordinates of Beni Slimane gauging station	Abscissa	km	X	557.54
	Ordinate	km	Y	322.248
	Altitude	m	Z	600.00
Morphology of the watershed	Area of the watershed	$\text{km}^2$	A	273
	Perimeter of the watershed	km	$P_r$	71
	Index of compactness	-	Kc	1.20
	length of the equivalent rectangle	km	$L_{re}$	24.20
	Width of the equivalent rectangle	km	$l_{re}$	11.3
Relief	Maximum altitude	m	$H_{max}$	1371
	Minimum altitude	m	$H_{min}$	600
	Average altitude	m	$H_{moy}$	940
	Global slope index	m/km	$I_g$	31.86
	Average slope	m/km	$I_m$	53
Water system	Length of the main river	km	$L_{mr}$	26
	Slope of the main river	m/km	$I_{mr}$	29.65
	Drainage density	$\text{km}/\text{km}^2$	$D_d$	2.40
	Torrentiality coefficient	$\text{km}^{-2}$	$C_t$	17.5
	Time of concentration	h	$T_c$	7.12



**Figure 2.** Pluviometric and hydrometric regimes in the El-Malah East river basin (1985/86 to 1996/97)

### 3 METHODS AND MATERIALS

The available database is made up of the daily mean flow discharges and instantaneous measurements of both flow discharge and suspended sediment concentration ( $QI, C$ )<sub>inst</sub> collected on the El-Malah Est river at the Beni Slimane hydrometric station by the National Agency of Water Resources (NAWR) of Algiers. It is also made up of daily mean precipitations (mm) collected at the five rainfall stations shown in Figure 1b. The instantaneous measurements of flow discharges and suspended sediment concentrations cover the period 1973/74–1988/89, i.e. 16 years. The daily mean flow discharges and the daily mean precipitations cover the period 1985/86–1996/97), i.e. 12 years. The choice of this period was guided by data requirements linked to the hydrometric station stopped in 1997.

The traditional method of the flow discharge measurements is based on using the regularly controlled and updated rating curve that makes it possible to transform the water heights in cm, read on a limnometric scale, into liquid flows in m<sup>3</sup>/s. For concentration, for each reading of water height, a sample of turbid water is taken from a single point (unique punctual sampling) on the shore on the surface of the Wadi by means of a 50 cl bottle. The filtered sediments on filter paper (0.45 μm) are then dried in the oven for 24 hours at a temperature of 105 °C. Brought back to the volume unit (1 liter), this charge is attributed to the suspended sediment concentration conveyed by the river in (g/l).

The suspended sediment concentration  $C$  and the liquid flow  $QI$  are generally linked by a power relationship [19, 29, 30, 31, 21, 32, 24, 33, 25, 34, 26]:

$$C = aQI^{b-1} \quad (1)$$

An empirical relationship, commonly known as the sediment rating curve, links the solid flow  $Qs$  to liquid flow  $QI$ :

$$Qs = aQI^b \quad (2)$$

where  $a$  and  $b$  are parameters representing the basin characteristics and are generally estimated by linear regression of the variables transformed into log.

It has been shown that the linear regression of the variables transformed into log can considerably reduce the statistical bias introduced into the calculation [35]. Also, an interesting prediction of the suspended sediment load can be extracted from this method of linking sediment discharges and their water discharges.

The approach consists in looking for a regressive power relationship that may better explain the suspended sediment discharge as a power function of the flow discharge collected at the Beni Slimane hydrometric station by subdividing the data set into interannual, annual, monthly and seasonal groups and by determining whether or not the coefficient of determination ( $R^2$ ) approached one.

Optimization of suspended sediment rating curves is validated by comparing the predicted against the observed values on scatter plots by comparing the efficiency factors ( $R^2$ ) of the observed and the predicted values and by fitting Normal distribution to residues data sets.

The best model is then selected based on the efficiency factor value approaching one and on the higher the fitting Normal distribution to residues data sets. A probability plot correlation test, based on the efficiency factor between the observed and the theoretical residues, can be employed to check the goodness of fit of this probability distribution.

The model efficiency factor between the predicted and the observed suspended sediment discharges is estimated, for all the validation sets, using the equation:

$$R^2 = 1 - \frac{\sum_{i=1}^n (\ln Q_{s_i} - \ln \hat{Q}_{s_i})^2}{\sum_{i=1}^n (\ln Q_{s_i} - \overline{\ln Q_s})^2} \quad (3)$$

where  $n$  is the total number of observations,  $Q_{s_i}$  the  $i^{\text{th}}$  observed value of suspended sediment discharge,  $\overline{\ln Q_s}$  is the mean of the observed values,  $\ln \hat{Q}_{s_i}$  is the  $i^{\text{th}}$  predicted value and  $\varepsilon_i = (\ln Q_{s_i} - \overline{\ln Q_s})$  is the observed residues.

The optimization of the suspended sediment rating curves can be validated by comparison between the estimated and the observed values of suspended sediment discharge and by fitting theoretical Normal distribution to residues data. More elaborate tests such as probability plot correlation PPC (coefficient of determination) and Kolmogorov-Smirnov K-S can be employed to check the goodness of fit of this probability distribution to the obtained residues data.

The model efficiency factor, between the observed  $\varepsilon_i$  and the Normal theoretical  $\hat{\varepsilon}_i$  residues is estimated using the equation:

$$R^2 = 1 - \frac{\sum_{i=1}^n (\varepsilon_i - \hat{\varepsilon}_i)^2}{\sum_{i=1}^n (\varepsilon_i - \bar{\varepsilon})^2} \quad (4)$$

where  $\bar{\varepsilon}$  is the mean of observed residues.

The Kolmogorov-Smirnov test compares the cumulative observed frequency distribution of residues  $F_0(x)$  with the Normal theoretical distribution of the sample  $F(x)$ :

$$D_{max} = |F(x_i) - F_0(x_i)| \quad (5)$$

The K-S maximum distance between the two cumulative distributions must always be lower than the critical tabulated values  $D_{n,\alpha\%}$ , especially near the centre of the distributions, where  $\alpha\%$  is the significance level and  $n$  is the sample size. When  $n$  is greater than 50,  $D_{n,\alpha\%}$  is calculated using the equations:

$$D_{n,1\%} = \frac{1.62762}{\sqrt{n}} \quad \text{and} \quad (6)$$

$$D_{n,5\%} = \frac{1.35810}{\sqrt{n}} \quad (7)$$

The suspended sediment rating curves retained can therefore be used to estimate the sediment intakes conveyed by the El-Malah East river at the Beni Slimane gauging station, depending on the daily mean discharge data available in the period (1985/86 to 1996/97).

The obtained results can finally be used to determine the specific sediment yield (or specific erosion) at the Beni Slimane hydrometric station using the equation:

$$Es = \frac{As}{A} \quad (8)$$

where  $Es$  is the sediment yield ( $t.km^{-2}.an^{-1}$ ),  $As$  is the annual sediment intake ( $t$ ), and  $A$  is the basin surface ( $km^2$ ).

## 4 RESULTS AND DISCUSSION

The study of solid transport in the El-Malah East river is done based on 2081 instantaneous values of concentration  $C$  and liquid flow  $Ql$  collected at the Beni Slimane station during 1973/74–1988/89, whose annual and intraannual variation in observation frequencies is illustrated in Figure 3. This figure shows that the suspended sediment concentration is distinguished during the spring and summer seasons. The months with the greatest number of concentration values are May and August, followed by July, June, April and September. The smallest number of observations was detected in November. On an annual scale, the years 1978/79, 1979/80, 1981/82, 1984/85, 1986/87, and 1988/89 have the greatest number of concentration values. The reasons for the reduction in the number of measures for the other years and months are not well known, while the absence of concentration measures during the years 1982/83, 1983/84, and 1987/88 is due to the almost total absence of flows (see Figure 12 for the year 1987/88).

Figure 4 represents 2081 instantaneous values of suspended sediment concentration and liquid flow observed on the El-Malah East river at the Beni Slimane hydrometric station during 1973/74–1988/89. The staggering concentration data on 14 orders of magnitude is illustrated in Figure 5. The statistical parameters of concentration  $C$ , liquid flow  $Qs$  and sediment discharge  $Qs$  are shown in Table 2.

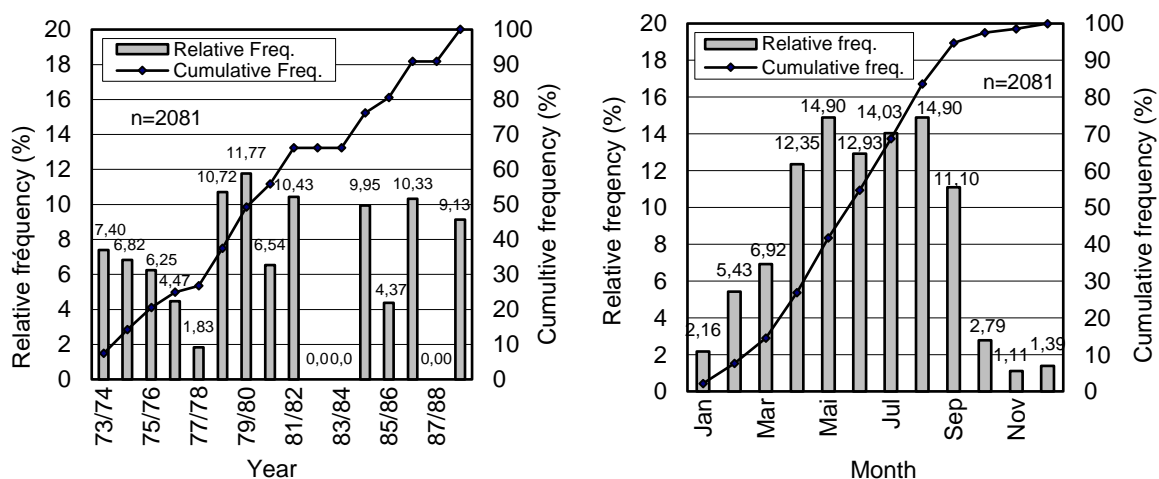
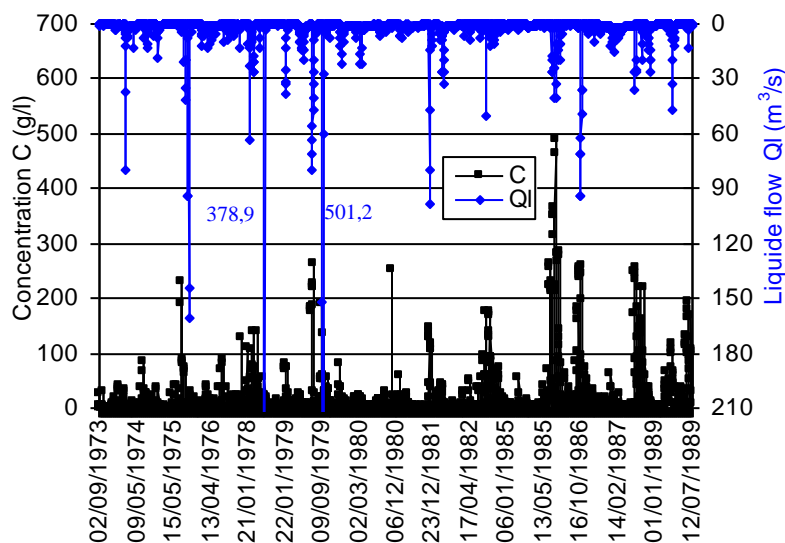


Figure 3. Frequencies of concentration observations during the study period



**Figure 4.** Distribution of instantaneous liquid flow ( $Ql$ ) and instantaneous concentration ( $C$ )

**Table 2.** Statistical parameters of concentration  $C$ , liquid flow  $Ql$  and sediment discharge  $Qs$

Statistical parameters	$C$ (g/l)	$Ql$ ( $m^3/s$ )	$Qs$ (kg/s)
Number of values	2081	2081	2081
Minimum	0.013	0.001	0.001
Maximum	486.80	501.20	25831.848
Mean $\bar{x}$	18.256	3.477	282.564
Variance	2086.25	355.238	3071843.191
Standard deviation	45.675	18.848	1752.667
Coefficient of variation	2.502	5.421	6.203
Skewness of the data	4.468	17.429	9.087

High concentrations on the El-Malah East river are quite frequent. Approximately 19.31 % (402 values) of all data exceed the average concentration at the Beni Slimane hydrometric station, and 4.95 % (61 values) exceed 100 g/l. The range between 0.1 and 2 g/l represents nearly 40.56 % (844 values) of the entire available sampling. The results shown in Figures 4 and 5 already anticipate the dispersion of points during the analysis of the "concentration – liquid flow" relationship as well as on the sampling quality during the study period.

The plot of sediment concentrations versus flow discharges (Figure 6) shows considerable dispersion of points along the horizontal axis in linear and logarithmic coordinates. The vertical variation of points seems greater on the left than on the right and does not encourage collecting samples to obtain estimates using least squares regression. To examine whether this variation is independent of the liquid flow, the suspended sediment concentrations have been separated into narrow ranges of liquid flow (Figure 7). These Figures (6 and 7) indicate significant variations in suspended sediment concentration for almost constant flow discharge. On the other hand, they show that the lowest liquid flow can convey the same concentration as the largest liquid flow (hysteresis effect).

During floods, we can observe different hysteresis loops: clockwise, counter-clockwise or figure eight loops (Figure 8).  $C/Q$  relationships are quite different. Sediment stock available on the river bank escarpments, river irregularities, downpour intensity and duration can explain this diversity of  $C/Q$  relationships.

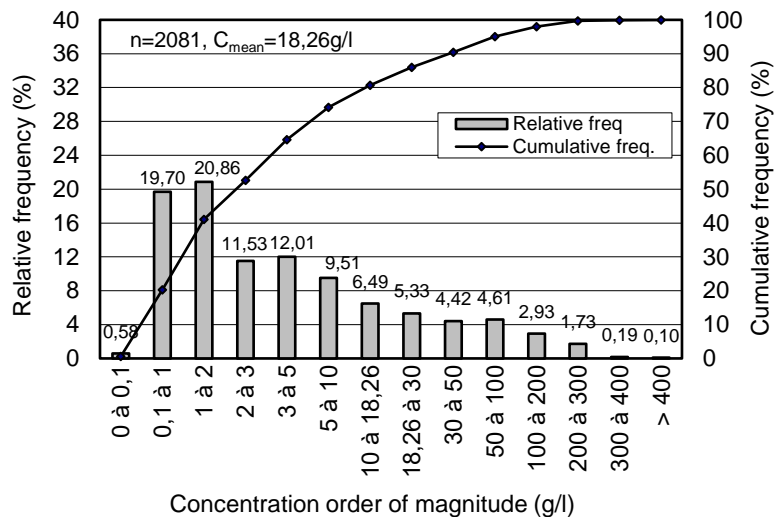


Figure 5. Frequency of observations according to the concentration order of magnitude

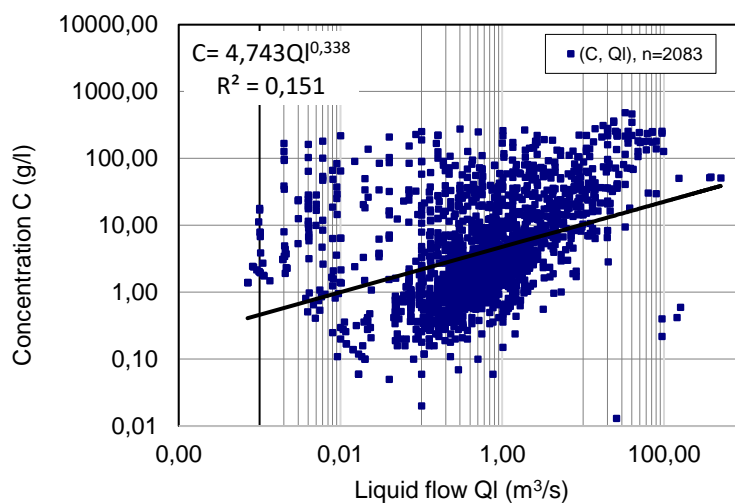
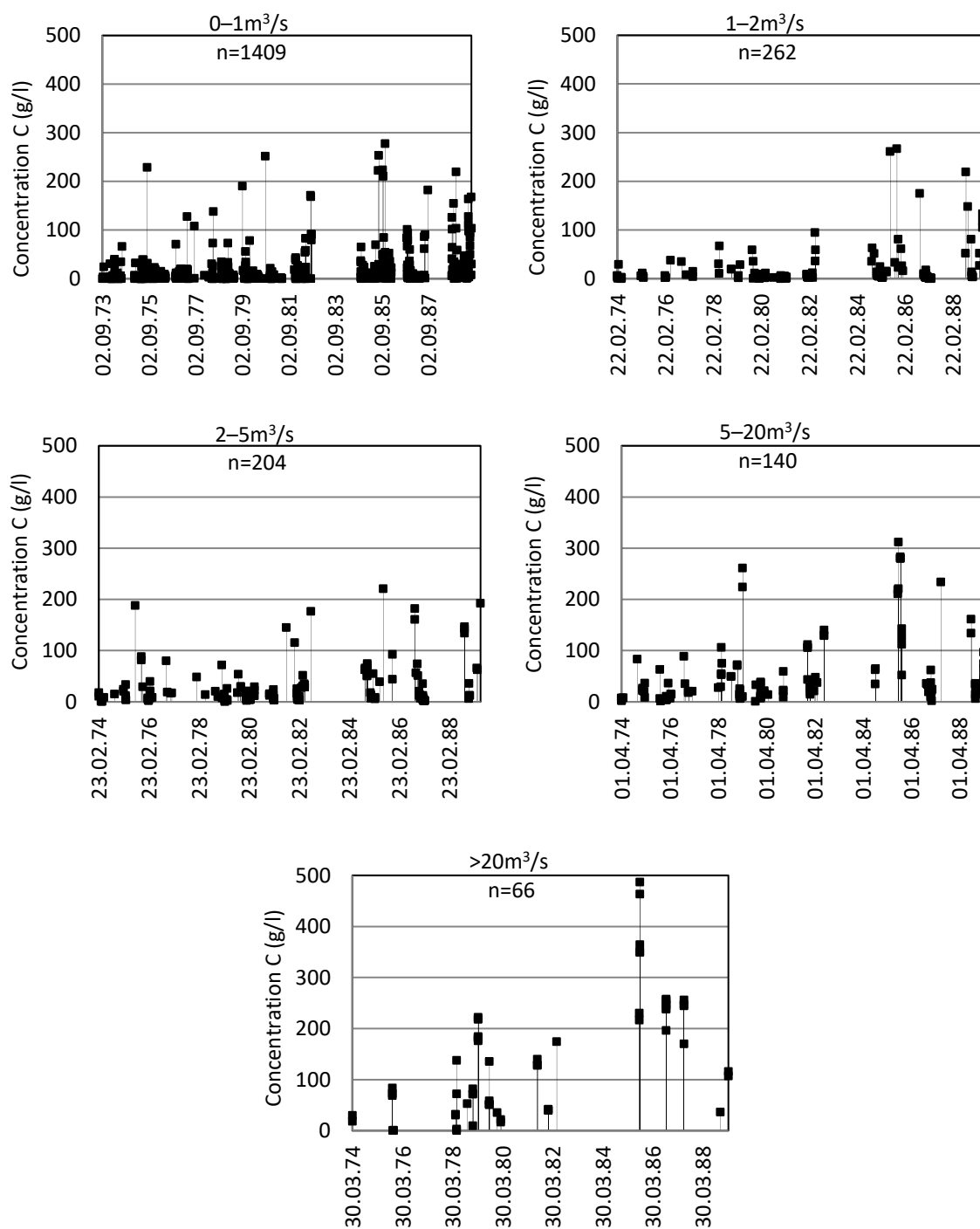
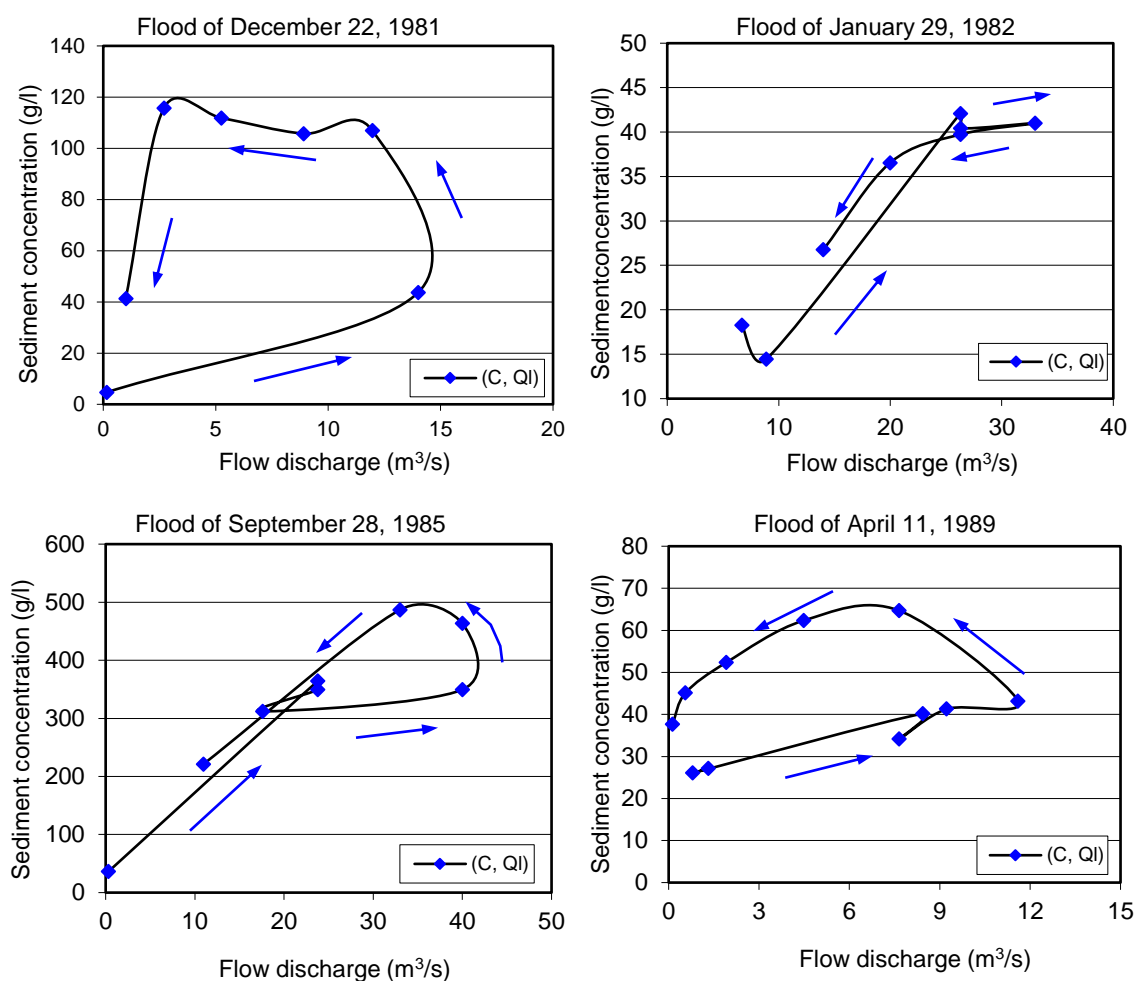


Figure 6. Plot of suspended sediment concentration – liquid flow



**Figure 7.** Separation of suspended sediment concentrations into narrow ranges of flow discharge



**Figure 8.** Examples of hysteresis loops during floods

For the homogenization of data, the methodological approach adopted in this paper consists in looking for a regressive model that can better explain the suspended solid flow through liquid flow by studying this relationship at different temporal scales. The obtained power relationships are shown in Tables 3 and 4. Figure 9 shows the solid transport rating curve obtained on daily (interannual) and seasonal scales.

The coefficient  $a$  generally varies between 2 and 106, and its variation is much more important in a monthly group than in annual and seasonal groups, while the parameter  $b$  ranges from 1.1 and 1.9 for all temporal scales. These values are comparable to those found in many arid and semi-arid regions; In Wadi Wahrane [36], Wadi Sebdou, Wadi Mouilah, and Wadi Sikkak [32], in Wadi Mina [37], in Wadi Harraza [38], in Wadi El Hammam [39], in Wadi Isser [13] and on the Arbucies river in the northeast of the Iberian Peninsula [40].

Parameters  $a$  and  $b$  may be related to the saturation rate of the watershed and the importance of suspended sediment transport, respectively [36, 32]. Models made on seasonal groups give good coefficients of correlation whose values vary from 0.8037 (in summer) to 0.9333 (in winter). The lowest coefficient of correlation may be explained by rainfall-runoff variability that characterizes the months of June, July and August.

These seasonal models are chosen for quantifying suspended sediment load conveyed by the El-Malah river at the Beni Slimane hydrometric station in the period of availability of daily mean flow discharges (1985/86 to 1996/97). This choice was motivated by the large number of measures collected in each season ( $n_{\text{mean}} = 520$ ), by the values of the obtained correlation coefficient ( $R_{\text{mean}}^2 = 0.8691$ ) and by an analysis making optimal the use

of these seasonal rating curves. Indeed, optimization of seasonal sediment rating curves has been validated by comparing the estimated and the observed values (Figure 10) and by fitting Normal distribution to residues data sets; the higher the fitting Normal distribution, the lower the dispersion of points around the sediment rating curve and vice versa. Fitting Normal distribution to seasonal residues is presented in Figure 11.

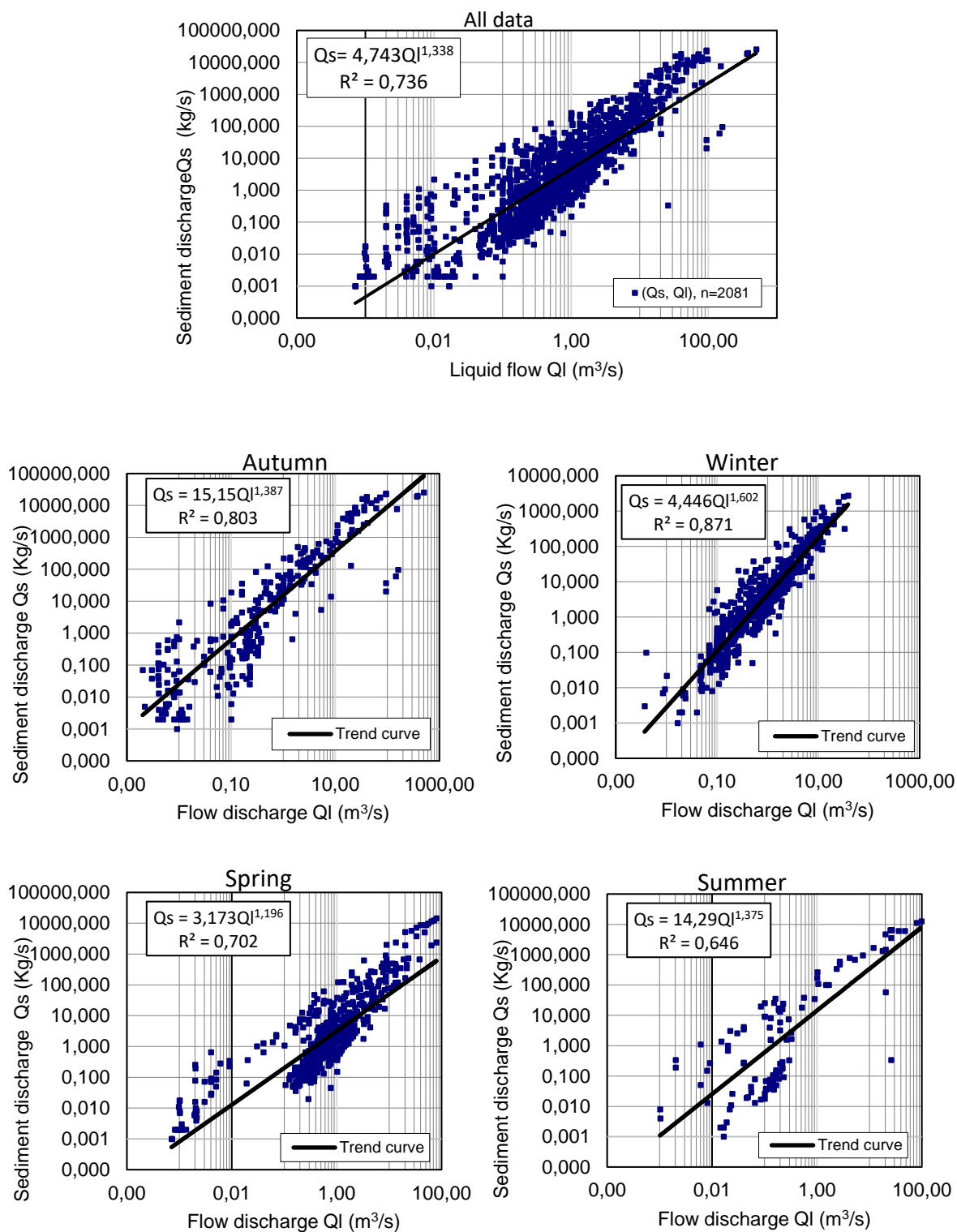
**Table 3.** Power models made in interannual and seasonal groups ( $Q_s=aQ^b$ )

Interannual (daily) group (73/74–88/89)					Seasonal group				
	<i>n</i>	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>	Season	<i>n</i>	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
All data	2081	4.743	1.338	0.736	Autumn	302	15.1500	1.3870	0.8030
					Winter	836	4.4460	1.6020	0.8710
					Spring	833	3.1730	1.1960	0.7010
					Summer	110	14.2900	1.3750	0.6460
					Mean	520	9.2648	1.3900	0.7553

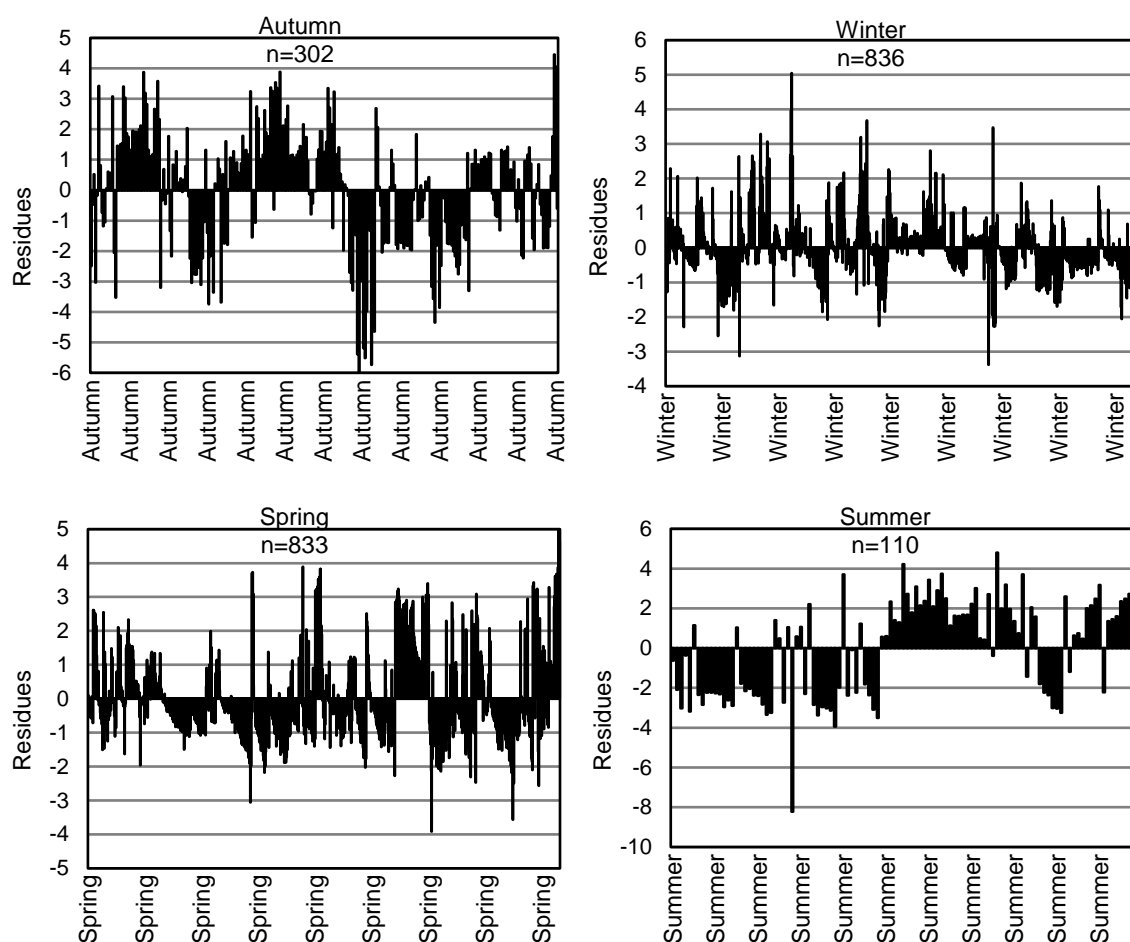
*n*: number of observations, *R*<sup>2</sup>: coefficient of determination

**Table 5.** Power models made in annual and intraannual groups ( $Q_s=aQ^b$ )

Annual group					Intra-annual group				
Year	<i>n</i>	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>	Month	<i>n</i>	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
1973/1974	154	2.021	1.442	0.670	September	45	47.02	1.259	0.863
1974/1975	142	3.961	1.801	0.802	October	113	26.97	1.461	0.863
1975/1976	130	3.001	1.255	0.746	November	144	6.607	1.309	0.749
1976/1977	93	7.076	1.894	0.779	December	257	5.536	1.669	0.861
1977/1978	38	5.550	1.464	0.709	January	310	5.443	1.662	0.902
1978/1979	223	5.614	1.634	0.915	February	269	3.182	1.541	0.827
1979/1980	245	3.250	1.697	0.805	March	292	2.866	1.302	0.703
1980/1981	136	2.507	1.837	0.827	April	310	3.613	1.157	0.737
1981/1982	217	5.374	1.791	0.821	May	231	3.033	1.256	0.618
1982/1983	/	/	/	/	June	58	2.861	1.143	0.491
1983/1984	/	/	/	/	July	23	105.6	1.299	0.931
1984/1985	207	5.481	1.308	0.704	August	29	38.74	1.591	0.804
1985/1986	91	28.40	1.598	0.894					
1986/1987	215	5.259	1.298	0.704					
1987/1988	/	/	/	/					
1988/1989	190	18.04	1.147	0.867					
Mean	160	7,3488	1,5512	0,7879	Mean	173	20,9559	1,3874	0,7791



**Figure 9.** Suspended sediment rating curve obtained in daily and seasonal groups



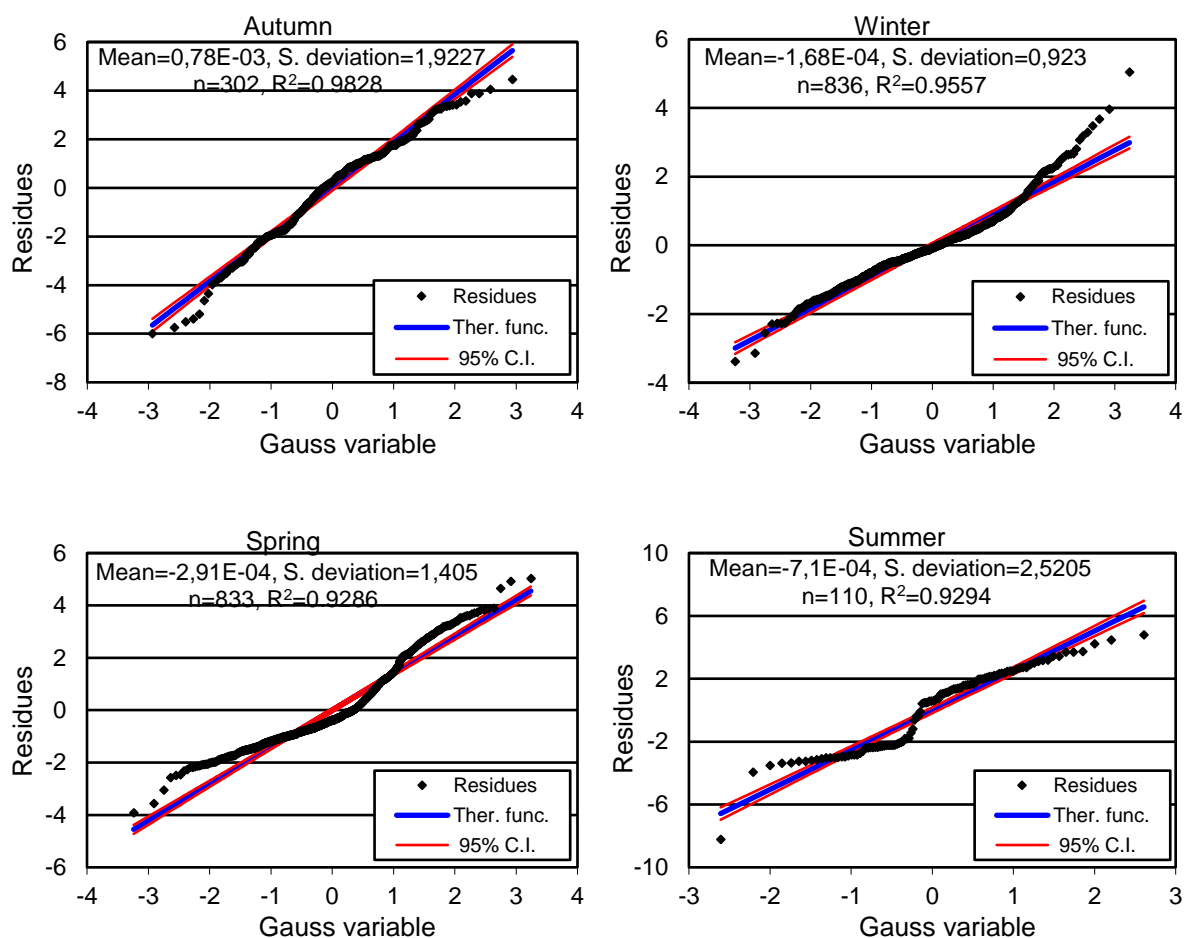
**Figure 10.** Regression residues on seasonal scale (1973/74 to 1988/89)

Probability plot correlation PPC (Figure 11) and Kolmogorov-Smirnov (Figure 12) tests are employed to check the goodness of fit of the Normal probability distribution to residues data. The results obtained show good coefficients of determination  $R^2$  for all the seasons. The null hypothesis of K-S is accepted with caution for winter, spring and summer because the maximum differences  $D_{max}$  between the cumulative observed frequency distribution of residues  $F_0(x)$  and the Normal theoretical distribution  $F(x)$  for a significance level  $\alpha = 5\%$  are slightly superior to the critical values  $D_{n, \alpha\%}$ . It should be emphasised that for a significance level  $\alpha = 1\%$ , the K-S null hypothesis is accepted for all the seasons.

However, the PPC test and graphical displays indicate a good fit of the Normal distribution to residues data and meet the specific criteria of residues (zero mean and standard deviation  $s$ ) for all seasons. The use of these seasonal sediment rating curves has highlighted annual, intraannual, and seasonal distributions of suspended sediment contributions conveyed by the El-Malah East river at the Beni Slimane hydrometric station by interpolation and extrapolation within and beyond observations (1986/86 to 1996/97) depending on the available daily mean flow discharges (Figures 13, 14 and 15).

The annual flow at the Beni Slimane gauging station varies from 0.40 (for 1987/88) to 22,934  $\text{mm}^3$  (for 1994/95) with a coefficient of variation  $CV=0.91$ . The years 1986/87, 1989/90, 1991/92, 1992/93, 1994/95, and 1996/97 provided, according to our results, nearly 80.18 % of the total suspended sediment load mobilized during the period 1985/86 to 1996/97. The lowest sediment load (0.0022 MT) is estimated for the hydrological year 1987/88, a very dry year with the lowest liquid intake (0.40  $\text{mm}^3$ ). The highest sediment load (0.1916 Mt) occurred during the 1994/95 hydrological year, a wet year with the highest liquid intake (22.934  $\text{mm}^3$ ). The coefficient of variation in the suspended sediment load is equal to 0.721. The annual mean flow of the El-Malah

East river at the Beni Slimane gauging station is estimated to be  $11.019 \text{ mm}^3$  with an effective rainfall of  $40 \text{ mm}$  and runoff coefficient of approximately  $10.2 \%$ . These liquid intakes bring nearly  $0.0888 \text{ Mt}$  of suspended sediment load, which represents a sediment yield of  $325.30 \text{ t.km}^{-2}.\text{year}^{-1}$ . The average annual suspended sediment load is about  $8.059 \text{ g/l}$ .



**Figure 11.** Fitting Normal distribution to residues data on seasonal scale (1973/74 to 1988/89) and PPC test

The monthly flow observed at the Beni Slimane hydrometric station varies from  $0.1788$  in August to  $2.5660 \text{ mm}^3$  in March with a coefficient of variation  $CV=0.761$ . October, January, February, March, and July provided nearly  $59.3 \%$  of the total suspended sediment load mobilized during 1985/86–1996/97. The lowest sediment load ( $0.0029 \text{ Mt}$ ) is estimated for the dry month of August, with the lowest liquid intake ( $0.1788 \text{ mm}^3$ ). The highest sediment load ( $0.0124 \text{ Mt}$ ) occurred for the wet month of January, with the second largest liquid intake ( $1.4789 \text{ mm}^3$ ) and the coefficient of variation of the suspended sediment load  $CV=0.442$ . The monthly mean flow (liquid intake) of the El-Malah East river at the Beni Slimane gauging station is estimated to be  $0.9183 \text{ mm}^3$ . These liquid intakes bring nearly  $0.0074 \text{ Mt}$  of suspended sediment load per month, which represent a sediment yield of  $27.106 \text{ t.km}^{-2}.\text{month}^{-1}$ .

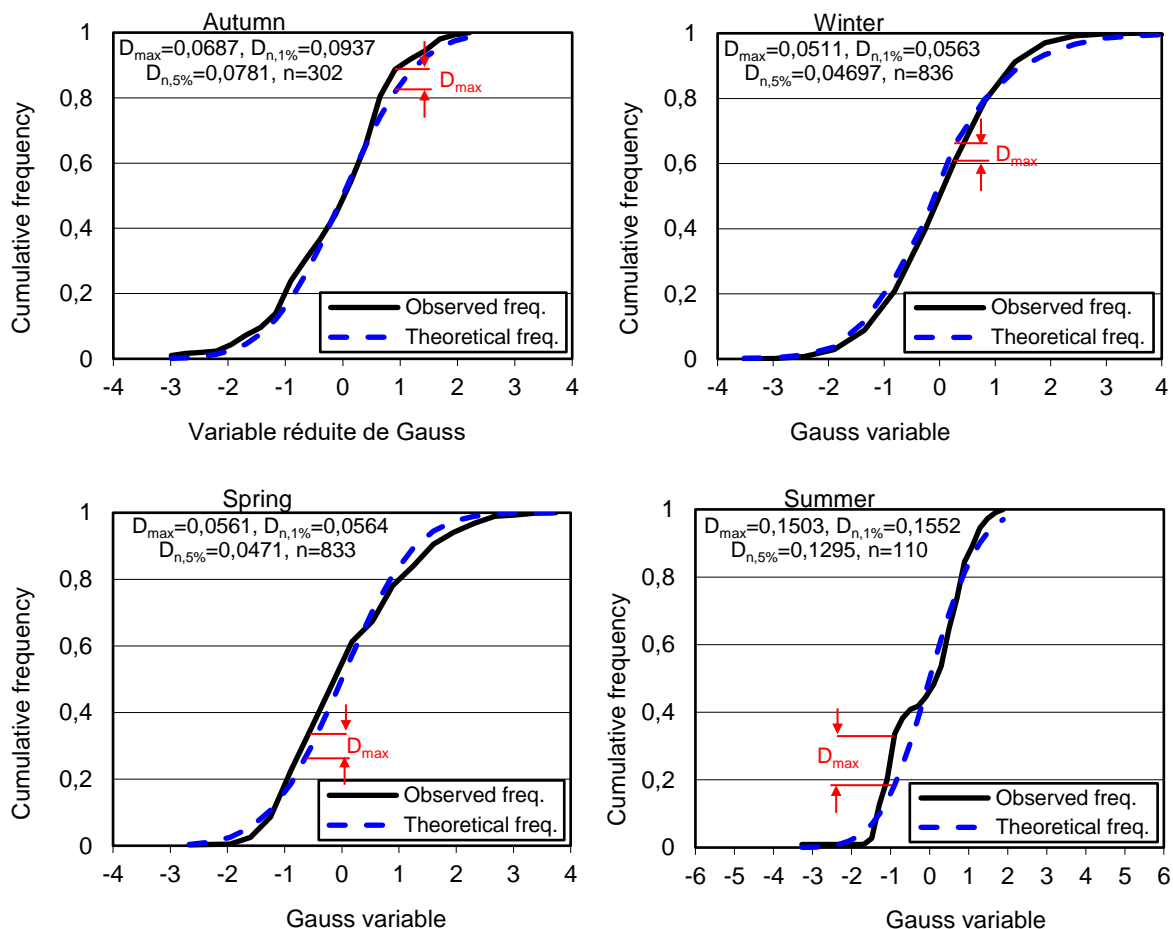


Figure 12. Kolmogorov-Smirnov test of fitting Normal distribution to seasonal residues

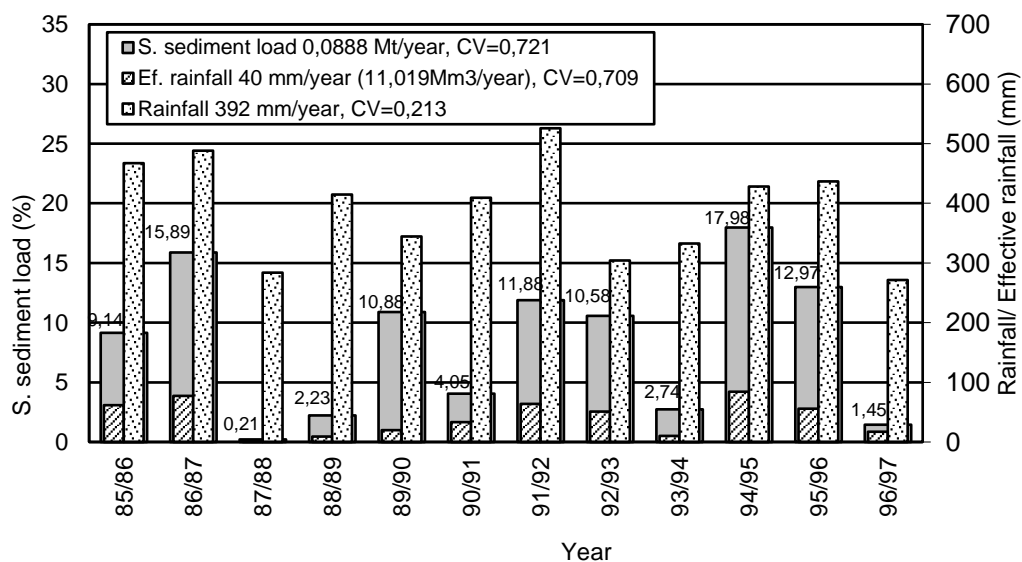
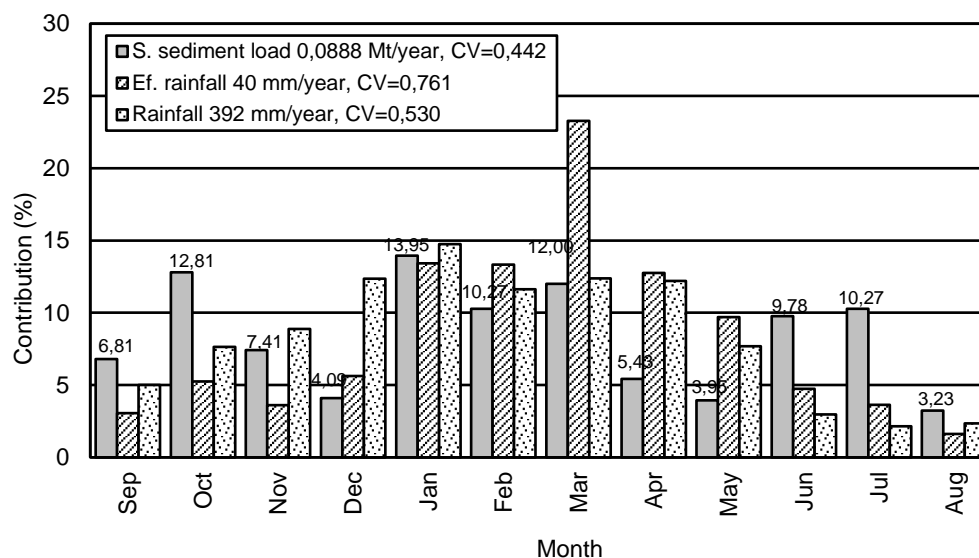


Figure 13. Annual variations of suspended sediment load, rainfall and effective rainfall (1985/86 to 1996/97)

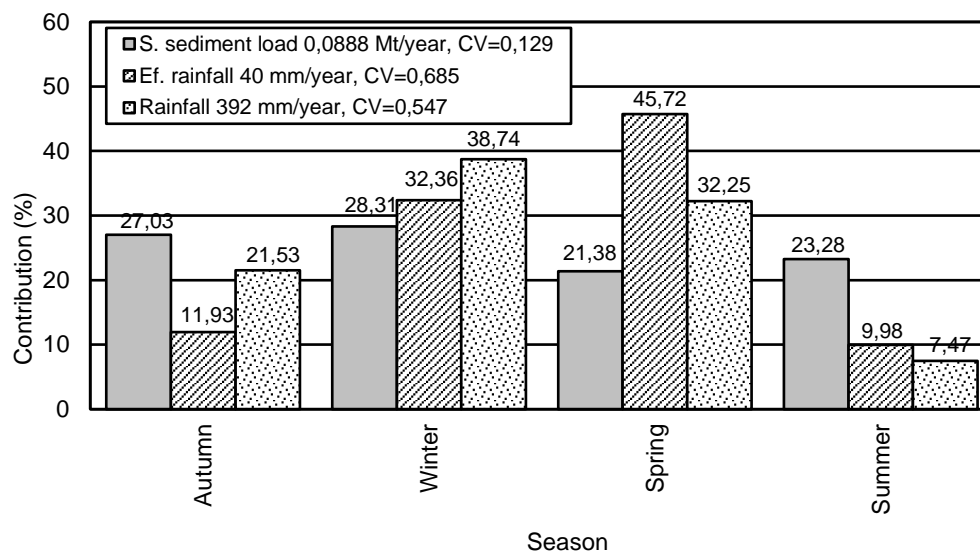


**Figure 14.** Monthly variations of suspended sediment load, rainfall and effective rainfall (1985/86 to 1996/97)

In response to the characteristics of the semi-arid climate, the flow regime in the El-Malah East river watershed shows a seasonal variation of flows, with maximums recorded in March, January, February and April. The results showed that the highest liquid intake occurs in spring (45.72 %), winter (32.36 %) and autumn (11.93 %) seasons. This distribution as well as the distribution of the monthly rainfalls (Figures 13 and 14) contributed to the conclusion that the runoff period does not always correspond to the rainy period. The highest precipitations occur in winter (38.74 %), spring (32.25 %) and autumn (21.53 %) seasons. The analysis of the intraannual distribution of suspended sediment contributions showed that winter and autumn participate with 28.31 and 27.03 %, respectively, of the total annual suspended sediment transports, while summer and spring participate with 23.28 and 21.38 %, respectively, emphasizing almost the same order of magnitude (approximately 25 %). The coefficient of variation of the seasonal suspended sediment load is  $CV = 0.129$ .

Therefore, summer and autumn low rainfall seasons provide approximately the same suspended sediment load as wet winter and spring seasons. It may be explained by the annual variation of land cover (very degraded, especially in summer and autumn) and by the nature of summer and autumn rainfalls (heavy and aggressive rainstorms). It can also be explained by the predominance of erodible marly and marly-limestone formations belonging to the lower, medium and upper Cretaceous. These lithological formations crack by dehydration during these dry seasons and deteriorate by several centimetres by forming a gravel carpet mixed with clay-limestone dust, which goes out in debacle with the first stormy showers. The low suspended sediment rate of the wet season winter may be explained by the fact that most parts of solid particles were transported by the first floods of summer and autumn.

Regarding precipitation and liquid intakes, the phase shift of the spring period compared to the winter period is explained by the nature of spring rains (significant aggressive and stormy rain).



**Figure 15.** Seasonal variations of suspended sediment load, rainfall and effective rainfall (1985/86 to 1996/97)

In Algeria, only suspended sediment transport is measured, and the bed load is taken equal to 30 % of the Suspended sediment load [41, 42]. Consequently, the El-Malah East river conveys at the Beni Slimane Station about 0.1154 Mt (0.0722 mm<sup>3</sup>) of suspended and bed load annually, representing a surface degradation of 423 t.km<sup>-2</sup>.y<sup>-1</sup>. This result is comparable to those found by many researchers who have worked in arid and semi-arid regions (Table 6).

**Table 6.** Surface degradation in some arid and semi-arid watersheds

Basin/Region	Surface degradation (t.km <sup>-2</sup> .y <sup>-1</sup> )	Reference
Maghreb	397	[43]
Tebaga (Tunisia)	336	[44]
El-Hachem (Algeria)	318	[45]
Sas Saf (Algeria)	461	[46]
Bassin de Harreza (Algeria)	470	[38]
Kebir basin (Algeria)	572	[24]
Bellah (Algeria)	610	[47]
Sebdou (Algeria)	343	[48]
Wadi Mina (Algeria)	450	[33]
Boukadir (Algeria)	446	[49]

## 5 CONCLUSION

In this paper, we conducted a statistical approach to analyse the hydro-sedimentary processes in the El-Malah East river watershed at the Beni Slimane hydrometric station (North Algeria), representing a sample of arid and semi-arid basins. They are generally characterised by a high solid transport rate due to the predominance of erodible marly and marly-limestone formations belonging to the lower, medium and upper Cretaceous, accidental relief and strong slopes, a very degraded vegetation cover, a great rainfall-runoff variability, and significant aggressive and stormy rain.

On one hand, the analysis of the instantaneous measurements of suspended sediment concentrations and flow discharges (1973/74 to 1988/89) indicate significant variations in suspended sediment concentration for almost constant flow discharge. On the other hand, they show that the lowest liquid flow can convey the same concentration as the largest liquid flow. For the homogenization of data, the methodological approach adopted in this paper consists of looking for a regressive model that can better explain the suspended solid flow through liquid flow, by studying this relationship at different temporal scales. The coefficient  $a$  generally varies between 2 and 106, and its variation is much more important in a monthly group than in annual and seasonal groups, while the parameter  $b$  ranges from 1.1 and 1.9 for all temporal scales. These values are comparable to those found in many arid and semi-arid regions.

Models made in seasonal groups give good coefficients of correlation whose values vary from 0.8037 (in summer) to 0.9333 (in winter). These seasonal models are chosen for the quantification of suspended sediment load conveyed by the El-Malah river at the Beni Slimane hydrometric station in the period of availability of daily mean flow discharges (1985/86 to 1996/97). This choice was motivated by the large number of measures collected in each season ( $n_{\text{mean}} = 520$ ), by the obtained values of the correlation coefficient ( $R_{\text{mean}}^2 = 0.8691$ ) and by an analysis making optimal the use of these seasonal rating curves (by comparing the estimated and the observed values and by fitting Normal distribution to residues data sets).

The use of these seasonal models has highlighted the intraannual distribution of the suspended sediment contributions conveyed by the El-Malah East river at the Beni Slimane hydrometric station estimated at 0.088 Mt per year, representing a specific degradation of about  $325 \text{ t.km}^{-2}\text{y}^{-1}$  ( $423 \text{ t.km}^{-2}\text{y}^{-1}$  of suspended and bed loads). This result is comparable to those found by many researchers who have worked in arid and semi-arid regions.

The results have also shown that the highest liquid intake occurs in spring (45.72 %), winter (32.36 %) and autumn (11.93 %) seasons. This distribution as well as the distribution of the monthly rainfalls allowed the conclusion that the runoff period does not always correspond to the rainy period. The highest precipitation occurs in winter (38.74 %), spring (32.25 %) and autumn (21.53 %) seasons. The analysis of the intraannual distribution of suspended sediment contributions showed that winter and autumn participate with 28.31 and 27.03 %, respectively, of the total suspended sediment load annually, while summer and spring participate with 23.28 and 21.38 %, respectively.

Finally, these results and findings can be verified and improved by increasing the size of the available series. They provide appreciable elements of comparison for others basins of the same order, located in semi-arid and arid regions and subjected to similar phenomena. They also allow river basin managers and policymakers to consider necessary actions to fight against land erosion, preserve human activities, increase the life of the Koudiet Acerdoune dam 60 km downstream from the watershed outlet, facilitate decision-making and planning, and ensure effective management.

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