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A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Quantification of suspended sediment load by double correlation in the watershed of Chellif (Algeria)

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Abstract

The sediment transport in rivers in Algeria is very high. However, it is poorly quantified in some wadis because of the absence and the shortage of data especially the concentration of fine particles and also the unavailability of gauging stations. To fill this gap, a technique for estimating sediment yield, based on data recorded at the gauging station has been developed. The estimation of suspended sediment yield was conducted by a statistical analysis with double correlation on average daily flow and solid concentrations. The results obtained by applying this model to the watershed Chellif are very encouraging because the correlation coefficients of the found models are between 61% and 91% for the first correlation and between 86% and 97% for the second correlation. The estimated quantity of suspended sediment load is between 2.35 and 4.12 million tonnes per year, it appears important; This is due to the vulnerability of the Chellif basin facing erosion, the importance of its area and the importance of fluid flows in wadi Cheliff and its torrential regime. Mention here some of the results and their significance to the study.

Key words: *Chellif, model, quantification, solid flow, statistics, watershed*

ISSUES AND PURPOSE OF THE STUDY

Algeria is a semi-arid country with an average of 200 to 400 mm of rain per year, its renewable water resources are low, irregular, and located in the coastal strip. To this end the National Agency for Dams (ANBT) realized until now about 60 major dams with a capacity of 6 billion m^3. But with a specific erosion rate between 2000 and 4000 t·km^{-2}·year^{-1} each year the Algerian water infrastructure is amputated with a capacity of 45 million m^3 [REMINI 2004; REMINI *et al.* 2009] due to siltation. Unfortunately, the problems of erosion and sediment transport can reach a scale likely to sterilize completely hydraulic works in water and rivers.

The most dramatic consequence of watershed erosion and sediment transport is undoubtedly the siltation of dams. Although several researchers have studied this in the last decade, the phenomenon of erosion and sediment transport in rivers [ACHITE, MEDDI 2004; 2005; ACHITE, OUILLON 2007; ARABI 1991; BOUCHELKIA 2003; 2013; BOUROUBA 1998; DEMMAK 1982; GHENIM 2008; TERFOUS *et al.* 2001], the phenomenon remains poorly understood and weakly mastered. Given the importance of this problem, this study attempts to evaluate the suspended sediment load at the outlet of watershed Chellif, by proposing a method for estimating by double correlations.

PRESENTATION OF THE STUDY AREA AND DATA COLLECTION

Watershed Chellif is located North West of Algeria with an area equal to 43700 km^2, and almost all soils are mainly alluvial fine elements derived from marl or clay, making them very sensitive to soil erosion. It is characterized by minimum altitude of 20 m, maximum altitude of 1983 m, its perimeter is 1383 km, the compactness index is 1.85, the length of the equivalent rectangle is 619 km and the length of its principal talweg is 759 m. The basin is crossed by the most important wadi in Algeria; the Chellif, flowing from east to west from the Boughezoul dam to the Mediterranean sea, it is long 250 km and has a vertical drop of 625 m as shown in Figure 1. The climate of this basin is Mediterranean in nature with hot and dry summers and cool and tempered winters, characterized by winds less than 10 km·h^{-1} and a high average sunshine ranging from 60–80% of the duration of the day, its rainfall is relatively low [BOUCHELKIA 2009; BOUCHELKIA, REMINI 2011].

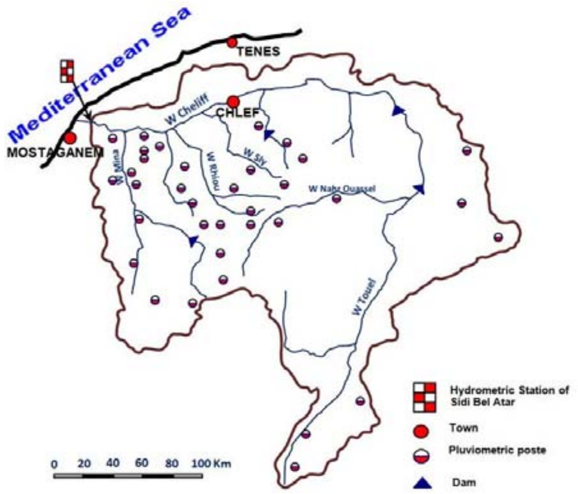

Fig. 1. Watershed of Chellif (Algeria); source: own elaboration

The data used in this article came from the National Agency for Water Resources (ANRH) as recorded in the gauging station of Sidi Belatar. The sampling method involved obtaining daily water samples and to analyze the samples in the laboratory for determination of solids concentrations and other sample characteristics. The sampling was validated by multiplying the number during floods or variable discharge (sampling each small time step “15 minutes per moment”). Data are representative as they extend over a period of 28 years (1972–2000). For the water discharge; this data series is complete and without flaw.

METHOD OF DOUBLE CORRELATION

The method of double correlation was proposed because it is more logical to make a correlation between liquid flow and concentration, because it uses the raw data collected at the gauging station and allows to integrate the estimated suspended sediment yield calculated from series of observed data with a second correlation between solid concentration and solid flow contrary to the method of one correlation that we have used in our previous works [BOUCHELKIA 2003; BOUCHELKIA *et al.* 2011; 2013] with direct correlation between liquid flow and solid flow, the latter is calculated by multiplying the liquid flow by its solid concentration taken in series of observations of gauging station. Using this approach, the estimation of the suspended sediment rate is based on double correlation (concentration – liquid flow) and (solid flow – concentration) the first one will correlate with the cumulative frequency curve of liquid daily mean flows to evaluate the inter-annual average concentration because this depends heavily on liquid flows and their frequencies, the second enable estimation of the probable uncertainties of the first correlation and hence estimate the suspended sediment rate, because the corresponding solid flow also depends on the solid concentration of water in wadi [BOUCHELKIA 2009].

STUDY STEPS FOLLOWED

1. Collection of data necessary to the study:
   a) one file of mean daily liquid discharges (rather long series without gaps) satisfying the homogeneity test;
   b) one file of pairs values (liquid flow rate, concentration) as long as possible satisfying the tests of homogeneity and independence;
   c) one file of pairs values (concentration, solid discharge) as long as possible satisfying the tests of homogeneity and independence.
2. Development of the cumulative frequency curve.
3. Correlation liquid flow – concentration and determination of model $C_s = F(Q)$.
4. Combination of the model $C_s = F(Q)$ with the cumulative frequency curve and determination of the inter-annual average concentration (C_{sm}) according to the actions described below in “Evaluation of suspended sediment load”.
5. Development of correlation model concentration – slid discharge $Q_s = F(C_s)$.
6. Evaluation of suspended sediment load [BOUCHELKIA 2009].

EVALUATION OF SUSPENDED SEDIMENT LOAD

The estimation of the mass of the suspended sediments were done by the following steps:

1) division of the cumulative frequency curve of the liquid discharge to multiple frequency intervals (f_i, f_{i+1});
2) determination of liquid flow rates achieved or exceeded *QI* corresponding to the median of each frequency interval;
3) for each *QI* liquid flow rate, the concentration corresponding solid was calculated using the statistical model $C_S = f(Q)$;
4) evaluation of the inter-annual average concentration by: $C_{sm} = \sum_{i=1}^{n} C_{si}(f_{i+1} - f_i)$ (based on UNESCO [1986]).

5) evaluation of the average inter-annual solid discharge by the predetermined model: $Q_s = F(C_s)$.
6) estimation of sediment yield drained by this wadi for given period [BOUCHELKIA 2009; BOUCHELKIA, REMINI 2011].

Two types of files were used:
- one file of mean daily liquid discharges as long as possible, complete and without gaps (1 complete and continuous of annual series, 4 complete and continuous seasonal series, 2 complete and continuous semester series) for the determination of tables cumulative frequency (frequency analysis of mean daily liquid discharges);
- one file of pairs values (Q, C_s), Q is mean daily liquid discharge.

EVALUATION OF SUSPENDED SOLID CONTRIBUTIONS

From database file of pairs (Q, C_s) which are result of raw observations collected at the Sidi Belatar station controlling Cheliff wadi (instantaneous fluid flow and instantaneous suspended solid concentration)files daily averages couples (Q, C_s) are prepared as well for liquid flow as for solids concentrations, according to the estimation period (annual, seasonal or monthly). The estimation of suspended sediment yield by double correction method is made according to the actions described above ("Method of double correlation").

CORRELATION SOLID CONCENTRATION – LIQUID FLOW (FIRST CORRELATION)

In Sidi Bel Atar station, more than 6312 data of daily mean liquid discharge and 1 190 pairs (Q, C_s) was selected covering the period 1972–2000. Table1 summarizes the parameters of pairs of samples used for each file. Figure 2 shows the relationship for annual solid concentration and liquid flow. It is interesting to note that the points cloud indicates a strong relationship:

$$C_s = KQ^A$$

where:

K, A – coefficients.

This powerful model had already been proposed in 1895 by Kennedy (in LEFORT [1992]).

Table 1. Characteristic of samples (Q, Cs)

Period	Number of pairs	Mean		Standard deviation		Covariance S_{XY}
		$\bar{x}$	$\bar{y}$	S_X	S_Y	
Annual	1190	1.23	0.87	0.60	0.43	0.16
Autumn	360	1.17	1.17	0.55	0.44	0.21
Winter	489	1.46	0.68	0.52	0.35	0.17
Spring	258	1.12	0.86	0.52	0.36	0.15
Summer	83	0.42	1.12	0.76	0.48	0.29
Humid season	849	1.34	0.87	0.55	0.45	0.16
Dry season	341	0.94	0.84	0.62	0.39	0.15

Source: own study.

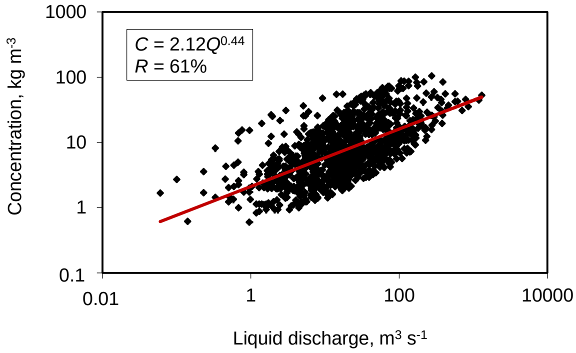

Fig. 2. Annual correlation between solid concentration and liquid discharge; source: own study

The same observations can be made of Figure 3 (a–f) representing seasonal relationships between the solid and liquid flow rates. Table 2 summarizes the different seasonal relationships and theirs correlation coefficients.

FREQUENCIAL STUDY OF LIQUID DISCHARGE

The distribution of the statistical observation classes allowed to trace the flow duration curves (cumulative daily mean liquid discharge frequencies) for annual periods as shown in Figure 4) and seasonal curves indicated in Figure 5a–f. Table 3 summarizes the statistic parameters of daily mean liquid discharges for each period.

Table 2. Relationships and theirs correlation coefficients

Period	Number of points	Coefficient			Correlation coefficient, %	Prediction interval	Relationship
		A	B	K			
Annual	1 190	0.44	0.326	2.12	61	±4.75	$2.12Q^{0.44}$
Autumn	360	0.71	0.340	2.19	89	±2.50	$2.19Q^{0.71}$
Winter	489	0.61	–0.214	0.61	91	±1.93	$0.61Q^{0.61}$
Spring	258	0.56	0.240	1.74	82	±2.53	$1.74Q^{0.56}$
Summer	83	0.50	0.906	8.05	79.5	±2.82	$8.05Q^{0.5}$
Humid season	849	0.51	0.195	1.57	62	±4.91	$1.57Q^{0.51}$
Dry season	341	0.41	0.454	2.84	65	±3.83	$2.84Q^{0.41}$

Source: own study.

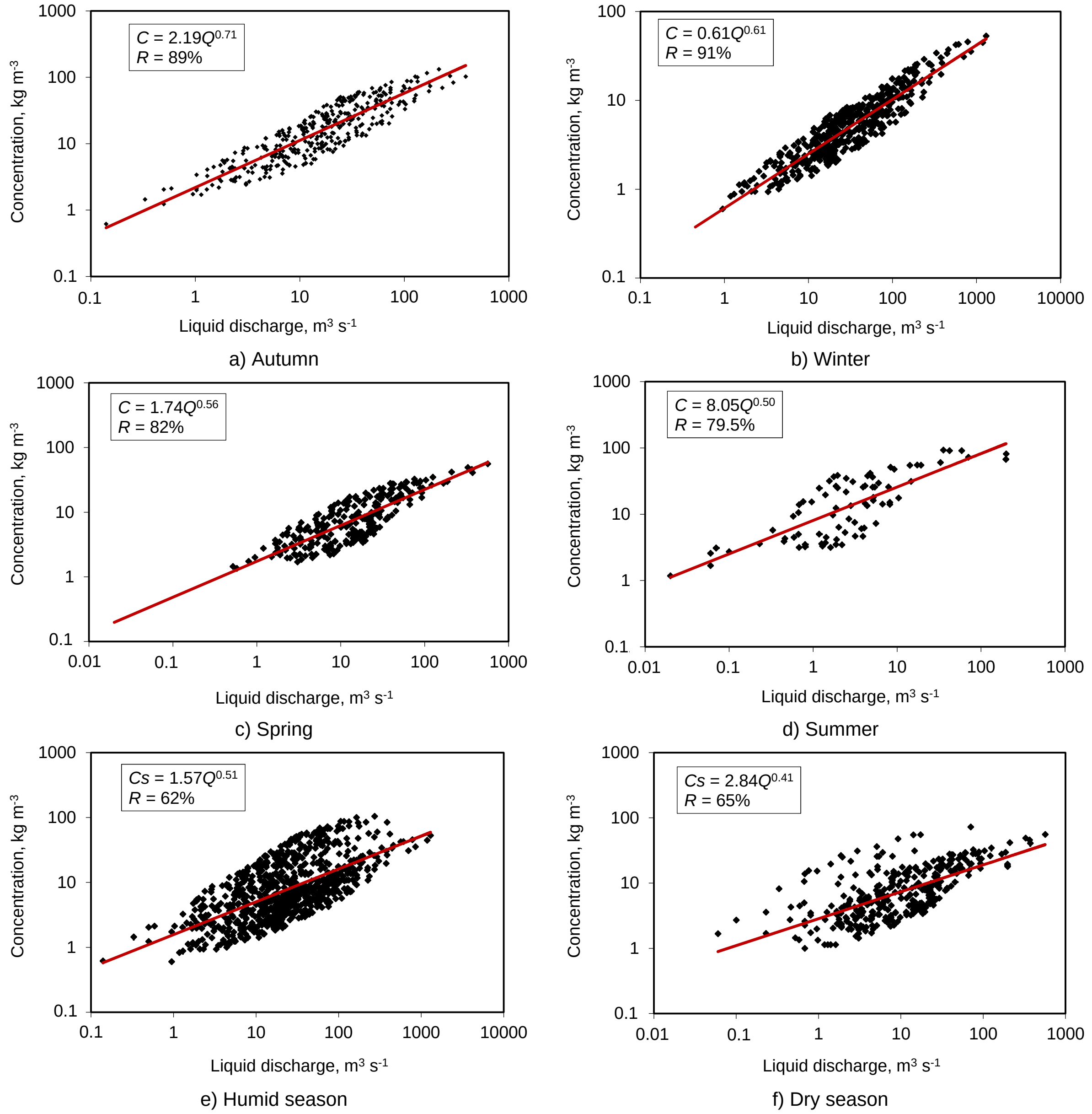

Fig. 3. Seasonal correlation between solid concentration and liquid discharge; source: own study

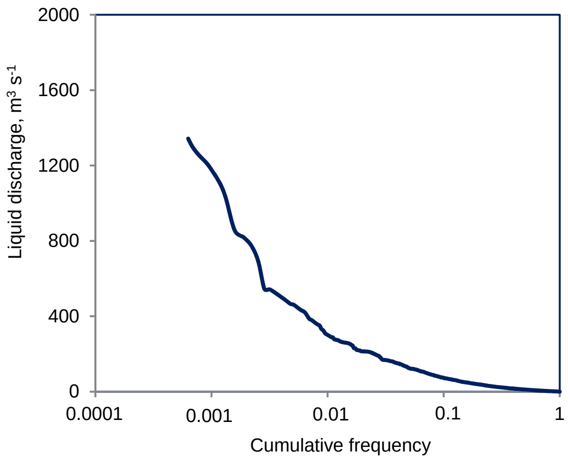

Fig. 4. Liquid discharge duration curve in annual scale; source: own study

Table 3. Characteristic of liquid discharges

Period	Taille	Mean and confidence interval	Standard deviation and confidence interval
Annual	6 312	32.14 ± 1.91	77.47 ± 1.35
Autumn	2 196	12.34 ± 1.23	29.50 ± 0.87
Winter	2 268	38.47 ± 3.10	75.27 ± 2.19
Spring	2 280	18.55 ± 2.45	59.69 ± 1.73
Summer	2 268	1.81 ± 0.01	2.04 ± 0.07
Humid season	4 464	25.69 ± 1.73	58.96 ± 1.22
Dry season	4 548	10.21 ± 1.25	43.12 ± 0.88

Source: own study.

ASSESSMENT OF INTER-ANNUAL AVERAGE CONCENTRATIONS

The model $C_s = KQ^A$ combined with the flow duration curve, allows to integrate the flows and their

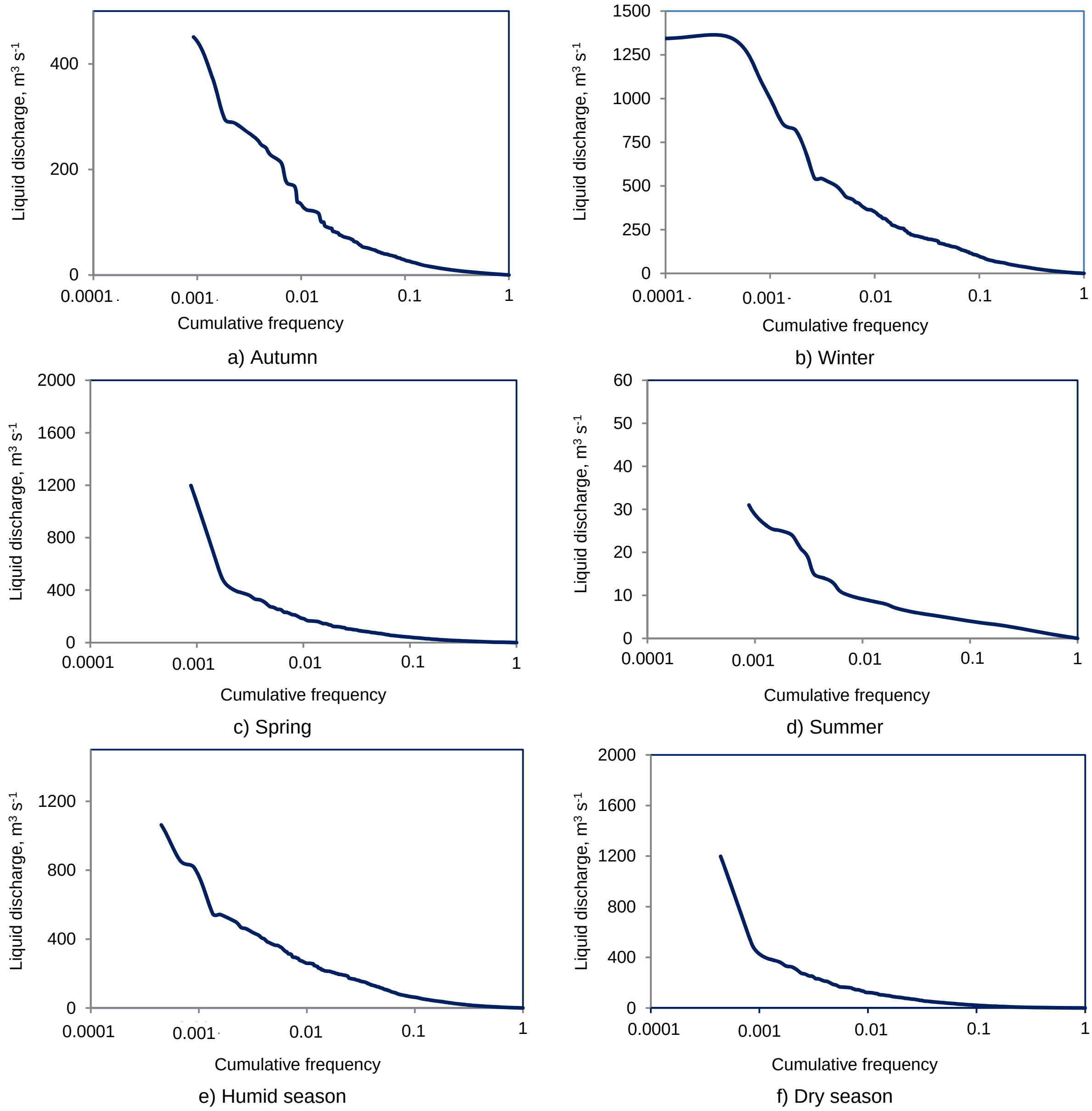

Fig. 5. Liquid discharge duration curve in seasonal scale; source: own study

frequency to better assess the inter-annual average solid concentration. The results obtained are shown in Table 4.

Table 4. Inter-annual average concentration of Wadi Chellif

Period	Mean liquid discharge $m^3 \cdot s^{-1}$	Average concentration $kg \cdot m^{-3}$
Annual	32.5	7.54
Autumn	12	10.5
Winter	39	4.5
Spring	19	6.6
Summer	2	10.0
Humid season	26	6.0
Dry season	10	7.3

Source: own study.

CORRELATION BETWEEN SOLID FLOW – CONCENTRATION (SECOND CORRELATION)

For a reliable estimate of suspended sediment yield, a second correlation was undertaken, this time the correlation concerning solid flows with recorded concentrations because solid flows are closely related to solid concentration in water within the Cheliff wadi. This second correlation can be characterized as a corrective correlation of the first correlation. For that station a relations $Q_s = F(C_s)$ was established for the same periods. The value paired data (C_s, Q_s) was reported on a logarithmic scale, and the scatter plot showed excellent correlation types $Q_s = \gamma C_s^{\alpha}$.

Figures 6 and 7 represent different annual and seasonal relationships of solid flow as a function of solid concentration. Table 5 summarizes the different seasonal relationships and their correlation coefficients.

SUSPENDED SEDIMENT YIELD

The fitting of the inter-annual average concentration in the model $Q_s = \alpha\, C_s^{\beta}$ allowed to determine the average suspended solid flow rate in the Chellif basin, which enabled the assessment of the solid yield transported by Chellif wadi and the specific degradation of its watershed. Table 6 summarizes the results obtained.

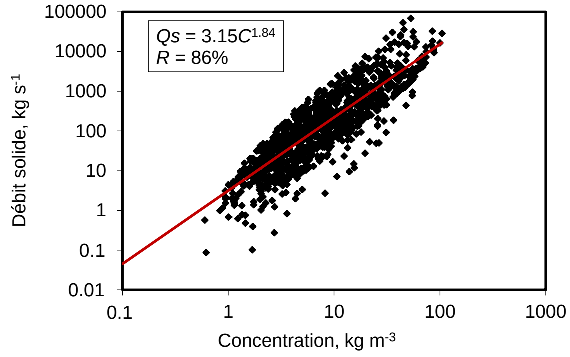

Fig. 6. Annual correlation between sediment discharge and solid concentration; source: own study

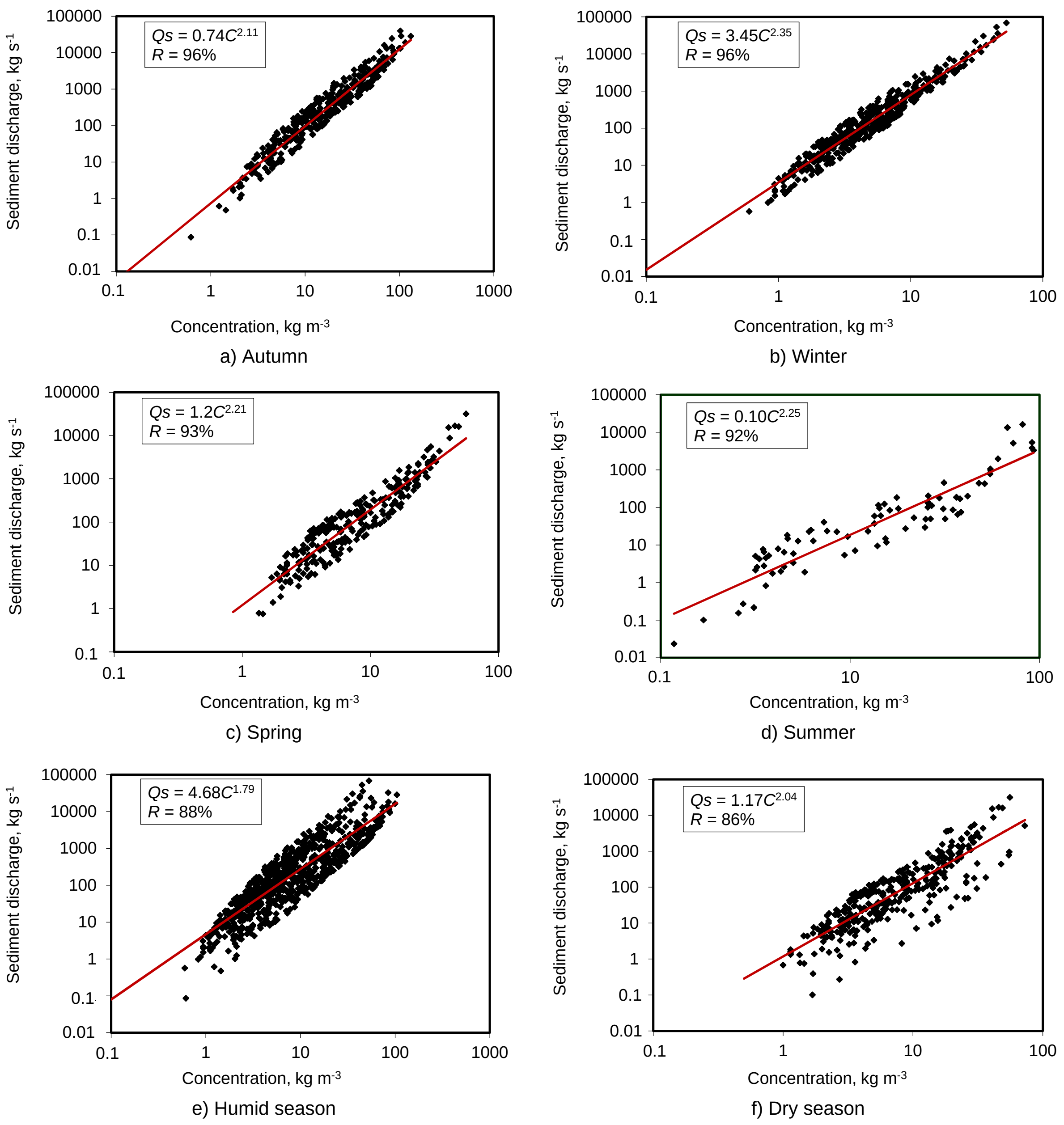

Fig. 7. Seasonal correlation between sediment discharge and solid concentration; source: own study

Table 5. Relationships and correlation coefficients

Period	Number of points	Coefficient			Correlation coefficient, %	Prediction interval	Relationship
		α	β	γ			
Annual	1190	1.84	0.498	3.15	86	± 28.36	$3.15C_s^{1.84}$
Autumn	360	2.11	–0.132	0.74	96	± 07.32	$0.74C_s^{2.11}$
Winter	489	2.36	0.538	3.45	97	± 04.97	$3.45C_s^{2.36}$
Spring	258	2.21	0.079	1.20	93	± 8.98	$1.20C_s^{2.21}$
Summer	83	2.26	–0.984	0.10	92	±26.68	$0.10C_s^{2.26}$
Humid season	725	1.77	0.670	4.68	88	± 24.68	$4.68C_s^{1.77}$
Dry season	341	2.04	0.069	1.17	86	± 24.02	$1.17C_s^{2.04}$

Source: own study.

Table 6. Suspended sediment contribution in Chellif basin

Parameter	Period						
	annual	autumn	winter	spring	summer	humid season	dry season
Solid suspension flow, kg·s^{-1}	130.53	108.44	121.65	77.69	18.73	114.37	34.70
Inter-annual average concentration, g·l^{-1}	7.30	10.61	4.54	6.62	10.01	6.09	5.27
Average concentration, g·l^{-1}	4.02	8.62	3.14	4.09	9.76	4.41	3.31
Solid contribution, 10^{6}t in period	4.12	0.85	0.96	0.61	0.15	1.80	0.55
Specific degradation, t·km^{-2} in period	94.20	19.56	21.95	14.02	3.38	41.27	12.52
Annualcontributionsolid,10^{6}t in year	**4.12**	**2.57**				**2.35**	
Erosion rate, t·km^{-2}·year^{-1}	**94.20**	**58.81**				**53.77**	

Source: own study.

INTERPRETATION OF RESULTS

In the first correlation (liquid concentration-speed) the best correlation is obtained by seasonal reasoning, particularly in autumn, winter and spring which reflects the influence of season on the phenomenon studied, except in summer where a coefficient correlation of 79% result probably indicating involvement of some special events in this season (summer rainfall, cultivated land), the most significant is that relating to the winter (91%) due to the regularity of discharges. In the other approaches (annual and semestrial) the correlation coefficients are between 61% and 65% significantly lower than the first confirming the variation of discharges according to the seasons.

In the second correlation method, satisfactory correlations were obtained because all correlation coefficients exceeded 86% while excellent correlations were found in seasonal applications (>92%). It should be noted that the largest estimated average concentration was obtained in summer and in autumn because in it there's intervention of floods due to the sudden and erratic rainfall falling on cultivated land, in autumn indicates the first rainfalls which falls on dry soil and bare of vegetation cover. The lowest concentration was obtained in winter as result of permanent leaching of the wadi in this season, while in other applications they are nearest to each other.

The specific degradation of watershed Chellif remains relatively important because it is subject to widely varying physical and climatic conditions (between 53.7 and 94.2 t·km^{-2}·year^{-1}) and is clearly less than the results found in a previous study on the watershed of Tafna (between 301 and 621 t·km^{-2}·year^{-1}) [BOUCHELKIA 2013] but remains well above the suspended sediment load found in the watershed of Oued Mouillah (between 17.73 and 28.41 t·km^{-2}·year^{-1} on period1974–1999) located within the Tafna basin [BOUCHELKIA 2011].

It is less than the result found by TERFOUS *et al.* [2001] for the watershed of Mouillah (126 t·km^{-2}·year^{-1} on a study period from 1977 to 1993), but it is noted that their estimate does not take account of frequency of liquid discharges and in the same manner, it is far from the specific degradation obtained by MEGNOUNIF *et al.* [2003] on a sub-basin in Tafna using data on 5 years of observation (1120 t·km^{-2}·years^{-1}).

In terms of solid intake, the values in seasonal and semestrial reasoning are relatively similar (2.56 and 2.4), which shows the precision of seasonal approach. It is noted that in winter the suspended sediment load are the most important (0.96·10^6 tones) because in this season the liquid flows are important and more regular and floods are more frequent than in other seasons, although the average concentration is greatest in autumn 8.62 g·l^{-1}.

CONCLUSION

This estimation approach allows the designer and manager of structures to better estimate sediment transport and to predict losses in capacity. This approach was applied to quantify the suspended sediment load in the station of Sidi belatar located at the outlet of the Chellif watershed during the period 1972–2000. The estimate was based on a double correlation (liquid discharge – solid concentration) and (concentration – solid discharge). The results showed that sediment yield in autumn and winter are the most abundant. They further indicate that erodibility of watershed of Chellif is very important, since the maximum value of solid contributions found is 4.12 10^6 t·year^{-1}. Different results are obtained depending on the application (annual, seasonal), but the importance and nature of the structure will be predetermining in the choice of application. A comparison of these with experimental and situ measurements allows to make the best choice.

The proposed method in this study can be used as a simple tool and directly applicable for estimating the suspended sediment load of all Algerian watersheds.

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Ilościowa ocena ładunku zawiesiny w zlewni Chellif (Algieria) metodą podwójnej korelacji

STRESZCZENIE

Słowa kluczowe: *Chellif, model, ocena ilościowa, przepływ części stałych, statystyka, zlewnia*

Rzeki Algierii transportują duże ilości zawiesiny. Jej ilościowa ocena w niektórych ciekach okresowych jest jednak utrudniona ze względu na brak danych, szczególnie o zawiesinie drobnocząsteczkowej. Brak jest również stałych przekrojów pomiarowych. Aby wypełnić tę lukę, opracowano metodę oceny ładunku zawiesiny na podstawie danych rejestrowanych w wybranym przekroju poprzecznym rzeki. Ocenę ładunku prowadzono za pomocą analizy statystycznej z użyciem podwójnej korelacji ze średnim dziennym przepływem i stężeniem zawiesiny. Wyniki uzyskane z zastosowaniem tego modelu do zlewni rzeki Chellif są obiecujące, ponieważ współczynniki uzyskane za pomocą modelu wynosiły od 61% do 91% w przypadku pierwszej korelacji i od 86% do 97% w przypadku drugiej korelacji. Oszacowany ładunek zawiesiny był znaczący i wynosił od 2,35 do 4,12 mln t·r^{-1}. Taki wynik jest pochodną podatności basenu rzeki Chellif na erozję i burzliwego przepływu wody w rzece.