GeoScience Engineering

ANALYSIS AND QUANTIFICATION OF WATER EROSION IN NORTHERN ALGERIAN WATERSHEDS

Mahieddine BELLOUT[1], *Djamel BOUTOUTAOU*[1]
1 *University Kasdi-MERBAH Ouargla, Laboratories Exploitation and Valorization of Natural Resources in Arid Zones, Ouargla, Algeria*
E-mail: belloutmahieddine@yahoo.fr

ABSTRACT

Algeria is characterized by a semi-arid climate, particularly vulnerable to erosion of agricultural land, where physical, hydroclimatic, geomorphological and socio-economic conditions are highly favourable to the onset and acceleration of this phenomenon. High concentrations of suspended sediments transported by rivers to dams and reservoirs represent a significant problem for water management and the sustainability of these infrastructures. During this study, solid transport data were collected from the Agence Nationale des Ressources Hydrauliques database. The data set includes a total of 132 hydrometric stations throughout the country. Exploiting pairs of instantaneous liquid flow measurements (m³/s) and instantaneous solid flow measurements (kg/s) has led to the establishment of regressions at different time scales, thus concluding that the power model is the most appropriate based on the coefficient of determination R^2. The average annual specific erosion varies from one watershed to another, generally between 11,75 and 5978,34 T/km².year. The principal component analysis (PCA) method was used to study the average monthly solid discharges of 132 hydrometric stations, and the results obtained highlight the presence of four hydrologically homogeneous groups. Multiple regression was performed on the four groups to highlight a potential relationship between the dependent variable, specific erosion, and other explanatory variables. The correlations indicate that each group is influenced by parameters distinct from the others, as in the case of group A, where the correlations between specific erosion, on the one hand, and the other hand, the Average slope of a watershed (Im), lithology index (IL), runoff coefficient (RC), and the normalized difference vegetation index (NDVI) are significant.

Keywords: Water Erosion; Regionalization; Watersheds; Algeria; Solid Transport.

1 INTRODUCTION

Water erosion is a major environmental problem that affects many regions of the world, particularly agricultural areas. Since the 1930s, scientists have begun to study this phenomenon in depth, which has allowed for a better understanding, quantification, and modelling of erosion in different environments. It is a geographical and environmental phenomenon whose impact and severity vary considerably from one site to another. This variability depends on several natural and human factors that influence the intensity of the process and its consequences. This phenomenon is a characteristic of the Maghreb region, whose water and soil potential are seriously threatened [19;17;1;15]. In Morocco, the annual cumulative land losses are estimated at 100 million tons; in Tunisia, water erosion totals 8.5 million hectares, representing 52% of the country's total area [15]; in Algeria, 45% of the Tellian region is affected, which amounts to 12 million hectares; approximately 6 million hectares are currently undergoing active erosion [20]. Algeria has extreme climatic conditions characterized by significant spatial and temporal precipitation variability. In autumn, it is expected to observe intense precipitation, often reaching intensities exceeding 45 mm/h, especially combined with often insufficient vegetation cover and sometimes inadequate management, causing severe floods accompanied by a rapid rise in waters carrying high suspended matter concentrations. This leads to significant consequences both upstream and downstream, affecting ecosystems, infrastructure, and populations, making this phenomenon particularly concerning. Generally, the

DOI 10.35180/gse-2024-0108

average annual specific erosion ranges between 2 000 and 4 000 t/km² [6]. The annual loss of storage due to sedimentation in dams is estimated at around 20 million cubic meters [13]. The modelling of the relationship between liquid flow and solid flow is crucial for anticipating the evolution of sediment transport in a watershed, particularly at its outlet or even in the reservoirs of downstream dams [10]. Different models can be used to explain this relationship. Among these models, the predominant one consists of a power function that establishes a link between the concentration of suspended sediments and the water flow rate [14]. Many studies have attempted to describe specific erosion based on various parameters and the hydrological characteristics of the watershed [11;22;21;16;5;4;6]. However, this work needs to be improved due to the need for more quality data. It is based on a regional approach to estimate specific erosion, considering each watershed's specificities and using adapted models and locally collected data. This study aims to establish regressions between liquid flow and solid flow at different time scales for 132 hydrometric stations, quantify solid transport and assess specific degradation in these rivers without measurement data. This requires adopting an innovative methodology that combines numerical models, remote sensing techniques, spatial data and empirical approaches.

2 METHODS

2.1 Presentation of the study area

Our study area is located in the northern part of Algeria, between longitudes «2° and 9°» West and East, respectively, and latitudes «33° and 37°» North, covering an area of around 365 000 km^2. It extends over a width of around 35 myriameters and 100 myriameters along the coast. Morocco and Tunisia form the western and eastern boundaries, respectively, the Mediterranean Sea, the northern boundary and the southern flanks of the Saharan Atlas, the southern boundary. It is characterized by a Mediterranean climate in its northern part and a sub-desert climate in its southern part (see Figure 1).

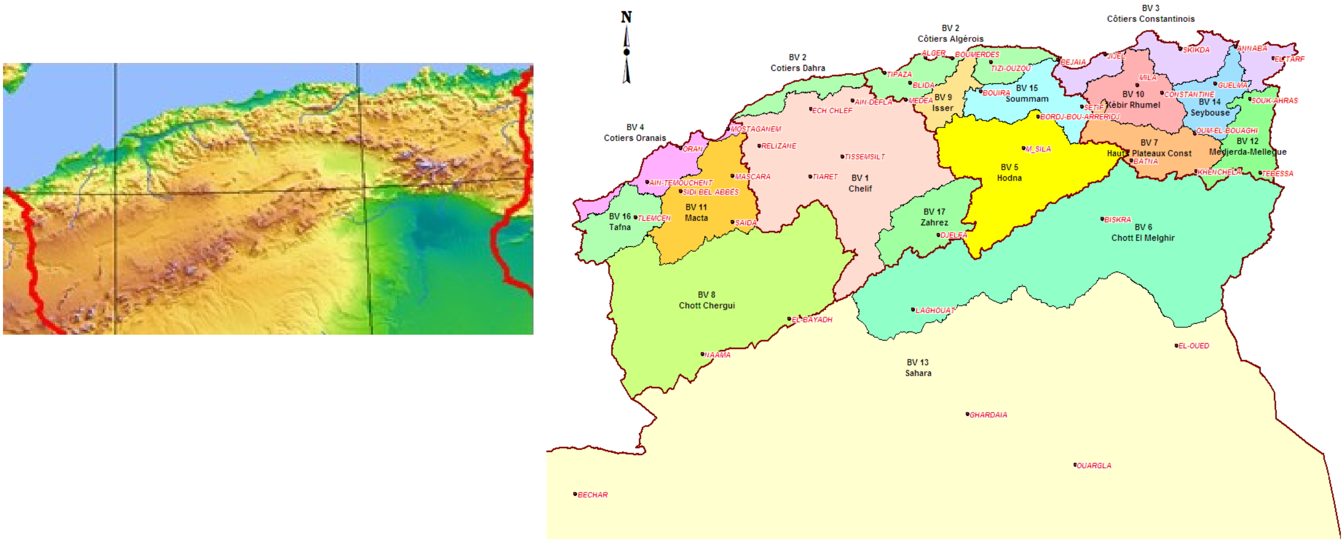


Figure 1. *Location of the study area*

2.2 Presentation of data

Collecting and formatting data is the initial phase of any statistical study: Duband (1989) states without exaggeration that this represents 30 to 50% of the work. Ambroise (1998) shows that applying any mathematical model presupposes prior knowledge of the data needed to develop it.

Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

The data used are instantaneous solid flow values, expressed in kg/m^3, derived from instantaneous liquid flow values, expressed in m^3/s, multiplied by the suspension concentration, expressed in g/l, measured at the catchment outlets.

There are two methods for measuring liquid flow: based on the tarage curve from the water heights recorded on a limimetric scale on the one hand, and on the other by depriving the water levels recorded by a float limnigraph. For each liquid flow measurement, a measure is performed to assess the load of suspension material, which is obtained from a sample of water taken on the banks of the water stream and then dried to have a load concentration in g/l; the solid flow is then deducted by the product of the concentration by the corresponding liquid flow Ql. These measurements are carried out at the watershed monitoring station, and the sampling frequency varies depending on the hydrological regime; it is intensified during rainy periods and periods of high loads up to ten minutes apart.

The collection of this data is the responsibility of the Algerian National Water Resources Agency (ANRH).

Figure 2 illustrates the spatial distribution of the 132 hydrometric stations collected in northern Algeria after these coordinates have been corrected.

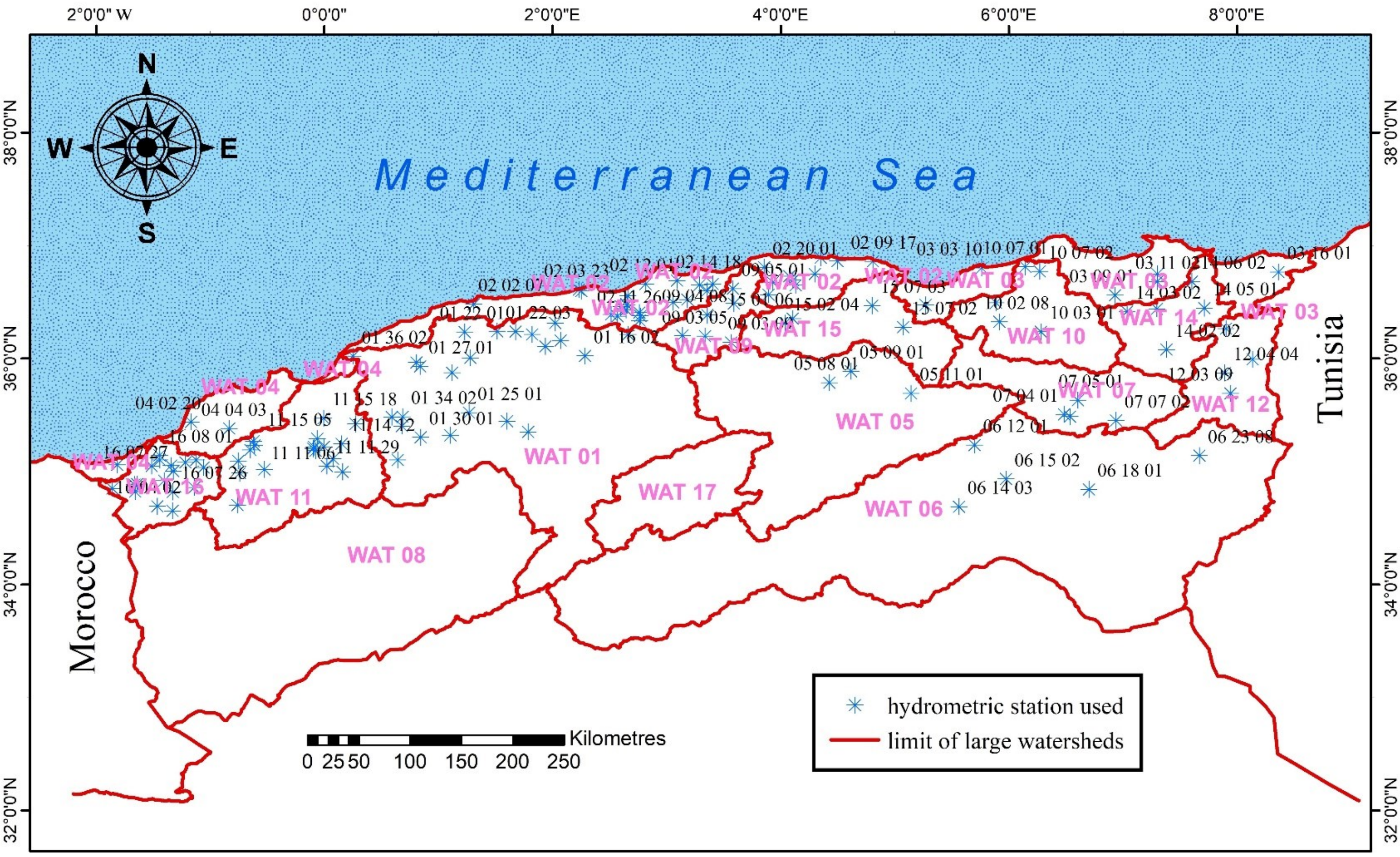


Figure 2. *The spatial distribution of the hydrometric stations used*

2.3 Hydromorphometric characteristics of collected watersheds

Conventional techniques used to study the physical complex of a watershed are mainly based on manual methods, the results of which are generally unreliable.

Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

Because of the systematic errors in the boundaries of the watersheds collected, and with the advent of new tools such as GIS and remote sensing, it has become easy to determine the shape, relief and typology of a hydrographic network. Therefore, we were obliged to delimit these watersheds to correct the existing errors.

2.4 Analysis method

2.4.1 Establishment of regression between liquid and solid flow

The data from the instantaneous values of solid and liquid flows were processed on different time scales: daily, monthly, annual, seasonal (autumn, winter, spring, and summer), wet season, and dry season, for all stations, in order to establish regression models and to have an initial idea of the dynamics of solid transport, specifically the liquid flow-solid flow relationship.

The main regressive models are:

- The linear model: $Y = aX + b$
- The parabolic model: $Y = aX^2 + b X + c$
- The power model: $Y = a X^b$
- The exponential model: $Y = a e^{bX}$
- The logarithmic model: $Y = a \ln X + b$

2.4.2 Annual solid input

The annual flow of suspended solids exported by the various rivers studied is calculated using the formula:

$$A_s = \sum_{j=1}^{N} (t_{j+1} - t_j) Q_j C_j \qquad (1)$$

Where: C_j is the concentration (g/l) measured at time t_j corresponding to liquid flow Q_j (m^3/s), N is the number of samplings carried out over the year in question, $t_{j+1} - t_j$ is the time step separating two consecutive samplings.

2.4.3 Solid transport modelling

The main objective of the modelling is to develop a model of specific erosion as a function of various climatic, hydromorphometric, geological and biophysiographic parameters (topography, vegetation cover, etc.) in t/km^2.year, in order to be able to generate a spatial model that will allow us to have the specific erosion at any point of the treated watershed.

3 RESULTS AND DISCUSSION

3.1 Characteristics of the basins at gauging stations

The hydromorphometric characteristics of some of the watersheds selected for this study are shown in Table 1.

Table 1. *The hydromorphometric characteristics of some watersheds*

Features	Settings	Symbol	Unity	Station codes								
				01 19 05	02 03 23	03 16 01	04 04 03	05 08 01	07 05 01	09 05 01	10 01 09	11 01 01
Physical characteristics	Surface	S	km^2	428,22	53,84	675,78	107,95	334,39	763,41	3615,56	927,31	961,47
	Perimeter	P	km	122,31	39,42	153,51	72,80	120,78	167,60	390,16	178,41	185,57
	Compactness index	K_c		1,66	1,50	1,65	1,96	1,85	1,70	1,82	1,64	1,68
	Length of equivalent rectangle	L	km	53,09	16,43	66,61	33,14	54,22	73,40	174,34	77,19	80,90
	Equivalent rectangle width	L	km	8,07	3,28	10,15	3,26	6,17	10,40	20,74	12,01	11,88
Features of the relief	Minimum altitude	H_{min}	m	330	12	33	140	557	879	115	396	927
	Maximum altitude	H_{max}	m	1 786	665	1 189	1 042	1 862	2 319	1 804	1 695	1 452
	Average altitude	H_{moy}	m	781,63	250,34	398,53	467,39	952,73	1 272,81	748,21	907,31	1 165,75
	Altitude corresponding to 5% of total surface area	$H_{5\%}$	m	1 255	476	829	746	1 448	1 762	1 130	1 274	1 276
	Altitude corresponding to 95% of total surface area	$H_{95\%}$	m	426	44	71	204	624	930	332	573	1 032
The slope indices	Overall slope index	Ig	%	1,56	2,62	1,13	1,63	1,52	1,13	0,45	0,9	0,3
	Rock slope index	Ip	%	4,64	5,84	3,82	4,67	4,32	3,87	2,63	3,64	2,15
	Average slope of a watershed	Im	%	23,43	24,15	19,05	16,71	15,51	16,03	20,19	22,85	7,44
	Specific gradient	Ds	m	323,12	192,89	295,84	169,91	277,89	313,18	275,22	276,54	93,52
Network settings hydrographic	Length of main watercourse	L_{cp}	km	44,85	18,36	49,52	31,64	40,15	69,63	175,35	70,28	66,38
	Average slope of main river	$\bar{I}$	%	2,16	1,99	2,05	1,74	2,25	1,68	1,01	1,28	0,93
	Order	O		7	5	7	5	6	7	8	7	7
	Drainage density	Dd	km/km^2	3,81	3,03	3,40	3,05	3,47	3,41	3,13	3,17	3,53
	Torrentiality coefficient	Ct		32,51	17,26	21,40	17,10	19,12	19,49	17,55	18,30	20,76
	Confluence ratio	Rc		1,88	1,73	4,11	6,15	1,90	1,89	1,81	1,88	1,94
	Length ratio	R_L		0,97	0,94	0,92	0,92	0,96	0,97	0,96	0,96	0,92
	Concentration time	Tc	H	8,83	4,61	11,66	2,19	8,38	13,54	25,01	12,56	18,09

The watersheds in our study area present a remarkable morphological diversity, with slope, basin shape and topography directly influencing water management and erosion risks. The most minor surface area watershed is at the SIDI BEKAI gauging station (5,52 km^2). The largest surface area corresponds to the watershed at the SIDI BEL ATTAR gauging station (43 952,76 km^2). On the other hand, the compactness index is more significant than one, varying between 1,19 and 2,49. Most of these watersheds have a relatively high to high relief, making them particularly sensitive to erosion. The length of the main rivers varies between 4,53 and 743,44 kilometres. We found that concertation times ranged from 2,43 to 89,26 hours.

As an illustration, the following figures (Fig 3, 4, 5, 6, 7). show some hydromorphometric characteristics of some of the watersheds studied.

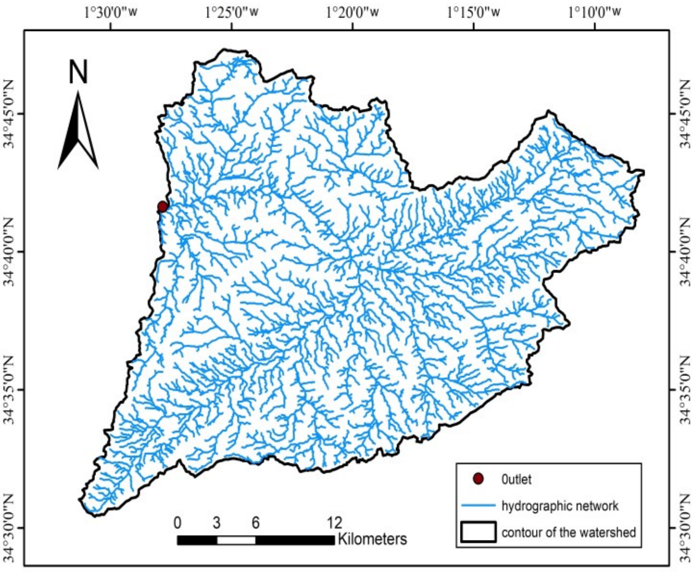


Figure 3. *Shape map of watershed 160402*

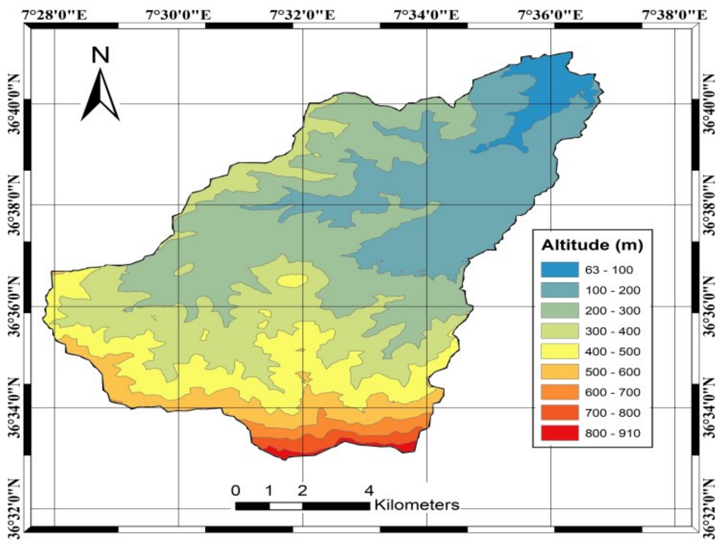


Figure 4. *Hypsometric map of watershed 140602*

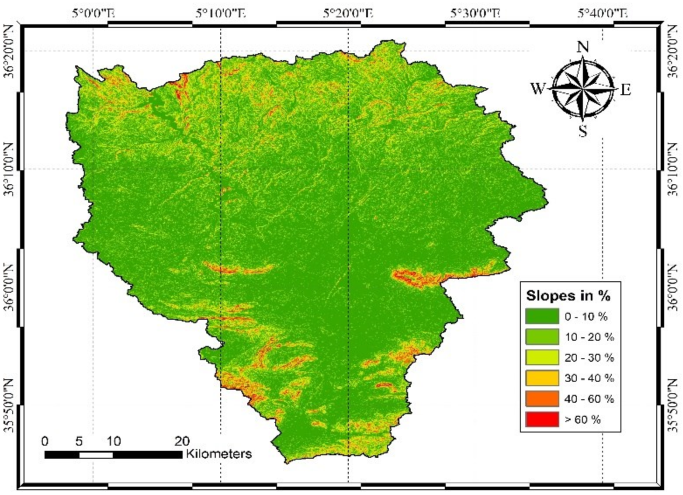


Figure 5. *Slope map for watershed 150702*

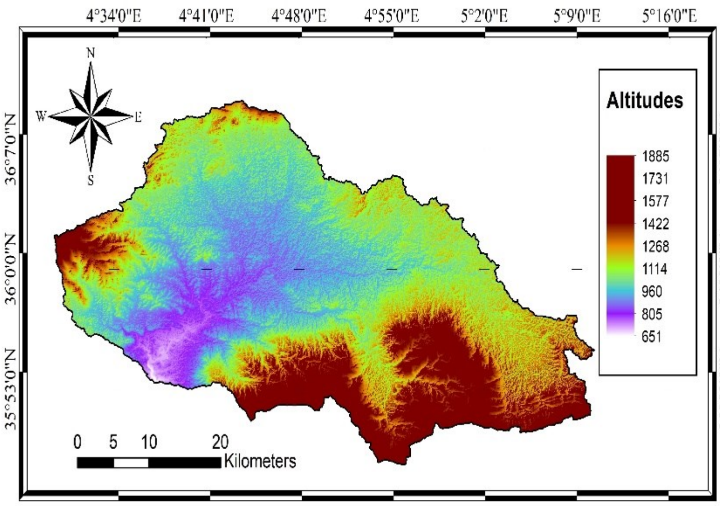


Figure 6. *Elevation map for watershed 050901*

Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

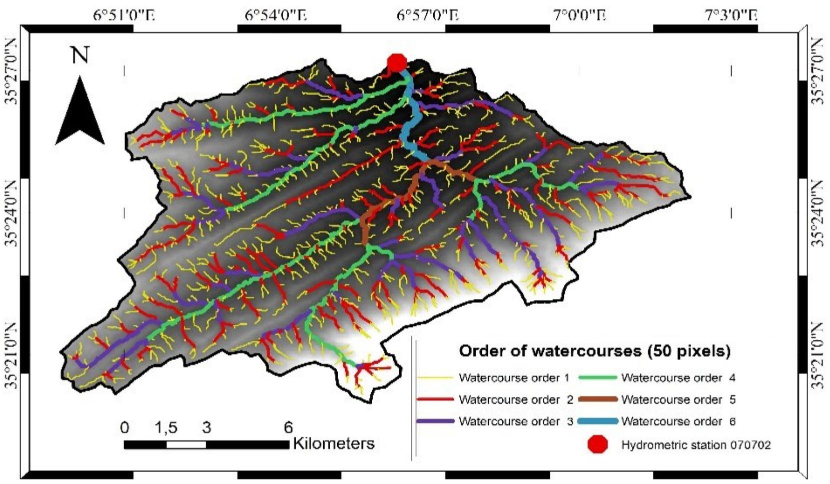


Figure 7. *River order map for watershed 070702*

3.2 Liquid and solid flow relationships

For all hydrometric stations at different time scales, according to Dagnellie (1992) referring to the coefficient of determination R^2, the power model is the most representative, as demonstrated by various studies conducted in Algeria [6;20;4;3].

As an illustration, figure 8 and table 2 represents the relationship between liquid and solid flows at different time scales of some watersheds in the study area.

Table 2. *Adjusted models for the different temporal scales and coefficients of determination*

Temporal scales	Selected model	Variation of parameter a	Variation of exponent b	Example for some watersheds		
				Station code	Determination coefficient (R^2)	Relationships retained
Interannual	Power: $Qs = a\,Ql^b$	0,08 - 85,39	0,79 - 1,91	013301	0,8462	$Q(s) = 1{,}5512Q(l)^{1{,}5905}$
				111003	0,8370	$Q(s) = 3{,}8633Q(l)^{1{,}226}$
				160202	0,8188	$Q(s) = 0{,}817Q(l)^{1{,}6391}$
Daily		0,02 - 46,46	0,93 - 2,68	040220	0,8608	$Q(s) = 3{,}3858Q(l)^{2{,}2042}$
				050801	0,8977	$Q(s) = 8{,}6642Q(l)^{1{,}1811}$
				110201	0,8638	$Q(s)= 1{,}0132Q(l)^{1{,}8457}$
Monthly		0,042 - 36,54	0,78 - 2,22	120309	0,8921	$Q(s) = 9{,}0018Q(l)^{1{,}2934}$
				160726	0,7932	$Q(s) = 0{,}3257Q(l)^{1{,}1612}$
				013001	0,8636	$Q(s) = 3{,}8449Q(l)^{1{,}475}$
Annual		0,03 - 50,69	0,84 - 2,06	012701	0,8437	$Q(s)= 49{,}003Q(l)^{1{,}0741}$
				021126	0,8774	$Q(s) = 7{,}3662Q(l)^{1{,}0781}$
				051101	0,9051	$Q(s) = 12{,}594Q(l)^{1{,}2501}$
Fall		0,04 - 36,54	0,78 - 2,22	140602	0,8430	$Q(s) = 1{,}503Q(l)^{1{,}855}$
				111201	0,9012	$Q(s) = 6{,}9786Q(l)^{1{,}3151}$
				120309	0,9560	$Q(s) = 8{,}7911Q(l)^{1{,}4071}$
Winter		0,04 - 36,54	0,78 - 2,22	150703	0,9214	$Q(s) = 4{,}405Q(l)^{1{,}1417}$
				030310	0,8309	$Q(s) = 2{,}1859Q(l)^{1{,}3114}$
				061403	0,9094	$Q(s) = 20{,}088Q(l)^{0{,}7837}$
Spring		0,03 - 50,69	0,84 - 2,06	070401	0,9004	$Q(s) = 4{,}5536Q(l)^{1{,}3204}$
				100701	0,7771	$Q(s) = 1{,}7525Q(l)^{1{,}1558}$

				111501	0,8399	$Q(s) = 2,3297Q(l)^{1,3072}$
Summer		0,07 - 59,33	0,89 - 2,09	061801	0,8976	$Q(s) = 8,9429Q(l)^{1,3026}$
				070403	0,8445	$Q(s) = 21,141Q(l)^{1,0079}$
				111403	0,9303	$Q(s) = 5,9639Q(l)^{1,3177}$
Dry season		0,03 - 17,51	0,86 - 1,88	013402	0,8756	$Q(s) = 14,802Q(l)^{1,2108}$
				111425	0,8766	$Q(s) = 16,513Q(l)^{1,4812}$
				160611	0,8381	$Q(s) = 11,532Q(l)^{1,6485}$
Wet season		0,09 - 48,79	0,94 - 2,12	021201	0,8583	$Q(s) = 1,9756Q(l)^{1,2682}$
				150106	0,8364	$Q(s) = 0,4842Q(l)^{1,4108}$
				050901	0,8820	$Q(s) = 3,8024Q(l)^{1,4696}$

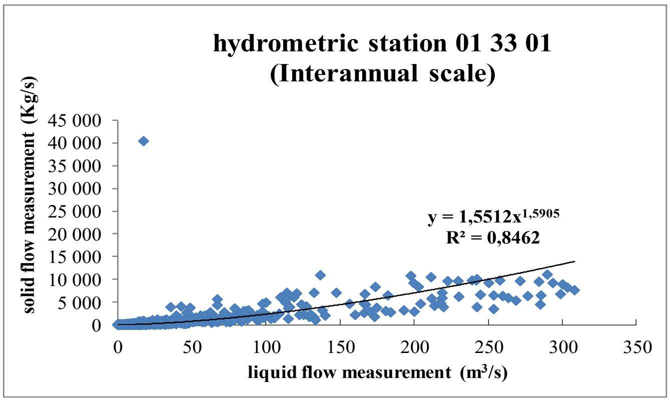
When expressing solid flows about liquid flows on an interannual scale, there is a very high dispersion of points, with values ranging from 0,08 to 85,39 for component a and 0,79 to 1,91 for exponent b. This dispersion can be explained by the fact that several factors control concentrations.

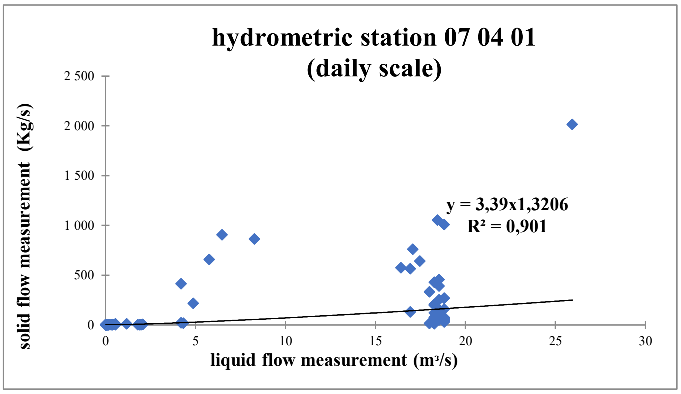
On a daily scale, the parameter a fluctuated from 0,02 to 46,46, while the exponent b also varied between 0,93 and 2,68.

Based on a monthly scale, it is possible to observe a decrease in the dispersion of points, characterized by a variation in the parameter a from 0,042 to 36,54 and in the exponent b from 0,78 to 2,22. The relationships on this scale are exciting and can be used in various studies.

On the annual scale, the dispersion of the points is not significant, with the parameter a and the exponent b varying respectively from 0,03 to 50,69 and from 0,84 to 2,06. Furthermore, just like monthly relationships, these relationships are exciting and can be used in various studies.

On a seasonal scale, the parameter a and the exponent b have different ranges of variation from one season to another, as each season has a rather distinct hydrological behavior. Autumn is characterized by precipitation on relatively dry soil, which promotes erosion and leads to significant solid concentrations. During the winter, the soil is relatively moist, making it more resistant to erosion, except when significant liquid inputs lead to considerable solid contributions. During the spring season, vegetation enhances the soil's resistance to erosion and often leads to a decrease in solid particle concentrations. During the summer, most waterways are dry; however, solid concentrations can be remarkable during floods.





Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

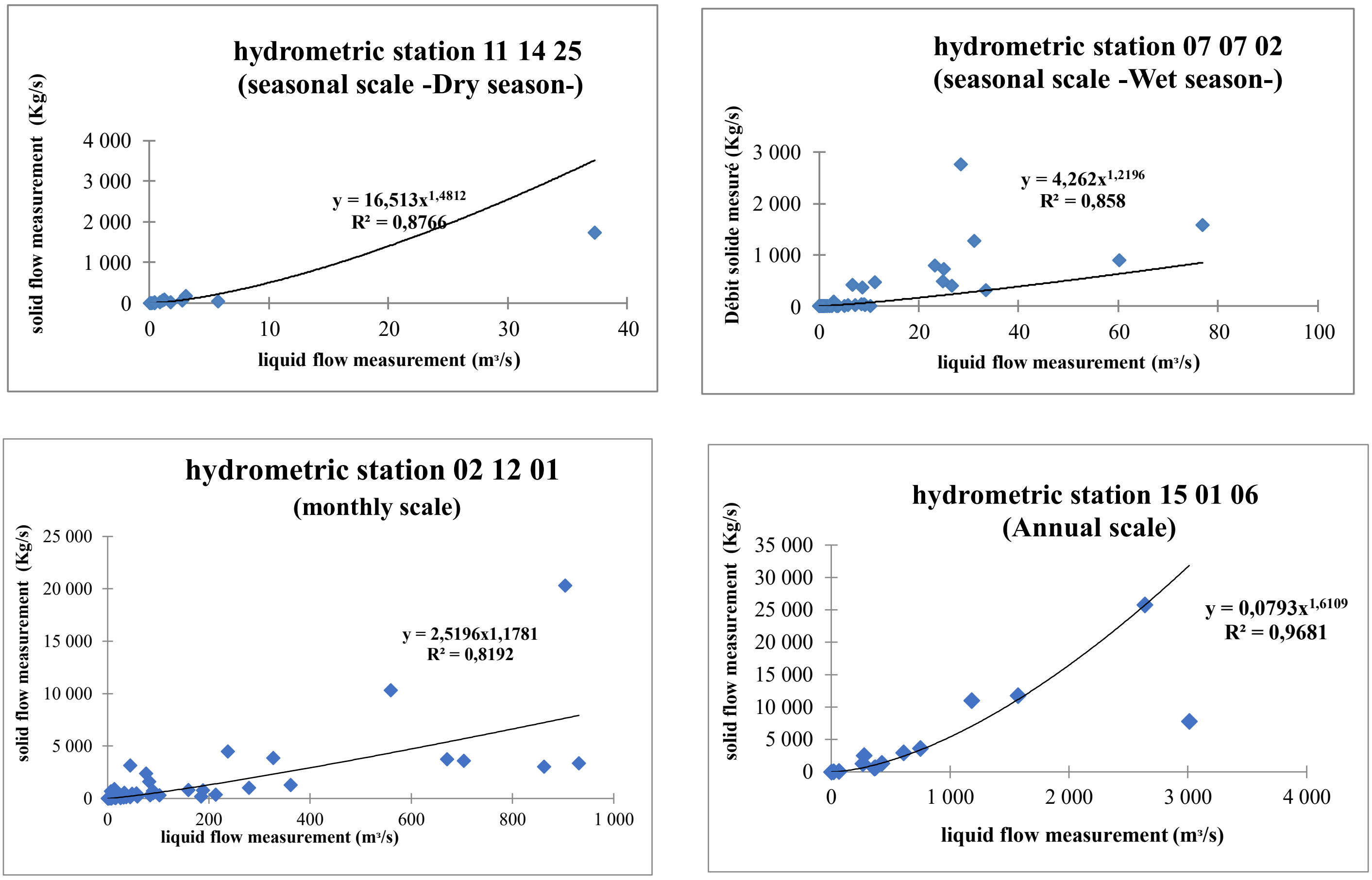
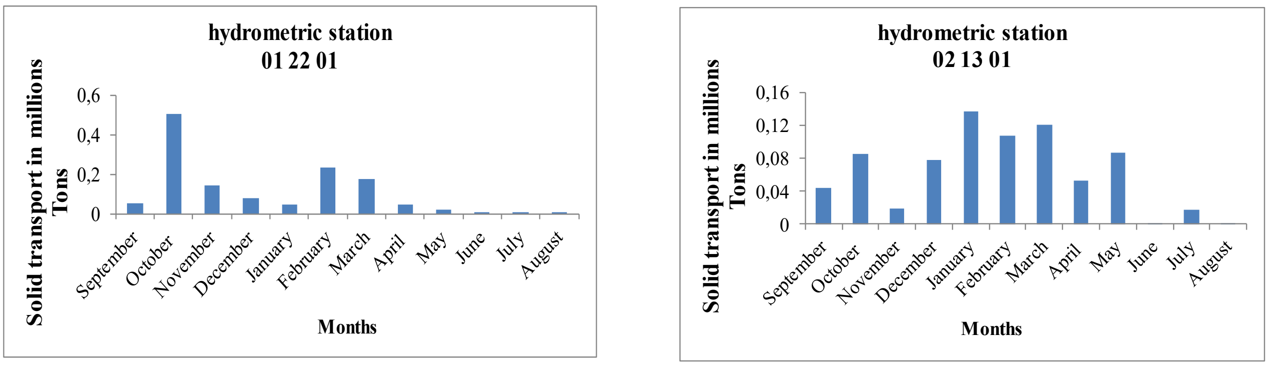


Figure 8. *Relationship between liquid flows and solid flows at different time scales*

3.3 Monthly distribution of solids input

The histograms illustrating the monthly distribution of solid inputs (Figure 9) show significant temporal and spatial variation in solid transport. The analysis of these monthly values shows that the amount of sediment transported throughout the year varies monthly and from one watershed to another. The solid transport in autumn remains the highest for most watersheds, far surpassing other seasons, due to several combined factors that promote erosion and intensify sediment transport, such as intense rainfall generating rapid runoff that carries away large quantities of fine sediments.



Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

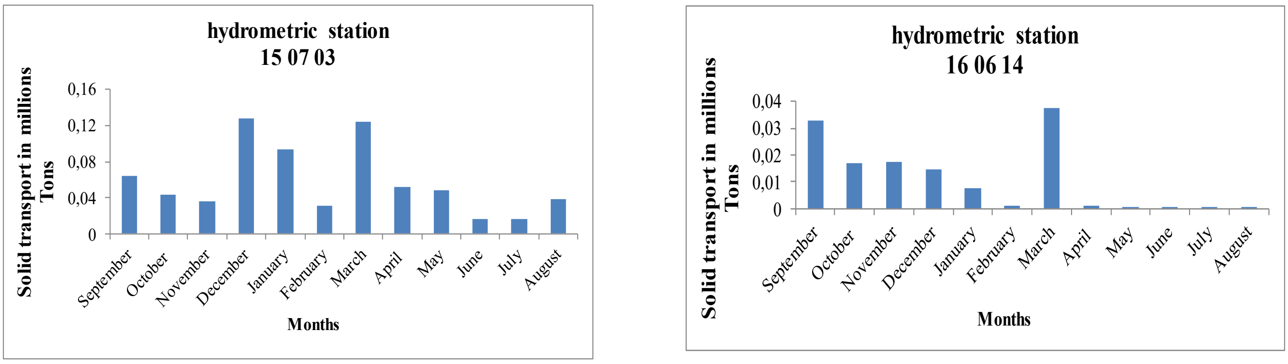


Figure 9. *Monthly distribution of solid inputs of some watershed*

3.4 Annual distribution of solid inputs

A significant year-to-year variation in solid inputs is observed in Figure 10 for most watersheds, illustrating that this phenomenon is far from uniform. These variations are closely related to liquid inputs, which are strongly correlated with precipitation at all time scales, serving as the generating factor, as well as the physical characteristics of the watersheds that give them their capacity to respond to water erosion (dominant lithology, vegetation cover, slope systems), as well as hydro-climatological data, which allow for an understanding of the temporal variability of solid transport.

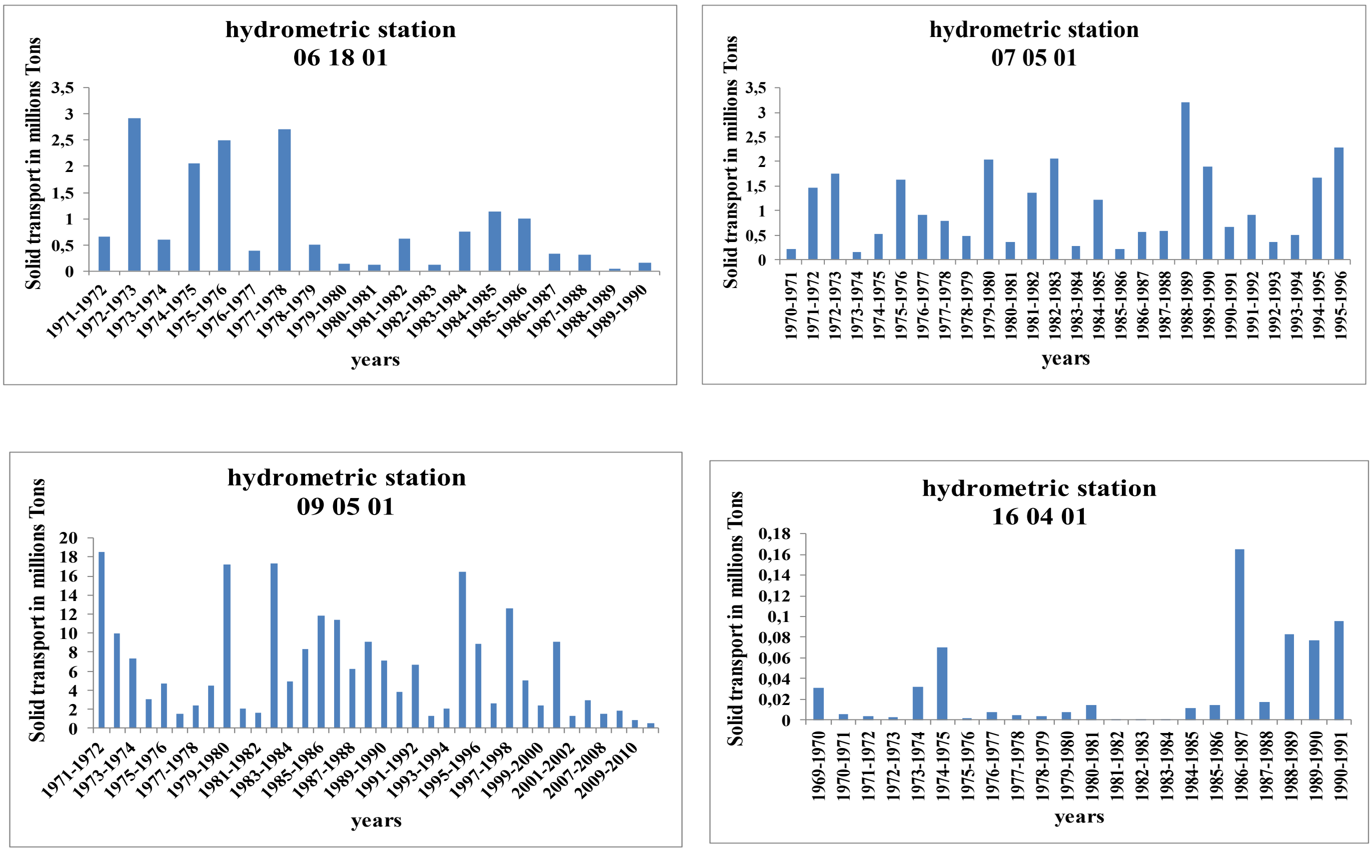


Figure 10. *Annual distribution of solid inputs of some watershed*

Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

3.5 Estimating specific degradation

Calculating specific degradation or specific erosion will give us an idea of the erodibility of each region. We do not have any measurements for calculating specific erosion, but solid transport is equal to 20% on average, according to some studies of Maghreb regions [18].The results of our calculations are presented in Table 3 for some watersheds.

***Table 3**. Specific erosion of some watersheds*

Station codes	Specific erosion (t/km^2.year)	Station codes	Specific erosion (t/km^2.year)	Station codes	Specific erosion (t/km^2.year)
01 33 01	349,21	06 14 03	56,02	12 04 01	139,93
02 13 01	2327,31	07 07 02	858,14	14 05 01	1079,83
03 16 01	914,54	09 03 05	388,95	15 01 06	620,48
04 04 03	662,08	10 07 01	1078,64	16 04 02	121,29
05 08 01	1487,53	11 10 03	160,67	16 06 01	120,94

The analysis of the results obtained shows that the erosive action varies from one basin to another, with a specific degradation in the study area ranging from 11,75 to 5 978,34 t/km^2.year. The minimum value is notable at the VILLAGE TAFNA station, while the maximum value stands out at the OULED FARES station.

Indeed, the degradation is particularly noticeable in areas with rugged terrain featuring steep slopes when the geological conditions and other parameters that influence this phenomenon are evident, as in the regions of Chlef, Blida, Boumerdès, Jijel, and Mila.

3.6 Regionalization of solid transport

In this study phase, we selected two mathematical techniques for multidimensional analysis: principal component analysis (PCA) and dynamic principal component classification (DPC).

These two techniques (PCA and DPC) were applied to monthly mean solid flows from 132 hydrometric stations to propose a classification of hydrological regimes.

Pearson (1901) first describes the principal component analysis, which is used to analyse and visualize a data set comprising individuals described by several quantitative variables, thus allowing the data to be studied in terms of correlation, namely to detect stations having the same behaviour.

The Dynamic Principal Component (DPC) automatic classification method was developed as part of a research project for the French Ministry of Agriculture [8]. The principle of this method [9] proposes partitioning *n* variables into *k* classes. This method's particularity lies in its focus on variables rather than individuals, as in most classification methods. This method is inspired by agglomeration techniques around moving centres and the properties of principal component analysis.

The results are presented in Table 4 and Figure 11.

***Table 4.** Results of the principal component analysis.*

Components	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
Eigenvalues	7,39	1,45	0,96	0,88	0,44	0,28	0,21	0,12	0,09	0,08	0,05	0,04
Variance explained (%)	61,60	12,10	8,00	7,36	3,63	2,35	1,74	1,04	0,78	0,64	0,40	0,35
Cumulative variance (%)	61,60	73,70	81,70	89,06	92,69	95,04	96,78	97,82	98,60	99,24	99,65	100,00

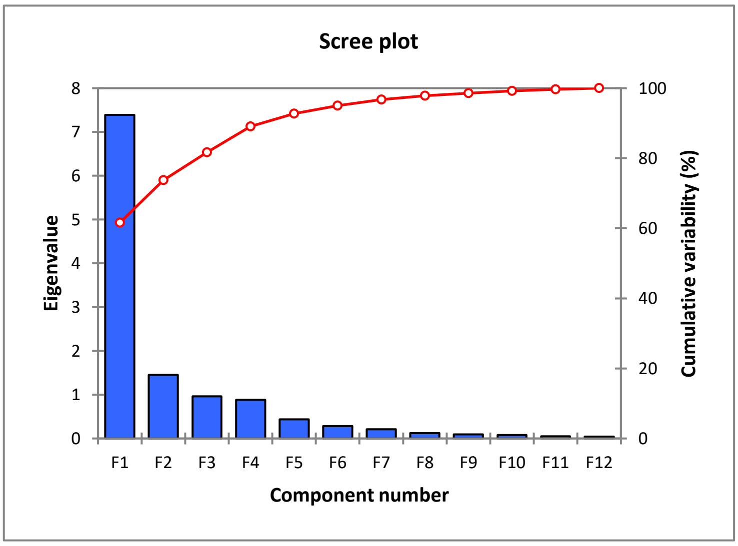


Figure 11. *Explained and cumulative variance of PCA results for the study area*

We note that the first two components explain a significant proportion of the total variance (73,70%), with the F1 component alone explaining 61,60%.

Projection of the variables onto the two main axes shows a clustering of the variables from November to May around the first factorial axis, with correlation coefficients exceeding 0,75. This forms the wet season, followed by a drop-off in the other months (June to October), which constitute the dry season. The first F1 component provides temporal information on seasonal variations in solid transport regimes. Stations positively correlated with this component are characterized by high solid flows. Projecting the variables onto the second principal component, F2, revealed a North-South separation, with the northern part correlating negatively with this component while the southern part correlates positively. Almost all stations fall into four groups. Figure 12 illustrates the spatial distribution of the different groups.

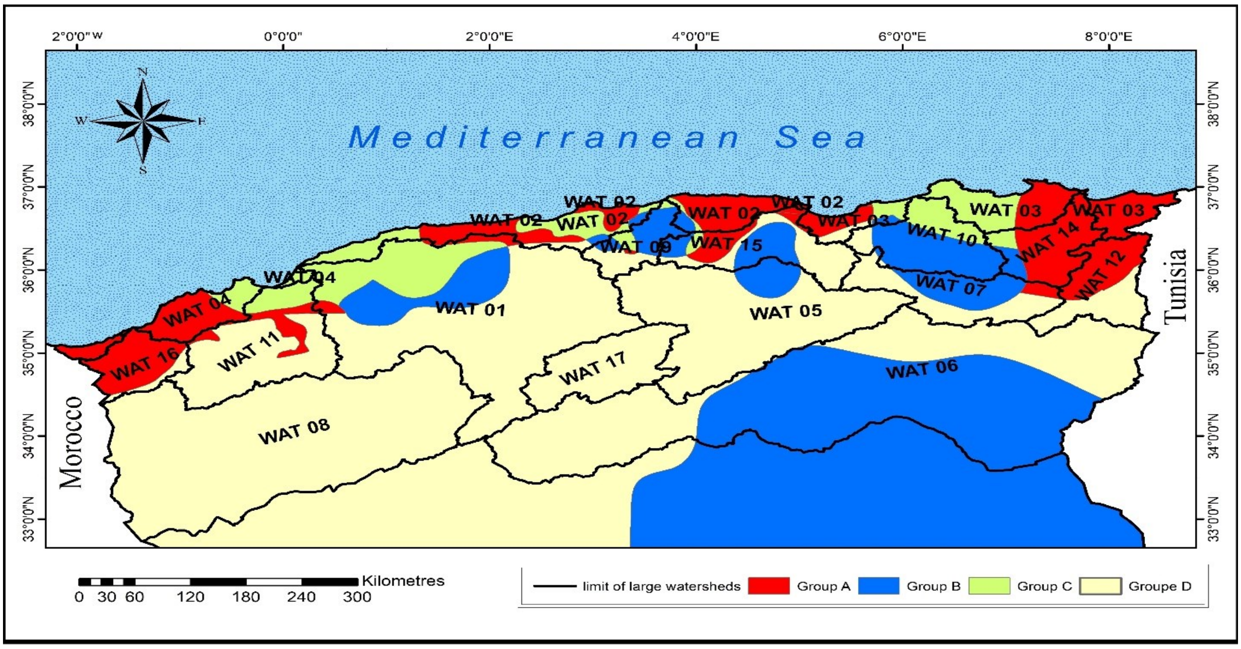


***Figure 12**. Spatial representation of the 04 groups identified in the study area*

Vol. 70 (2024), No. 2
pp. 01–16, ISSN 1802-5420
DOI 10.35180/gse-2024-0108

3.7 Multi-variate analysis of the "specific erosion" variable

Multivariate analysis aims to model the joint distribution of several variables, namely the variation of the variables taken individually and the correlations between them.

The study of multiple regressions was carried out using "XLSTAT" statistical software, which enabled us to validate the final parameters. After several trials, the specific erosion model is non-linear, with the exponential model being the most representative.

Here are the most representative models in each group:

Group A

$$Es = exp(5{,}037 + 0{,}048 \cdot Im + 0{,}018 \cdot IL + 0{,}043 \cdot Ce + 0{,}031 \cdot NDVI)$$

where

Im: Average slope of a watershed (%), can be calculated using the following expression $Im = H\left(\frac{0{,}5l_1 + l_2 + l_3 + \cdots + 0{,}5l_n}{S}\right)$
H: Equidistance between two contour lines (m);
l_i: Length of contour line of order $1,2,3,\ldots,n$ (km);
S: Watershed area (km^2);

IL: Lithology index, which refers to the percentage of shale with limestone and clay with argillites (%);

Ce: Runoff coefficient (%) is the ratio, expressed as a percentage, between the quantity of water drained and precipitated;

$NDVI$: The normalized difference vegetation index (%), calculated using ArcGIS software from images from the ETM+ sensor on the Landsat 7 satellite and images from the OLI and TIRS sensors on the Landsat 8 satellite, calculated by the formula: $NDVI = \frac{PIR-R}{PIR+R}$,
PIR: light reflected in the near-infrared spectrum;
R: light reflected in the red range of the spectrum.

Es: Specific erosion ($t.km^{-2}.year^{-1}$).

Group B

$$Es = exp(4{,}249 + 1{,}531 \cdot Kc + 0{,}043 \cdot Ce + 0{,}001 \cdot IL + 0{,}004 \cdot NDVI - 0{,}091 \cdot Tc)$$

where

Kc: Compactness index; this index is established by comparing the stylized perimeter of the basin to that of a circle with the same surface area, and is determined by the following relationship $K_c = 0{,}28\frac{P}{\sqrt{S}}$,
P: Basin perimeter (km);
S: Basin area (km^2);

Ce: Runoff coefficient (%);

IL: Lithological index (%);

$NDVI$: The normalized difference vegetation index (%);

Tc: Time of concentration (hours); This is the time it takes for the furthest water particle to reach the outlet. It is calculated by the GIONDOTTI formula, i.e.:

$$Tc = \frac{4\sqrt{S} + 1.5 \cdot L_{cp}}{0.8\sqrt{H_{moy} - H_{min}}}$$

S: Watershed area (km^2);
L_{cp}: Length of main watercourse (km);
H_{min} : Minimum altitude (m);
H_{moy} : Average altitude (m).

Group C

$$Es = exp(10{,}849 + 0{,}509 \cdot \bar{I} + 0{,}001 \cdot Cof + 0{,}011 \cdot Ce + 0{,}056 \cdot NDVI - 0{,}003 \cdot H5\%)$$

where

$\bar{I}$: Average slope of main watercourse (%); the slope is determined from the longitudinal profile of the watercourse using the following relationship:
$\bar{I} = \frac{\sum_{i=1}^{n} I_i}{n}$
I_i: partial slope of section i;
n: total number of segments;
Cof: Fourier orographic coefficient (m^2/km^2), corresponds to half the difference in elevation between the highest and lowest points in the area covered by the watershed, squared and divided by the area of the watershed;
Ce: Runoff coefficient (%);
$NDVI$: The normalized difference vegetation index (%);
$H5\%$: Altitude corresponding to 5% of total surface area (m), is derived from the hypsometric curve.

Group D

$$Es = exp(2{,}587 + 0{,}464 \cdot Ce + 0{,}011 \cdot P + 0{,}443 \cdot Ig - 0{,}080 \cdot Le - 0{,}056 \cdot NDVI)$$

where

Ce: Runoff coefficient (%);
P: Average annual precipitation (mm);
Ig: Overall slope index (%); this index is used to classify watersheds, and is calculated using the formula:
$I_g = \frac{D}{L}$
D: Vertical drop (m);
L: Length of equivalent rectangle (km).
Le: Average inter-annual water runoff (mm);
$NDVI$: The normalized difference vegetation index (%).

The models that emerged from the stepwise regression analysis were exponential models for the four groups, with regression coefficients of 0,88, 0,87, 0,93, and 0,94 for groups A, B, C, and D respectively. The results obtained show that specific erosion, according to their groups, is proportional to the average slope of a watershed, lithological index, flow coefficient, compactness index, mean mainstream slope, orographic Fournier coefficient, mean interannual precipitation and overall slope index, but inversely proportional to vegetation index, time of concentration and elevation corresponding to 5% of total area.

A steeper average slope generally increases erosion intensity in a watershed due to the runoff acceleration and the water's increased ability to move sediments. Lithology plays a crucial role in the erosion and transport processes; schists with limestones and clays/claystones are indeed more vulnerable to erosion due to their physical and chemical characteristics. The flow coefficient directly affects the speed of the fluid through a conduit or around a surface, which influences the shear forces exerted by the fluid on that surface. These shear forces are one of the main drivers of erosion, as they can dislodge solid particles from the surface. The compactness index influences erosion mainly by modifying the dynamics of water flow. Watersheds with a high index tend to present conditions favourable to faster erosive processes due to the concentrated and faster flow of water. The Fournier orographic coefficient plays an essential role in water erosion by influencing the distribution and intensity of runoff. More substantial withdrawals on exposed slopes reveal more intense runoff in mountainous areas where this index is high, leading to more severe forms of erosion. The amount of precipitation is one of the most determining factors in the erosion process, particularly in influencing runoff and the soil's ability to absorb water. The more abundant and intense the precipitation, the more severe the erosion will likely be. NDVI is a key indicator of vegetation cover and is crucial in managing water erosion. Dense vegetation cover, associated with a high NDVI, is generally beneficial for reducing soil erosion caused by water. At the same time, a low NDVI indicates insufficient vegetation cover and a greater vulnerability to erosion. The concentration time influences the speed and amount of water that runs off, which, in turn, affects the amount of erosion in a watershed. A short concentration time can exacerbate erosion, while a more extended time can help limit the effects of runoff. The influence of the height of the hypsometric curve on water erosion can be explained by the increased ability of high-altitude areas to manage water (thanks to better infiltration and vegetation protection). In contrast, low-altitude areas, which are more vulnerable, experience more significant runoff and, thus, more pronounced water erosion.

There are a multitude of criteria for evaluating the performance of a model, and we have chosen the Nash and Sutcliffe criterion as the best-known and most widely used.

Table 5. *Nash criteria and quality*

Group	Nash values (%)	Quality
A	84,71	Very good
B	82,35	Very good
C	90,92	Excellent
D	90,41	Excellent

We find that the Nash and Sutcliffe criterion values are excellent for groups C and D and very good for groups A and B according to the Kachroo classification.

These results show that the models used are generally reliable for all groups.

4 CONCLUSION

This study provides a comprehensive assessment of solid transport and specific erosion in the watersheds of northern Algeria, a region characterized by semi-arid Mediterranean climates and significant sensitivity to land degradation. By analysing data from 132 hydrometric stations, we developed empirical models that illustrate the relationships between liquid and solid flows at different temporal scales. The results show that erosion rates vary significantly across different watersheds, with specific erosion values ranging from 11.75 to 5978.34 T/km²/year. Factors such as the slope of the watershed, lithology, runoff coefficients, and vegetation cover significantly influence sediment dynamics, with rugged terrain and steep slopes contributing to higher erosion rates. Our regionalization approach, combining principal component analysis (PCA) and dynamic principal component classification (DPC), has identified four homogeneous groups based on the observed solid transport regimes. The study also demonstrates the effectiveness of exponential regression models for estimating specific erosion based on hydrological and physical parameters. This modelling approach provides a valuable tool for predicting and managing erosion risks in Algerian watersheds. Given the observed temporal and spatial variability, a targeted and watershed-specific approach is essential for more effective water and land management strategies, particularly in combating erosion. Future research should focus on improving data quality and extending models to other regions of Algeria by integrating more variables, such as land use changes and climate scenarios, to refine the understanding of erosion dynamics and improve management practices within a sustainable development framework.

REFERENCES

[1] ACHIT, M. and MEDDI, M. Spatial and temporal variability of streamflow and solid yields in semiarid areas. Case of the oued Mina basin (Northwest Algeria). *Journal of Water Science*. 2005, vol. 18, special issue, pp. 37- 56. Available from: https://doi.org/10.7202/705575ar.

[2] AMBROISE, B. Streamflow generation within small rural catchments in a temperate environment: 1 – Processes and factors. *Journal of Water Sciences*. 1998, vol. 11, no. 4, pp. 471-496. Available from: https://doi.org/10.7202/705317ar.

[3] BENKHALED, A. and REMINI, B. Variabilité temporelle de la concentration en sédiments et phénomène d'hystérésis dans le bassin de l'Oued Wahrane (Algérie). *Hydrological Sciences Journal.* 2003, vol. 48, no. 2, pp. 243–255. Available from: https://doi.org/10.1623/hysj.48.2.243.44698.

[4] BOUANANI, A. *Hydrology, solid transport and modelling study of some sub-basins of the Tafna (NW - Algeria).* State doctoral thesis. Tlemcen, Algeria: University of ABOU BEKR BELKAID, 2004.

[5] BOUCHELKIA, H., BELARBI, F. and REMINI, B. Quantification of suspended sediment yield by statistical analysis: the case of Mouillah watershed. *Water and Environment Journal*. 2011, vol. 19, pp. 29–41.

[6] DEMMAK, A. *Contribution to the study of erosion and solid transport in Northern Algeria*. Doctor of Engineering thesis. Paris: University of Pierre et Marie Currie, 1982.

[7] DUBAND, D. *Applied statistics in hydrology*. National Higher School of Hydraulics, France, 1989.

[8] LABORDE, J.P. *Data analysis and automatic mapping in hydrology. Elements of Lorraine hydrology*. Doctoral thesis. National Polytechnic Institute of Lorraine, National School of Applied Geology and Mining Exploration of Nancy, 1984.

[9] LABORDE, J.P Automatic classification of variables using Dynamic Principal Components. *Quantitative and applied spatial analysis*. 1991, vol. 30, pp. 53-66. ISSN 0751-7297.

[10] LEKFIR, A.; BENKACI, T. and DECHEMI, N. Suspended sediment assessment using fuzzy logic approach, application to Beni Amrane reservoir (Algeria). *Journal of Water Science.* 2005*,* vol. 19, no. 3, pp. 247-257.

[11] MEDFOUNI, M.N.; KORICHI, K. and MAROUF, N. Artificial Neural Networks vs Long Short-Term Memory Prediction of Solid Flow in Tafna Basin (North-West Algeria). *Ecological Engineering & Environmental Technology*. 2024, vol. 25, no. 3, pp. 275–286. Available from: https://doi.org/10.12912/27197050/181208.

[12] PEARSON, K. On lines and places of closest fit to a system of point in space. *Philosophical magazine*. 1901, vol. 2, no. 11, pp. 557-572.

[13] REMINI, B. L'envasement des barrages. *Bull. Réseau Erosion*. 2000, vol. 20, pp. 165 -171.

[14] REMINI, W. and REMINI, B. Sedimentation in dam in North Africa. *Larhyss Journal*. 2003, vol. 2, pp. 45–54. ISSN 1112-3680.

[15] SEMARI, K. and KORICHI, K. Water erosion mapping using several erosivity factors in the Macta Basin (North-West of Algeria). *Acta Hydrologica Slovaca*, 2023, vol. 24, no. 1, pp. 101-112. Available from: https://doi. org/10.31577/ahs-2023-0024.01.0012.

[16] SENOUCI, F. Specific degradation and solid transport in semi-arid zones – Case of the Oued Ouahrane watershed. Master's thesis. Chlef, Algeria: University of Hassiba BEN BOUALI, 2013.

[17] TERFOUS, A., MEGNOUNIF, A. and BOUANANI, A. Study of suspended solid transport in Oued Mouilah (North West Algeria). *Journal of Water Sciences*. 2001, vol. 14, no. 2, pp. 173–185. Available from: https://doi.org/10.7202/705416ar.

[18] TOUAÏBIA, B. and ACHITE, M. Contribution to the mapping of specific erosion in the Wadi Mina basin in the semiarid zone of northern Algeria. *Hydrological Sciences Journal*. 2003, vol. 48, no. 2, pp. 235–242. Available from: https://doi:10.1623/hysj.48.2.235.44691.

[19] TOUAIBIA, B.; AIDAOUI, A.; GOMER, D. and ACHITE, M. Temporal quantification and variability of sediment discharge in a semiarid area in northern Algeria. *Hydrological Sciences Journal*. 2001, vol. 46, no. 1, pp. 41–53. Available from: https://doi.org/10.1080/02626660109492799.

[20] ZEGGANE, H. *Study of the hydrological behavior of watercourses in Algeria, case of the Isser watershed, Algeria*. Doctoral thesis in science. University of Kasdi-Merbah, Ourgla, Algeria, 2017.

[21] ZEGGANE, H. and BOUTOUTAOU, D. Quantification and multivariate analysis of water erosion in the Mediterranean region. A case study of the Isser basin. northern Algeria. In: *TECHNOLOGIES AND MATERIALS FOR RENEWABLE ENERGY, ENVIRONMENT AND SUSTAINABILITY: TMREES*. 2016. Available from: https://doi.org/10.1063/1.4959411.

[22] ZEYNEB, T.; NADIR, M. and BOUALEM, R. Modeling of suspended sediment concentrations by artificial neural network and adaptive neuro fuzzy interference system method – study of five largest basins in Eastern Algeria. *Water Practice and Technology*. 2022, vol. 17, no. 5, pp. 1058–1081. Available from: https://doi.org/10.2166/ wpt.2022.050.