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Quantification of solid particle transport in suspension in a stream: Case of Wadi Zeddine Ain-Defla, Algeria

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Abstract: Arid and semi-arid areas are characterised by differentiation in meteorological conditions. Sometimes the rains are rare and not very intense and at other times they are dense and very intense, resulting in torrents that often lead to strong soil erosion. Most of the time, the losses occur at the solids level because the erosion effect is too high. In this study, we want to evaluate the transfer of solid sediments as a function of liquid transport in the basin of Wadi Zeddine at Ain Defla in Algeria. To understand this phenomenon, we used the data of liquid flows (Q_l, m^3·s^{-1}) and concentration of suspended sediments (C, g·dm^{-3}), transported in the river, the data collected by the NWRA (National Water Resources Agency), over 24 years have been used to find a relationship between these two quantities, to estimate the quantity of solid transport Q_s (kg·s^{-1}) in the watercourse of the catchment area studied. The results obtained show a good correlation between solid and liquid flows, with a correlation coefficient estimated at 90%, and the average annual sediment supply recorded at the outlet of the Wadi Zeddine watershed is estimated at around 88,048 Mg, which corresponds to 202 Mg·km^{-2}·y^{-1} erosion rate. This value is comparable to those found in other regions with similar hydrological regimes.

Keywords: Algeria, concentration of sediment, erosion, liquid flow, solid flow, suspension, Wadi Zeddine

INTRODUCTION

Water erosion is a very urgent issue, as large amount of solid matter is transported each year. This transport seriously threatens water and soil potential and is becoming increasingly severe [Bergaoui *et al.* 1998]. The silting up of hydraulic reservoirs influences the potential of water reserves, including its storage capacity by around 30·10^6 m^3 [Remini 2002]. This calls for fast and efficient intervention, and quantification of the solid matter transport based on reliable mathematical formulas [Elahcene, Remini 2009].

Algeria is a country with limited water resources, confirmed by [Bouanani 1999]. According to [Hadjadj 1997], the loss in soil is estimated to be 120·10^6 (Mg·y^{-1}). Amount of soil deposited in dams and reservoirs increases, reaching 484·10^6 m^3 in 1996 [Djeziri 1998]. It reached 700·10^6 m^3 in 2000 [Remini 2002]. There are 63 dams in operation in Algeria. Each year, 45·10^6 m^3 of silt is deposited at the bottom of 57 large dams in the country, representing an annual loss of storage capacity equal to 0.7% of the total capacity [Remini 2008].

Considering the urgency of this issue, the study of solid matter transport has become essential. A large number of researchers have tried to explain complex mechanisms of solid matter transport and quantify the volumes of sediments transported.

To determine solid matter transport parameters (liquid flows, rain, soil moisture, solid flows, etc.) and to understand the functioning of watersheds in the production of sediments, several authors in Algeria and elsewhere have based their work on the analysis of the solid charge evolution in the suspension as a function of liquid flows. These authors included Etchanchu and Probst [1986], Kattan *et al.* [1987], Probst and Amiote Suchet [1992], Terfous *et al.* [2001], Benkhaled and Remini [2003], Elahcene *et al.* [2013], Bouguerra *et al.* [2017], Kheniche *et al.* [2019] etc.

The present work seeks to: 1) provide a relatively exhaustive description of processes influencing the intensity of erosion and sedimentation; 2) search for reliable and simple statistical models to estimate and predict the quantities of solids that transit through the outflow from watersheds; 3) highlight relationships applicable to regions or watersheds in which measures are rare or non-existent.

In this context, this work deals with statistical modelling of solid matter transport in the watershed of the Wadi Zeddine based on relations connecting solid flow (Q_s) to liquid flow (Q_l), to determine the number of solid matter sources in the watershed. A series of data from 24 years (1990 to 2013) was collected from the National Water Resources Agency (Fr. Agence Nationale des Ressources en Eau) [NWRA 2017] to analyse and determine the general rule. Our interest in this basin is mainly motivated by the absence of studies devoted to it in this field and by the availability and diversity of data to implement this type of study.

Ain Defla is an Algerian province, which is mainly agricultural, and it is known in the country for its fertile land. Unfortunately, the land has gradually degraded. This degradation is due to many factors, including water erosion. Most of this land is exposed to torrential runoff or is located on the banks of rivers, which makes it more vulnerable to water erosion and, consequently, the loss of organic matter and suspensions.

To study the rate of degradation in this catchment area of Wadi Zeddine, the study compares results with other basins. Thus, we know if the phenomenon studied is more aggressive or the rate of degradation is within the standard.

Due to the importance of the region and the absence of such studies on this watershed, with the availability of important information on the monthly and annual distribution of suspended solids from 1990 to 2013 (National Water Resources Agency, NWRA), the study could be performed on this particular region.

MATERIALS AND METHODS

NATURAL CHARACTERISTICS

Zeddine is a municipality in the province of Ain Defla, which is located in the north of the country, 140 km southwest of the capital Algiers. The watershed of 435 km^2 draining this region is called Wadi Zeddine. The watershed spreads out between 1.8° 35.9' and 2.1°36.0' E and 1.95°36.13' and 2°35.8' N (Fig. 1).

The prevailing climate in the area of Wadi Zeddine is Mediterranean, characterised by wet and dry seasons. The annual rainfall is very irregular, it varies between 200 and 379 mm·y^{-1}, the average annual rainfall is 245 mm, with the coefficient of variation of 37.5% [NWRA 2017].

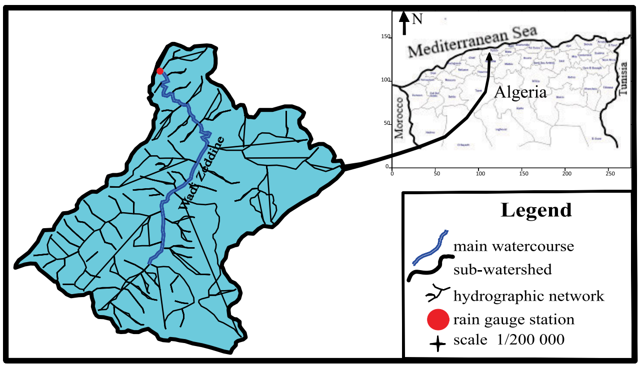

Fig. 1. The geographical location of the Wadi Zeddine watershed; source: own elaboration

The plant cover consists mainly of scrubs, which represent about 30% of all forests (degraded). The vegetation cover of the watershed is subject to overgrazing and it is spatially discontinuous and weak. Table 1 summarises all of its morphometric characteristics to understand the study area.

Table 1. Morphometric characteristics of the Wadi Zeddine watershed

Designation		Symbol	Unit	Value
Surface		S	km^2	435
Perimeter		P	km	113.30
Length of the main thalweg		L		*34.25*
Slope of the main thalweg		S_{max}	%	0.97
Compactness index		K_G	–	1.52
Equivalent rectangle	length	L_r	km	47.49
	width	l_r		09.16
Elevation	maximum	H_{max}	m	1759
	average	H_{av}		1307.30
	median	H_{med}		800
	minimal	H_{min}		323
	frequency 95%	$H_{95\%}$		520
	frequency 5%	$H_{5\%}$		1370
Average slope of the watershed		I_m	m·km^{-1}	16.40
Overall slope index		S	%	01.79
Rock slope index		S_r	%	1.57
Drainage density		D_d	km·km^{-2}	0.74
Hydrographic density		F	km·km^{-2}	20.07
Time of concentration		T_c	h	4.45
Runoff volume		V_r	m^3·h^{-1}	7.69

Source: NWRA [2017].

The Wadi Zeddine basin is characterised by a semi-arid climate, threatened by severe erosion of agricultural land. The latter will eventually settle in reservoirs or the sea causing silt build-up and pollution. This phenomenon constitutes a major problem in watersheds. Indeed, the specific erosion rate reaches some of the highest values in North Africa, where these rates vary between 100 and 2000 Mg·km^{-2}·y^{-1}, as shown in Table 5, with a suspended matter concentration varying between 16 and 40 g·dm^{-3}.

DATA AND METHODS

The data were collected from the services of the National Water Resources Agency of Blida. The file includes a series of 3047 values of height of water (H, cm), of liquid flows (Q_l, m^3·s^{-1}), and suspended sediment concentration (C, g·dm^{-3}) for a period of 24 years from 1990 to 2013. The solid flows (Q_s) are deduced following a transformation of readings of the heights, made on a limnimetric scale using the calibration curves, established by the services of the (NWRA) and at each reading of the water heights. A sample of water loaded on the bank of Wadi Zeddine is taken to a container to deduce the concentration of the solid load in the suspension (C, g·dm^{-3}). The solid flow (Q_s) (kg·s^{-1}) is estimated by the product:

$$Q_s = C \cdot Q_l \tag{1}$$

RESULTS AND DISCUSSIONS

RELATIONS SOLID FLOW-LIQUID FLOW

The solid matter transport in rivers and streams is a very important process. Its spatial and temporal variability is very high and data are generally unavailable or scarce [Bouguerra *et al.* 2017].

The NWRA program allowed us to obtain the solid flow in (kg·s^{-1}) for each height taken based on suspended materials observed and using the aforementioned relationship (Eq. 1). To determine the solid flow-liquid flow rate, different mathematical methods based on regression models have been applied to the studied series, taking into account the rainfall data from the basin. The results obtained are shown in Figure 2.

ANALYSIS OF RESULTS

According to Figure 2, the application of different methods to analysis the solid flow data as a function of the liquid flow in the Zeddine basin had shown that the correlation is cramped between them. Clouds of points are well attached to the regression line. This indicates the relationship between the flows (Q_s and Q_l).

The relations obtained are shown in Table 2.

Table 2. Relations obtained in the watershed of the Wadi Zeddine (1990–2013)

Function	Relationship	R^2 (%)	r
Power	$Q_s = 14.35Q_l^{1.43}$	81	0.90
Linear	$Q_s = 159Q_l - 353.3$	66	0.81
Polynomial	$Q_s = 1.15Q_l^2 + 58Q_l - 16.36$	73	0.85
Logarithm	$Q_s = 629 \ln(Q_l) + 657$	16	0.40
Exponential	$Q_s = 14.35e^{0.12Ql}$	36	0.60

Explanations: R^2 = coefficient of determination, r = correlation coefficient. Q_s = solid flow, Q_l = liquid flow. Source: own study.

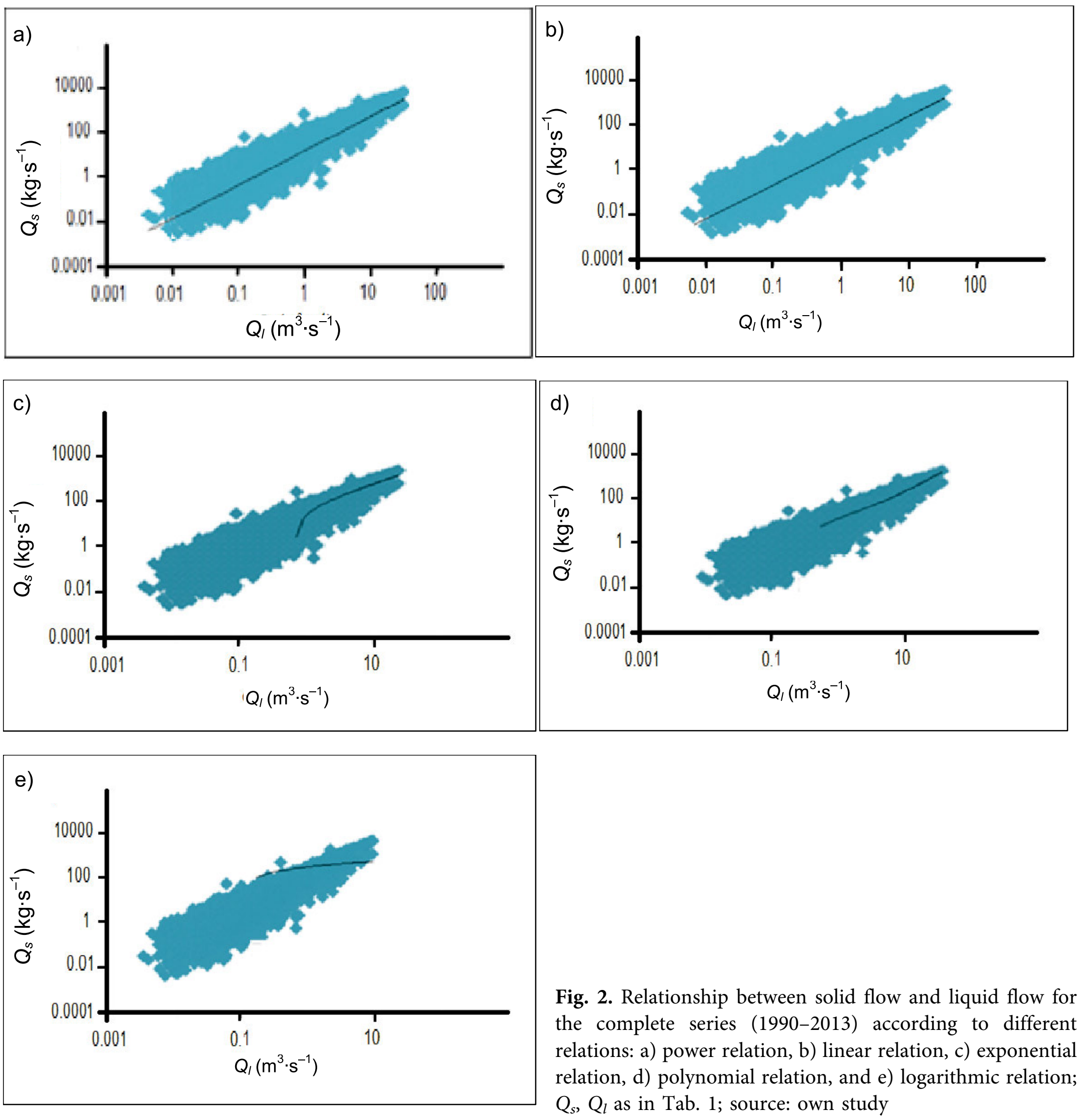

Fig. 2. Relationship between solid flow and liquid flow for the complete series (1990–2013) according to different relations: a) power relation, b) linear relation, c) exponential relation, d) polynomial relation, and e) logarithmic relation; Q_s, Q_l as in Tab. 1; source: own study

Table 2 shows that for the sets of functions used, the correlation is good with the correlation coefficient greater than 80%, except for the exponential function where a coefficient is slightly above average (60%) and barely below for the logarithm function with 41%. It can be concluded that the correlation ratios between solid flow and liquid flow were used to quantify and evaluate suspended solids transport in Wadi Zeddine. For example, the correlation coefficient is 90% for the power model, and the power relationship provides the best correlation factors.

To estimate the solid intake, we used the power model, which gave us the solid flow value as a function of liquid flow according to the following relationship:

$$Q_s = 14.35 Q_l^{1.43} \tag{2}$$

with a correlation coefficient (*r*) 0.90. Results are shown in Table 3.

Table 3 shows that 1994/1995 was the most active year, with erosion at its maximum, and had a very important solid contribution of up to 837,112 Mg. For the series of years studied, it was found that 50% of the annual average suspended solids inputs were less than 100,000 Mg. The other half had an overall average of the entire sample estimated at 88,048 Mg. In the winter season, floods occur which stimulate the transport of suspended sediments as they are characterised by strong turbulence due to extreme flows and sudden and irregular precipitations. It is also characterised by high concentrations and high flows, especially in the period from January to April, when the average monthly suspended solids input exceeds 100,000 Mg. From the solid inputs A_s (Mg), we can determine the abrasion rate (the erosion rate) A_{ss} (Mg·km^{-2}·y^{-1}) by the relation:

$$A_{ss} = A_s / S \tag{3}$$

where: S = surface of the basin (435 km^2).

The results are shown in Table 4 and Figure 3.

According to Table 4, the rate of erosion significantly varies from year to year. For example in 1994/1995, we recorded a rate of 464 Mg, against only 22 Mg recorded in 1999/2000. The overall annual contribution of sediments recorded at the outlet of the Wadi Zeddine watershed was evaluated at 88,048 Mg, which corresponded to specific degradation of 202 Mg·km^{-2}·y^{-1}. Based

Table 3. Monthly and annual distribution of suspended solids in the watershed of Wadi Zeddine (1990–2013)

Year	Value for month (Mg)												A_s (Mg)
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
90/91	51302	13202	6702	18863	20532	36354	649616	167092	16737	612	0	0	81751
91/92	0	8432	22	0	322494	28522	73273	384344	69979	7629	9691	763	75429
92/93	7097	10516	6340	3379	1011	18563	12898	24389	27637	0	0	16350	10682
93/94	11531	7439	286	28571	47391	209713	5605	6136	0	0	0	0	26389
94/95	319913	138526	59744	192855	837112	414022	395245	40382	15322	9052	0	736	201909
95/96	16502	30513	8121	3308	38167	546432	682100	287493	196432	86932	613	0	158051
96/97	145203	48510	1718	4998	71344	12929	729	250991	69281	0	0	2008	50643
97/98	30561	63105	446495	83344	38930	26502	13826	23159	781382	25645	474	2185	127967
98/99	15358	27013	3660	3095	137307	228964	898855	62200	5884	3117	0	0	115454
99/00	241	0	265	70472	25275	7726	671	3431	0	5217	0	0	9441
00/01	5871	126877	450948	105423	650888	303477	172800	194257	44683	307	0	0	171294
01/02	2308	3607	75244	3824	13390	107	3302	183	5365	0	0	18734	10505
02/03	3523	2274	55549	7195	371198	799210	109648	66782	31190	22291	0	26764	124635
03/04	79407	1827	29833	39278	39485	45146	161669	6705	20006	185	0	0	35295
04/05	37210	357	15035	12964	25838	86511	198044	25042	5908	19980	1389	0	35690
05/06	0	44185	16988	109492	177881	573266	438869	53215	231226	5339	501	6490	138121
06/07	45759	0	0	14432	0	3323	107280	183992	67583	2856	0	0	35435
07/08	127894	46179	196151	7937	18012	3416	24917	5633	7185	6209	0	0	36961
08/09	5130	22559	36492	232529	380452	481396	351557	206415	64414	10208	0	0	149263
09/10	2764	4177	3398	114718	49379	569778	528260	84511	20036	2732	0	40491	118354
10/11	0	16264	27251	39652	73155	550417	107314	27579	46674	13168	1	0	75123
11/12	0	2571	10492	2235	2439	169850	105269	1024904	60358	13154	0	0	115939
12/13	0	10633	29962	11177	175666	289899	346054	271772	246702	63957	2189	1218	120769
Average	**39460**	**27338**	**64378**	**48250**	**152928**	**235023**	**234252**	**147852**	**88434**	**12982**	**646**	**5032**	**88048**

Explanation: A_s = suspended solids intake.
Source: own study based on data from National Water Resources Agency.

Table 4. Annual distribution of specific abrasion rate (A_{ss}) in the watershed of Wadi Zeddine (1990–2013)

Year	A_s (Mg)	A_{ss} (Mg·km^{-2}·y^{-1})
90/91	81751	188
91/92	75429	173
92/93	10682	25
93/94	26389	61
94/95	201909	464
95/96	158051	363
96/97	50643	116
97/98	127967	294
98/99	115454	265
99/00	9441	22
00/01	171294	394
01/02	10505	24
02/03	124635	287
03/04	35295	81
04/05	35690	82
05/06	138121	318
06/07	35435	81
07/08	36961	85
08/09	149263	343
09/10	118354	272
10/11	75123	173
11/12	115939	267
12/13	120769	278
Average	**88048**	**202**

Explanations: A_s = solid inputs.
Source: own study.

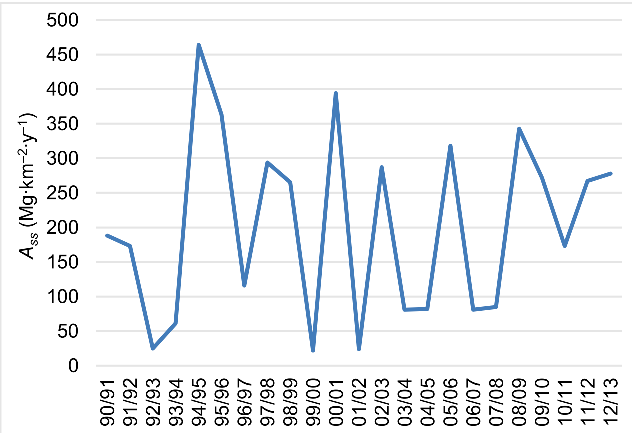

Fig. 3. Annual variation of specific abrasion rate (A_{ss}) in the watershed of Wadi Zeddine (1990–2013); source: own study

on Table 4 and comparison of results with studies by a few other authors studying the Maghreb zone, we can see that the erosion in the watershed of Wadi Zeddine generally follows the same mathematical laws and shows similar results or the same interval. Some examples of these results from the watershed of Algeria and Morocco are shown in Table 5.

Table 5. Specific degradation values published for neighbouring watersheds

Watershed	A_{ss} (Mg·km^{-2}·y^{-1})	Source
Morocco	1000–5000	WALLING [1984]
Morocco	397	PROBST and AMIOTTE SUCHET [1992]
Morocco	750	SNOUSSI [1988]
Tafna (Algeria)	150	SOGREAH [1967]
Mazafran (Algerian coastal)	1610	BOUROUBA [1997]
Isser (Lakhdaria, Algeria)	2300	BOUROUBA [1997]
Eastern Algeria	145	BOUROUBA [1998]
Ebda (Algeria)	1875	MEDDI [1999]
Mouilah (Algeria)	126	TERFOUS *et al.* [2001]
The high Tafna (Algeria)	1120	MEGNOUNIF *et al.* [2003]
Sebdou (Algeria)	937	BOUANANI [2004]
Sikkak (Algeria)	170	BOUANANI [2004]
Mina (Algeria)	187	ACHITE and MEDDI [2005]
Abd (Algeria)	136	ACHITE and OUILLON [2007]
Saf Saf (Algeria)	461	KHANCHOUL *et al.* [2007]
Sebdou (Algeria)	1330	GHENIM *et al.* [2007]
Bellah (Algeria)	610	ELAHCENE *et al.* [2013]
Boumessaoud (Algeria)	518	BOUGUERRA *et al.* [2017]
Mellegue amont (Algeria)	1104	KHENICHE *et al.* [2019]
Zeddine Ain Defla (Algeria)	202	this study

Explanation: A_{ss} = specific abrasion rate.
Source: own elaboration based on the literature.

CONCLUSIONS

The results obtained show the presence of a very close and significant link between the solid flow and the liquid flow. This link is presented mainly by the power formula (Eq. 2) which represents a proportional relation between the two flow rates, with a correlation coefficient r = 0.90.

Based on this relationship, we calculated daily flows of suspended solids for a reference period of 24 years (1990–2013). The results found are then transformed into the annual value expressed in Mg of suspended solids. The average annual sediment input recorded at the outlet of the Wadi Zeddine watershed is estimated at 88,048 Mg, which corresponds to specific degradation of 202 Mg·km^{-2}·y^{-1}. In comparison with the adjacent watersheds and neighbouring countries, we note that the specific degradation in Wadi Zeddine is acceptable, but it is still very dangerous for the soil, nature, and biodiversity. This study emphasises that the solids transport in the Wadi Zeddine watershed occurs mainly during floods.

The results collected constitute a database that can be used for studies designed to protect dams and reservoirs against siltation.

The study shows that the protection of soils accumulation at dams should be our priority and for this reason we must:

- carry out reforestation on the sides of valleys, river banks, and near dams and reservoirs to avoid lateral landslides;
- provide periodic maintenance at the level of the dam and containment by clearing silt.

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