Analysis Of Two Years Of Suspended Solids Transport Upstream Of Sidi Mohamed Ben Abdellah Reservoir, Morocco

Mohamed Abdellah Ezzaouini, Gil Mahé, Ilias Kacimi, Abdelaziz Zerouali

Abstract : A limited number of studies have been conducted in Morocco to estimate dams siltation rate based on suspended solids concentration (SSC) field measurements. The present article provides an evaluation of the siltation rate through an inventory of field measurements data which has been collected upstream of Sidi Mohamed Ben Abdellah (SMBA) Dam reservoir. The analysis was based on measurements performed according to a predefined protocol at four hydrological stations located immediately upstream of the dam during the hydrological years of 2016/2017 and 2017/2018. The analysis was also based on several bathymetric field surveys performed throughout the reservoir area since the construction of the dam. Field measurements show that recorded sedimentation depth at the four stations during the first year was 14% higher than the second year although it had an excess of rainfall and runoff compared to the first year. Estimated correlation coefficients between flow rates and suspended solids concentration was ranging from 0.20 to 0.42. Those between solids and liquids flow rates have higher correlation coefficients ranging from 0.75 to 0.91. Seasonal analysis and the adoption of the threshold did not improve significantly the relationships between these parameters. Moreover, only 18% of the dam siltation originates from upstream sources. The main hypothesis that we can formulate is that the dam's sediments most likely come from the erosion of its banks.

Keywords : Sediment transport, Suspended solids concentration, Dam, Bouregreg, Morocco.

1. INTRODUCTION

Water erosion is at the origin of large quantities of sediments carried along by rivers during flooding events in the Bouregreg basin towards the reservoir of the SMBA dam; the extent of the phenomenon can be observed through the color of the water in the flooded rivers [1]. These suspended solids are produced on skeletal soils, poorly protected by sparse vegetation [[2],[3],[4],[5]]. In mountainous areas, these quantities increase on steep slopes, depending on the nature of the soil and the vegetation cover combined with human activities. Indeed, the situation of the dam (SMBA), which has already lost 132 10^6 m^3 of its capacity since its commissioning in 1974, poses serious problems for water resource managers in terms of loss of storage capacity, which has an impact on the life span of the structure and the quality of the water in the reservoir [[6],[7],[8] To study this phenomenon, the Basin Agency has set up a network to measure the concentration of suspended solids at the four hydrological stations located immediately upstream of the SMBA dam to study the transport of solid matter. As few studies have been carried out in Morocco to estimate the silting rate based on the measurement of solid transport, this article deals with this issue through an inventory of the silting of the SMBA dam reservoir based on the analysis performed measurements according to a predefined protocol at four hydrological stations located immediately upstream of the dam during the hydrological years of 2016/2017 and 2017/2018, and bathymetric surveys conducted at the reservoir area since its commissioning.

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2 DATA AND METHODS

2.1 Study area

The Bouregreg Basin, located within the North-West region of Morocco, covers an area total of approximately 10210 km² at with a downstream exit point located at Bouregreg River mouth, North of Rabat City. Figure 1 show the location of bouregreg basin.

Fig. 1. Bouregreg Basin location map

The area is characterized by a highly varying geographic and geomorphologic framework, composed of two natural areas: The Middle Atlas Mountains with high undulating topography extending over the high Bouregreg area, and the Zaêrs plateaus in the form of plains crisscrossed by deep valleys in the north-west.

2.2 Hydro-Pluviometric Context of the Study Period

Rainfall analysis at Bouregreg watershed gauging stations during the two years' timeframe showed that the year 2016/2017 was in deficit by 10% and the year 2017/2018 was in surplus by 26% from the average over the entire basin. Figure 2 summarizes the annual rainfall deviations recorded from the average of each gauging stations calculated since it became operational.

TABLE 1
Water inflows during the study period at the selected stations

Hydrological station	River	Inflows (10^6 m^3)			Deviation from average (%)	
		2016/2017	2017/2018	Mean year	2016/2017	2017/2018
AguibatZear	Bouregreg	122.26	221.53	227.69	-46	-3
Ras Fathia	Grou	95.04	162.86	194.26	-51	-16
Ain Loudah	Korifla	13.39	23.50	18.92	-29	+24
Sidi Mohamed Cherif	Machraa	3.78	12.93	16.71	-77	-23
Total ($10^6 m^3$)		234.47	420.82	457.58	-49	-8

TABLE 2
Characteristics of the hydrological stations concerned by the study

Hydrological station	River	Start year	ID number	Watershed Area (Km^2)	Lambert Coordinates X	Y	Z	Number of samples since 2016
Aguibat Zear	Bouregreg	1977	3118/13	3881	394.500	368.150	90	1080
Ras Fathia	Grou	1975	989/20	3485	394.250	351.800	100	968
Ain Loudah	Korifla	1971	2673/20	699	373.750	329.150	175	374
Sidi Mohamed Cherif	Machraa	1971	2674/21	656	385.850	328.200	270	919

TABLE 3
CSSmax and Qmax recorded at the hydrological stations under study

Hydrological station	River	SSC max (g/l)	Date SSCmax	Qmax (m^3/s)	Date Qmax
Aguibat Zear	Bouregreg	34.2	30/08/2017 02:00	265.9	07/03/2018 14:00
Ras Fathia	Grou	55.4	24/02/2017 22:00	423.8	07/03/2018 09:00
Ain Loudah	Korifla	20.2	19/02/2017 18:00	103.9	11/12/2017 18:00
S. Mohamed Cherif	Machraa	26.6	30/11/2017 04:00	62.6	13/10/2016 07:00

TABLE 4
Solid transport flows at the studied stations

Hydrologic Station	River	Flows in tons		Flows in m^3	
		2016/2017	2017/2018	2016/2017	2017/2018
AguibatZear	Bouregreg	742 334	439 735	494 889	293 157
Ras Fathia	Grou	673 551	740 083	449 034	493 389
Ain Loudah	Korifla	28 155	48 422	18 770	32 281
S. Mohamed Cherif	Machraa	68 759	92 324	45 839	61 549
Total		1 512 799	1 320 564	1 008 533	880 376

TABLE 5
Relationship between liquid and solid flow rates at the hydrological stations under study

hydrological station	River	Correlation coefficient R^2	Equation QL=f(Qs)
AguibatZear	Bouregreg	0.91	$3.50\,Qs^{1.1475}$
Ras Fathia	Grou	0.87	$1.96\,Qs^{0.6477}$
Ain Loudah	Korifla	0.87	$2.32\,Qs^{0.5852}$
Sidi Mohamed Cherif	Machraa	0.75	$0.98\,Qs^{0.613}$

Water inflows at the hydrological stations concerned were below average during the two hydrological years covered by the study. The deficits varied between 29% during 2016/2017 and 8% during 2017/2018 despite the excess rainfall during this year. Table 1 summarizes the inflows recorded at the 4 hydrological stations covered by the study.

2.3 Protocol for the measurement of solid transport

The determination of solid transport flows will be calculated during the hydrological years 2016/2017 and 2017/2018 at the hydrological stations of Aguibat Zear on the Bouregreg river, Ras Fathia on the Grou river, Ain Loudah on the Krifla river of Sidi Mohamed Cherif on the Machraa river, and using the measured concentrations of suspended solids located immediately upstream of the SMBA dam reservoir to determine the quantity of silt entering the dam. The characteristics of the hydrological stations concerned by the sampling are presented in the table 2. The study of solid transport at the Dar Soltan hydrological station on the Bouregreg river realized by the Hydraulic Directorate in Morocco in 1971, stipulates that the samples carried out far from dead zones and bottoms of the river are representative of the average concentration of the measurement section with a margin of error that does not exceed 10% [9]. For this reason, samples are taken from the bed of the river in a 1-liter bottle about 2 m from the banks accessible far from dead zones and bottoms of the river.

Observers from the hydrological stations concerned take one sample every hour at the time of floods and one sample per day during low water periods. At each instantaneous sampling, the date, time, and the height of the water to scale are noted on the bottle. The samples

are then analyzed in the laboratory as follows:

- the filter membranes (0.45µm) are numbered, then emerged in distilled water to activate the pores;
- they are dried at 105°C for 35 minutes and then weighed (initial mass);
- the solution is stirred then a precise volume is taken and filtered under vacuum;
- the filter membranes are dried at 105°C for 35 minutes and then weighed (final mass).

The weight of suspended matter is given as follows: Weight (g) = (Final mass - Initial mass). The concentration is therefore deduced: SSC(g/l) = (Final Mass - Initial Mass)/V, where V: Volume in liter.

3 RESULTS AND DISCUSSIONS

3.1 Assessment of the silting of the SMBA dam

The SMBA dam was commissioned in 1974 with an initial capacity of 508.6 10^6 m^3 and was raised in 2007 to a capacity of 974 10^6 m^3. It is intended solely for the supply of drinking water to the coastal zone between Rabat and Casablanca, which has a population of nearly 8 million inhabitants. The analysis of the 7 bathymetric surveys carried out between 1974 and 2013 by the Water Research and Planning Department, allowed to draw up an inventory of the silting of the SMBA dam reservoir. Indeed, SMBA reservoir siltation rate was estimated at 2.65 10^6 m^3/year, i.e. a specific degradation of 270.4 m^3/Km²/year before raising. After the Dam crest was raised, siltation rate increased to 9.49 10^6 m^3/year, i.e. a specific degradation of 968.37 m^3/Km²/year, which increased siltation rate by 400% [15]. Thus, the total siltation of the SMBA dam reached 132 10^6 m^3. Subsequently, the dam exceeded its dead section and lost 32 10^6 m^3 of its effective capacity since its commissioning. These results show that the silting rate of the dam reservoir is equal to 9.49 10^6 m^3/year. This is explained by the management method, which has changed from seasonal management favoring evacuation by the restitution bodies before raising the water level, to multi-year management favoring storage after raising the water level. This siltation rate represents a real threat to sustaining surface water resources in the Bouregreg basin and meeting drinking water demand [[10], [11]].

3.2 Calculation of the solid transport flow

During the hydrological years 2016/2018 and 2017/2018, the maximum flows (Qmax) and maximum concentrations of suspended solids (SSCmax) recorded at the four stations involved in the study are summarized in Table 3. We calculated the flow in weight and volume at the selected hydrological stations. To achieve this, we first linearly extrapolated the concentrations of suspended solids overall instantaneous flows rates and then calculated the solids flows from the liquid flows for the hydrological years 2016/2017 and 2017/2018 using the following formula :

$$Q_s = Q_i.SSC \quad (1)$$

Q_s: Solid flow rate in (Kg/s)
Q_i: Liquid flow rate in (m^3/s)
SSC : Suspended solids Concentration in (g/l)

The liquid and solid volumes of the two hydrological years are in turn calculated as follows :

$$V_{total} = \sum_{i=1}^{n} (Q_t + Q_{t+1}).\Delta t / 2 \quad (2)$$

Qt: Solid or liquid flow rate at time t
Δt : time variation in seconds

The transport of bottom solids is taken equal to 10% of the total volume of suspended solids [9], which remains an empirical but widely used value. Finally, the soil density, which is of the order of 1.5 t/m^3, is used [10] to calculate the volumes of suspended solids entering the dam over the observation period. Table 4 summarizes the calculation of solids transport flows over the two hydrological years studied. The calculation of the solid transport flow rate at the hydrological stations shows that the dry hydrological year 2016/2017 generated a total of 1.01 10^6 m^3 against 0.88 10^6 m^3. This result is explained by the vegetation cover which is less important in the dry year combined with agro-sylvo-pastoral practices[12]. Figure 5 shows the cumulative solid transport at the Aiguibat Zear hydrological station. We observe that a single event can contribute more than 50% of the annual solid transport flow.

3.3 Analysis of SSC, liquid and solid flow rate

Analysis of the relationship between solid flows (Qs) and liquid flow rates (QL) on the one hand, and concentrations of suspended solids (SSC) and liquid flows rates (QL) on the other, will be done using the method of least squares to determine the trend line that best fits the available sample data [13].

3.3.1 Analysis of SSC, liquid and solid flow over the entire sample

In general, liquid flow rates and concentrations of suspended solids show weak correlations ranging from 0.20 to 0.42. There is also a wide dispersion in the relationships at low flow rates. On the other hand, solid and liquid flow rates have good correlation coefficients ranging from 0.75 to 0.91, due to the presence of flow at both parameters. The relationships between solid and liquid flow at the four hydrological stations is a power function [14]. The results are summarized in Table 5.

Figure 3 shows some of the results of the analysis of the relationships between the different series.

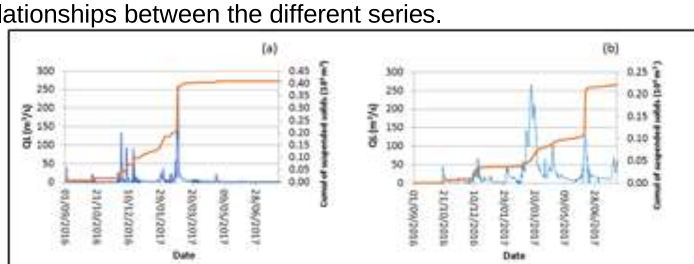

Fig. 3. (a) and (b) Instantaneous flow and total suspended solids at Aguibat Zear hydrological station during respectively 2016/2017 and 2017/2018

3.3.2 Analysis of CSS, liquid and solid flow beyond a liquid flow threshold

To refine the correlation coefficients between liquid flow rates and SSC and to avoid the low water dispersion zone, we will first test the relationships between the different parameters above a certain liquid flow threshold at the hydrological stations studied. The selected flow thresholds are 10 m^3/s for the hydrological stations that control the small basins, namely Ain Loudah and Sidi Mohamed Chérif, and 20 m^3/s for the Aguibat Zear and Ras Fathia stations that control the big basins. Indeed, the adoption of liquid threshold did not improve the correlation coefficients between liquid flow rates and SSC between liquid and solid flows. On the contrary, there has been a marked decrease in these coefficients. They thus vary between 0.005 and 0.27 for the best correlation between liquid flow and SSC and between 0.029 and 0.59 for the correlation between liquid flow and solid flow.

Figure 4 presents the results which respectively shows the best and the bad correlation rates between the different series.

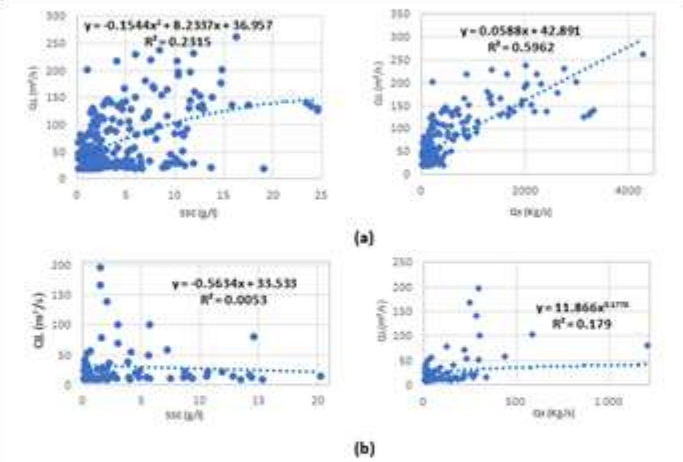

Fig. 4. (a) and (b) relationship between liquid flow rates, SSC and solid flow respectively at Aguibat Zear and Ain Loudah station

3.3.3 Analysis of SSC, liquid and solid flow at rising curve and falling curve of flood

The analysis of the correlation coefficients between liquid flow rates and SSC is slightly improved in falling curve of the flood, thus varying between 0.12 and 0.41 for the correlation between QL and SSC, and between 0.70 and 0.90 for the correlation between QL and Qs. while in the rising curve of the flood correlation coefficients are relatively weak in general and vary between 0.12 and 0.39 for the correlation between QL and SSC and between 0.54 and 0.90 for the correlation between QL and Qs.

Figure 5 presents the results which respectively shows the best and the bad correlation rates between the different series.

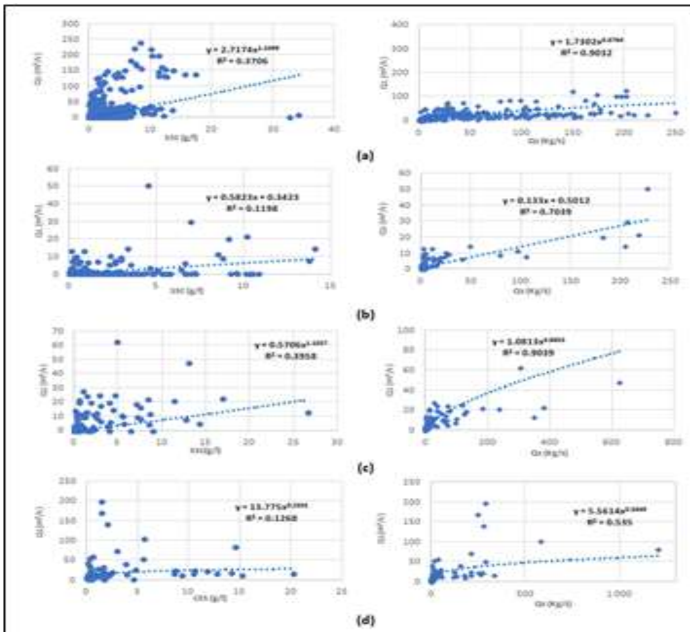

Fig. 5. (a) and (b) relationship between liquid flow, CSS and solid flow at falling curve of the floodrespectively at Aguibat Zear andSidi Mohamed Cherif stations
(c) and (d) relationship between liquid flow, CSS and solid flow at rising curve of the floodrespectively at Sidi Mohamed Cherif and Ain Loudah stations

Examination of flood rise and flood recession flows representations with SSC showed that, in general, the concentrations of suspended solids at rising limbs are higher than at falling limbs of the flood. Suspended solids are more diluted after the flood peak has passed and the leaching of the basins occurs during flooding.

Figure 6 summarizes the results at the four hydrological stations studied.

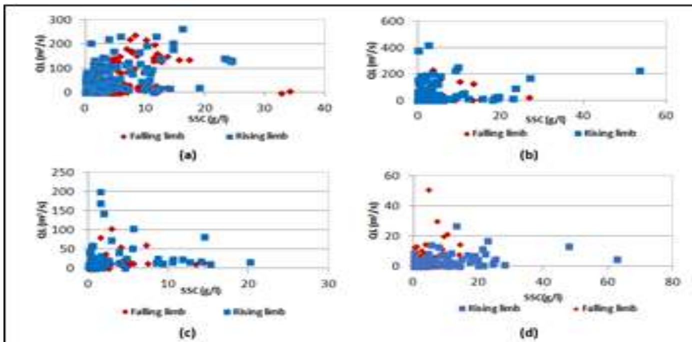

Fig. 6. (a), (b), (c) and (b) Relationship between liquid flow and SSC in falling limb and rising limb at respectively Aguibat Zear, Ras Fathia, Sidi Mohamed Cherif and Ain Loudah

3.3.1 Analysis of SSC, liquid and solid flow by season

In this part, we will test the correlations of the measurements by season, i.e. summer, autumn, winter, and spring.

a. Summer

Correlation coefficients between liquid flow rates and SSC are slightly improved during the summer at the majority of stations [5] hallouz, ranging from 0.063 to 0.69 for the correlation between QL and SSC and from 0.85 to 0.97 for the correlation between QL and Qs.

b. Autumn

Correlation coefficients between liquid flow rates and suspended solids concentrations in the fall are of the same order of magnitude as those in the summer at the majority of stations, ranging from 0.10 to 0.69 for the correlation between QL and SSC and from 0.7 to 0.97 for the correlation between QL and Qs.

c.Winter

Correlation coefficients between liquid flow rates and suspended solids concentrations in the fall are slightly lower than in previous seasons at the majority of stations, ranging from 0.11 to 0.46 for the correlation between QL and SSC and from 0.63 to 0.84 for the correlation between QL and Qs.

c.Spring

Correlation coefficients between liquid flow rates and suspended solids concentrations in spring are comparable to previous seasons at most stations, ranging from 0.08 to 0.64 for the correlation between QL and SSC and slightly lower compared to other seasons between 0.72 and 0.93 for the correlation between QL and Qs. At the end of this analysis, the relationships between solid/liquid flow rates and liquid flow rates/SSC, by season, slightly improved the correlation coefficients during the summer and fall. They remained generally in the same order of magnitude.

4 CONCLUSION

The study showed that the phenomenon of erosion is extremely complex in the Mediterranean region [15]. On one hand, a single event can contribute to more than 50% of the cumulative transport of solid matter, the dry year 2016/2017 recorded a 14% more accumulation of solid on suspension than the wet year 2017/2018. Therefore, this phenomenon depends on several parameters such as the nature of the soil and its previous moisture content, slopes, rainfall intensity, vegetation cover, and runoff water level [[5],[16],[17]] . Thus, the analysis of suspended solids concentrations at hydrological stations located upstream of the SMBA dam reservoir during the two years of observation generally showed that liquid flow rates and suspended solids concentrations exhibit weak correlations. The treatment of these measurements by season, at rising and falling limb of the flood, and with flow threshold, did not significantly improve the correlation coefficients, which remain in same order of magnitude. Those between liquid and solid flow rates show acceptable correlations. Adopted equations predicted significant deviations from the observed values mainly for large flows. This does not allow reliable forecasting models to be established from the relationships found between the different parameters. The frequent bathymetric field surveys have also shown that the measured volumes remain well below the siltation rate of the dam, which is $9.49\ 10^6\ m^3$/year, which means that only 18% of the dam's sediments come from upstream. This rate seems very low, and as it is only calculated over two years, the measurements will continue regularly to increase the time series and obtain a more accurate average. The main hypothesis we can formulate is that sediments in the reservoir area are most probably coming from the erosion of its overbanks [18]. The Bouregreg Basin Agency will continue the field measurements and it will extend them to the cover the entire basin. The agency is also planning to develop granulometric and geochemical studies on the sediments to correlate them with the hypothesis of its origin.

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