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EVOLUTION, FORECASTING AND MANAGEMENT OF SILTATION IN ALGERIAN DAMS

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EXTENDED ABSTRACT

L'interrimento degli invasi artificiali pone enormi problemi al livello del serbatoio idrico; porta alla riduzione della capacità utile della diga, al blocco dei dispositivi di drenaggio, al degrado della qualità dell'acqua e in definitiva alla stabilità della struttura. Diversi autori concordano sul fatto che il fango segue un modello di potenza e si sviluppa in modo diverso nel tempo a seconda di determinati fattori limitanti. L'obiettivo principale di questo articolo è studiare l'evoluzione dell'interrimento nelle dighe algerine.

Il confronto dei risultati dei rilievi batimetrici delle tre fasi studiate con i calcoli ottenuti utilizzando il modello prescelto (Orth, 1939) mira a rafforzare l'efficacia di questo modello predittivo, che potrebbe essere generalizzato per la stima dell'interrimento in aree prive di stazioni di misura, in condizioni climatiche e idrologiche simili, e fornire informazioni accurate agli ingegneri in caso di esplorazione di nuove dighe.

Questo lavoro è stato svolto secondo un approccio comparativo semiquantitativo che tiene conto della comparazione tra rilievi batimetrici e i calcoli effettuati attraverso il modello adottato. L'analisi storica dei dati dei tre rilievi batimetrici studiati ha spiegato bene le variazioni temporali della capacità d'invaso e dell'interrimento in ciascuna diga. Il risultato mostra che l'interrimento è irregolare e molto variabile tra le dighe e assume generalmente un comportamento accelerato. Inoltre, i dati di insabbiamento stimato medio annuo, forniti dall'agenzia nazionale per le dighe, variano tra 0.2 e 1.5 Mm^3/anno. La più grande diminuzione osservata della capacità totale delle dighe è stata registrata durante la prima fase che è passata da 906 Mm^3 a 554.47 Mm^3 seguita da un rapido aumento dell'insabbiamento osservato tra il 1986 e il 2004 di circa 348.53 Mm^3 con il totale cumulato misurato che ha raggiunto il suo massimo nel 2010 (388.5 Mm^3), accelerando durante le tre fasi studiate a causa dell'incremento dell'erosione media durante le ultime due fasi di insabbiamento.

L'erosione specifica non è il solo fattore che spiega la sedimentazione negli invasi, ad esempio lo spartiacque della diga di Boughezoul che si trova nell'Atlas del Sahara occidentale ha registrato un basso trasporto solido specifico dell'ordine di 533.07 Mg km^{-2} y^{-1} e interrimento osservato nel 2010 di 49 Mm^3, d'altra parte lo spartiacque di Chafia che si trova sul versante nord presenta una forte erosione dell'ordine di 597.7 Mg $km^{-2}\cdot anno^{-1}$ e un interrimento di 12.6 Mm^3.

La sedimentazione cumulata totale osservata nel 1986 ha raggiunto 230.86 Mm^3 ovvero il 25.48% della capacità iniziale delle dighe studiate, successivamente questa cumulata ha raggiunto 348.53 Mm^3 o una percentuale di circa il 38.46% nel 2004 con un aumento di 117.67 Mm^3 di limo in 18 anni, nel 2010 l'accumulo totale di limo è diventato 388.5 Mm^3 ovvero il 42.88% della capacità totale osservata delle dighe studiate. D'altra parte, l'aumento della sedimentazione tra il 2004 e il 2010 è stato di 39.97 Mm^3 ovvero il 10.28% dell'insabbiamento totale delle otto dighe; questa differenza può essere spiegata con la diversa durata che caratterizza ciascuna fase. Quando si divide il volume di interrimento registrato durante ciascuna fase per gli anni corrispondenti, si osserva che l'interrimento è rapido nell'ultima fase (6 Mm^3), poi nella seconda fase (6.53 Mm^3) e sembra relativamente lento nella prima fase (4.6 Mm^3).

Le fasi di accelerazione dell'interrimento possono essere riassunte in base all'interrimento medio annuo in Mm^3 dato dall'ANBT:
- insabbiamento basso, inferiore a 0.50, caratterizza le dighe di: Zerdaza, Chafia, Bakhadda e Ksob;
- insabbiamento medio, compreso tra 0.50 e 0.60, riguarda le dighe di Boughezoul e Foum Elgherza;
- insabbiamento elevato, maggiore di 0.60, interessa le dighe di Gharib e SMBA e attesta una sedimentazione accelerata.

Si noti bene che il modello di Orth (1939) ha dato risultati prossimi e comparabili a quelli ottenuti dai rilievi batimetrici, il che lo qualifica ad essere applicabile in condizioni climatiche fisiche e litologiche simili; i risultati di questo modello sono confermati da un test statistico ampiamente utilizzato (Nash test) e dal confronto con i risultati delle indagini batimetriche disponibili.

La gestione dell'insabbiamento richiede un intervento biologico attraverso diverse tipologie di rimboschimento e interventi meccanici basati essenzialmente sull'allestimento di bacini di decantazione, sul sollevamento della diga e su operazioni di dragaggio. Diventa necessario effettuare un'attenta diagnosi delle sorgenti di insabbiamento e l'esame di tutti i fattori fisici, litologici e morfometrici di ciascun bacino idrografico per realizzare una gestione integrata e sostenibile dell'interrimento delle dighe. In definitiva, il contrasto all'interrimento richiede una conoscenza e una comprensione a priori dei fattori e dei processi che generano e accelerano questo fenomeno.

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ABSTRACT

The aim of this study was to improve the sedimentation estimates and to know the evolution of the siltation of 8 Algerian dams according to a semi-quantitative approach which takes into account the comparison of the bathymetric surveys and the calculations carried out by empirical formulas widely used in Algeria (F. Orth). The initial capacity of the 8 considered reservoirs was 906 Mm^3, it was reduced to 675.14 Mm^3 in 1986 about 524.5 Mm^3 in 2010, It is noticed a decrease of 370.5 Mm^3 or 58.6% between the initial capacity and the last bathymetric survey in 2010.

The average annual siltation is clearly varied according to the following phases:

- a weak alluvial phase had started with the impoundment until 1986 and showed less than 0.50 Mm^3 of silt;
- an average alluvial phase extends between 1986 and 2004 and presents values varying between 0.50 Mm^3 and 0.60 Mm^3;
- a high alluvial phase spread between 2004 and 2010, it gives considerable volumes which annually exceeds 0.60 Mm^3.

On the other hand, F. Orth model gives results close and comparable to those obtained by bathymetric surveys for most dams, which qualifies the application of this model in similar conditions in the absence of gauging stations.

***Keywords**: dam, siltation, erosion, bathymetric surveys, comparative approach, management*

INTRODUCTION

At first, erosion by gullying and other physico-chemical mechanisms remove fine particles from their initial positions and begin to contribute to the formation of siltation (Brambilla *et alii*, 2015; Bouannani, 2005)

In the second phase the sediments will be drained by streams to the dam. Finally, the particles settle at the bottom of the lake of the dam.

Siltation of dams poses enormous problems for the reservoir, it reduces the usable capacity of the dam and sometimes prevents bottom emptying but in some cases siltation has an effect on the degradation of water quality and the stability of the structure (Remini, 1997; Mama & Okafor, 2011). The Algerian territory is sub-divided into five hydrographic basins, this helps to correlate resources with areas of greatest need. The basins are: Oranie - Chott Chergui, Chellif - Zahres , Algérois - Hodna – Soumam, Constantinois - Seybouse -Mellegue and the South, these large watersheds include the dams concerned by this study which aims at siltation, evolution and forecasting which remains a problem in the distaination of future dams (Ouaman, 2009).

This study mainly targets the analysis and comparison of the evolution of siltation in certain Algerian dams characterized by varied physical and hydro-climatic factors.

Mebarki (2010) showed that due to the rapid silting up the reservoirs lost a lot of their initial capacity (2 to 3) per year on average. Moreover Remini *et alii* (1997) pointed out that estimated sedimentation of the Foum El Gherza Reservoir as a polynomial function of time. Remini *et alii* (1997) established two relationships giving annual sediment inflows as a function of operational time, a power function for Maghreb's reservoirs having a high sedimentation rate, and a linear function for those having a low rate (Tebbi *et alii*,2012).

This contribution explains the current and future prediction situation of siltation through the adoption of a comparative method between mathematical models that are widely used in studies of estimation of siltation such as the method of F. Orth (1934) and the analysis of bathymetric surveys. Several authors agree that silt follows a potency pattern and develops differently over time depending on some limiting factors such as erosion, the nature of lithological formations, torrential rains and floods. (Mebarki, 2010; Khanchoul, 2012).

The techniques used for the fight against siltation can be biological such as reforestation and can be mechanical such as the construction of settling ponds along the wadis, the raising of the dyke of the dam, dredging, etc. But in many cases the manager of the dam comes up against the higher cost of the execution of certain modifications which forces the adoption of the cheapest technique, the most available and the easiest to apply.

Faced with these conditions, it is necessary to make a careful diagnosis of the sources and factors of siltation. At the end, the fight against siltation requires a priori knowledge and understanding of the factors and processes generating and accelerating this phenomenon (Megnounif *et alii*, 2003; Remini & Hallouche, 2005; Hallouz *et alii*, 2019) and there is a need to integrate anti-erosion measures before dam construction.

MATERIALS AND METHODS

The data used in this study come from the following bodies responsible for the management, control and monitoring of hydraulic projects:

- ONM (National Meteorological Office): Source of rainfall data;
- NWRA (National Water Resources Agency): Source of flow rates and rainfall data;
- NADWT (National Agency for Dams and Water Transfer): Source of technical data and bathymetric surveys.

To determine the evolution of siltation as a function of time in the dams studied, it becomes necessary to exploit the results of the three bathymetric surveys available; each survey interprets the behavior of the siltation in a phase.

It is important to make a comparative study between the results obtained of Orth's analytical model (1934) and the results of the completed bathymetric surveys to show the effectiveness of the model for future use in similar locations, this selected relation was used for the estimation of siltation in some Algerian dams and showed good results (Saidi, 1991; Touaibia, 2010).

Orth (1934) was among the first to study the prediction of siltation, the residual capacity has been demonstrated to vary over time as a function of an exponentially decaying law, this formula was applied to 16 Algerian dams for the purpose of estimating siltation, its application was given the following results:

The difference between the measured and estimated siltation showed the effectiveness of the application of this model in relation to the number of dams and in relation to the number of total bathymetric surveys taken into consideration for each case:
56% of cases of difference between the measured and estimated volume have an average absolute deviation <5%;
81% of cases of difference between the measured and estimated volume have an average absolute deviation <10%;
18.7% of cases of difference between the measured and estimated volume have an average absolute deviation >10%.

The difference between the volumes of siltation measured and those estimated by this formula.

The formula takes into account the change between residual and normal capacity over time and can be written as follows:

$$Vst = Crn - Ct \quad (1)$$

Where,
Vst : volume of accumulated sediments
Crn: the normal holding capacity in (hm^3).
Ct: it is the residual capacity after t years of service in (hm^3).
Calculation of *Vst* requires knowledge of *Sd* and *Ct.*
Orth (1939) assumes that $Sd = V = 1$ during the first year of operation.
Sd : the solid flow transferred to hm^3.
SSL: the solid load of the specific degradation (abrasion rate) in (T / km^2 / year).
t: the number of years .
Ys: density of materials (T/m^3).
A: catchment area (km^2).
With Residual capacity (*Ct*):

$$Ct = Crn\left(1 - \frac{Sd}{Crn}\right)^t \quad (2)$$

$$Sd = (SSL * S * t)/Ys \quad (3)$$

STUDIED DAMS

The Zerdaza dam is located in the Saf-Saf wadi basin with an area of 345 km^2, whose climate is Mediterranean, cold and relatively humid in winter, and hot in summer. The supply of drinking and industrial water to the city of Skikda The dam was commissioned in 1945 and its dyke was raised in 1977

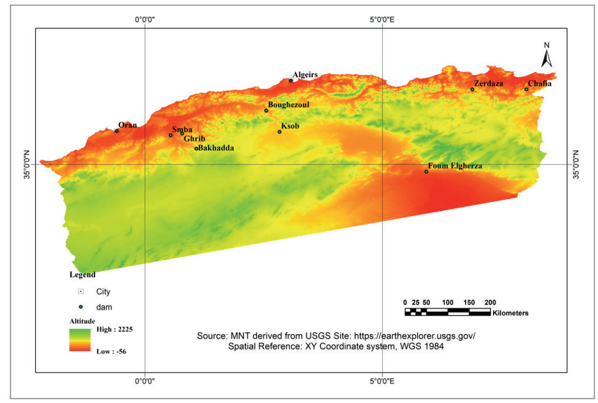

Fig.1 - Location of the studied dams

after this elevation its capacity became 32 Mm^3.

The Chafia dam was commissioned in 1965, located on the Bouamoussa wadi. Its maximum height is 55 m on the bottom of excavations. The spillway consists of an overflow tower, equipped with a cylindrical valve, extended by a gallery under the embankment and a projection dissipation basin. The development experienced a number of malfunctions during its operation.

Ksob Dam: with a capacity of 11.5 10^6 m^3 and a height of 32 m built in 1939 for the irrigation of the Ksob perimeter. The dike of the dam had been raised in 1975 and reached 43 m to bring its capacity to 31 Mm^3.

The Foum el Gherza dam is an arch dam commissioned in 1950, located on the Labiod wadi, near Biskra with a capacity of 47 Mm^3 its maximum height is 73 m on the bottom of excavations. The reservoir is also characterized by considerable siltation which reduced the initial capacity by two thirds.

The SMBA dam is located downstream of the Oued Mina watershed, 20 km from the capital of the wilaya of Relizane and 300 km west of Algiers with a capacity of 235 Mm^3, the dam of SMBA was put into operation in 1978, it is intended for the irrigation of the perimeter of the Mina and the supply of drinking water to the town of Relizane

The Bakhadda dam is one of the first rock fill dams built in Algeria. It is located on the upper reaches of MINA, a tributary of the Oued Chélif near the village of Machraa Sfa, 25 km west of the wilaya of Tiaret. It is mainly intended for irrigating the plain of Relizane. As early as 1945, the idea of an elevation emerged: by raising the level of the reservoir by 5 m the capacity of the reservoir would have increased from 36 to 56 Mm^3.

The Boughezoul dam is located 80 km south of the wilaya of Medea. The impoundment of this dam had started in 1934 after heightening in 1987, its storage capacity became 55 Mm^3, this dam is intended to protect the Gharib dam downstream against the effects of floods and siltation.

The Gharib dam is located in the Cheliff valley 7 km upstream from the center of Oued Cheurfa, 45 km from Khemis Meliana (W. Ain Defla) its construction was carried out between 1927 put into service in 1939, capacity from 280 Mm^3.

The dams concerned by this study are shown in Figure 1.

Morphometric parameters play a primordial role in water erosion, which is the main cause and source of materials feeding dams by solid supply (Demak, 1982; Khanchoul *et alii*, 2012). According to Probst & Suchet (1992), the acceleration of siltation is interpreted by the vulnerability of soils to erosion. Table 1 contains the morphometric elements of the 8 basins concerned by this study:

RESULTS AND DISCUSSION

Temporal evolution of the measured siltation (siltation phases)

Table 2 and figure 2 show the siltation and capacity data of three bathymetric surveys: 1986, these data express real volumes which serve to better identify the phenomenon.

Confirmation of the estimated data (the effectiveness of the chosen model) necessarily involves comparison with the measured data (results of the bathymetric surveys). (Megnounif *et alii*, 2003; Lahlou, 1990).

The dams concerned by this study are located in watersheds

Parameters	**Basin**	**Labiod**	**Bouamoussa**	**Safsaf**	**Ksob**	**(Chelif)**	**Mina**	**Chelif**	**Mina**
	Dam	F.El Gherza	Chafia	Zerdaza	Ksob	Gharib	SMBA	Boughezoul	Bakhadda
S (Km^2)		1300	575	345	1460	1378.63	6100	19724.76	1280
P (Km)		206	176	81	180	175.67	363	946.26	155
Hmax(M)		2328	1405	1220	1585	1500	1339	1750	1283
Hmin (M)		150	153	206	590	400	190	650	190
Hmoy (M)		1081.3	702.5	628	1070	895	945	1155.54	999
H50 (M)		1170	620	580		870	1010	1180	1010
Ig (m Km^{-1})		24,67	22	22.37	15.8	16.44	28	18	22
Kc		1.59	2.06	1.26	1.3	1.32	1.28	1.88	0.28
Ct		13.26	16.51	22.1	14	15	18	15	18
Dd (Km Km^{-2})		2.53	3.6	3.5	4	5.6	3.8	0.58	0.90
L (Km)		85	23	24.6	66.24	79.91	145	288	130
Ds (m)		889.48	295	400.17	450	344	477	380	473
P (mm)		328.2	798.5	642	320.7	330.5	326.8	280	336
Sd (Hm^3)		0. 84	0.24	0.32	0.45	3.7	2.38	0.61	0.25
SSL ($T/km^2/Y$)		581.82	794.85	724.11	574.9	583.9	580.55	533.07	588.78
Plant cover%		47	70	71	12	41	30	<10	45
Vulnerable Lithology (%)		46.55	59	60.20	50	52.5	53	55	53

Tab. 1 - Morphometric and hydrological parameters of watersheds and their dams studied

Dam	**Impoundment of dams**	**Yearly Siltation (Mm^3)**	**Capacity (Mm^3)**	**Ca(Mm^3) 1986**	**Slt(Mm^3) 1986**	**Ca(Mm^3) 2004**	**Slt(Mm^3) 2004**	**Ca(Mm^3) 2010**	**Slt(Mm^3) 2010**
Zerdaza	1945 Elevation of the dike 1977.	0.45	31	20.78	10.22	16	15	13	18
Chafia	1965	0.124	171	168.40	2.6	158	10	156	12
Gharib	1939	2.49	280	165.57	114.43	115.30	164.7	112	168
Bakhadda	1936 Elevation of the dike, 1958.	0.082	56	45.44	10.56	39.94	16.06	37.5	18.5
SMBA	1978	1.17	235	215	20	180	55	165	70
Ksob	1940 Elevation of the dike 1977.	0.39	31	16.43	14.57	12.34	18.66	11	20
F. Gherza	1950	0.59	47	23.14	23.86	14.89	32.11	14	33
Boughezoul	1934	0.57	55	20.38	34.62	18	37	16	49
∑			906	675.14	230.86	554.47	348.53	524.5	370.5

Tab. 2 - Characteristics of the studied dams

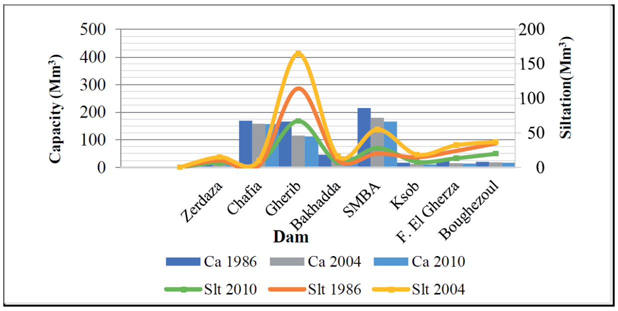

Fig. 2 - Evolution of the measured capacity (Ca) and siltation (Slt) of the studied dams

distributed over a large part of the country. A first analysis led to the identification of the variability of the hydro mor-phometric and the climatic characteristics of the studied area (Table1). The annual average siltation estimated by the ANBT. (Table 1) shows a variation between 0.082 Mm^3/year and 2.49 Mm^3/year (Table 2).

The initial total measured capacity of the basins studied was 906 hm^3 it was reduced to 675.14 Mm^3 in1986 when it about 524.5 hm^3 in 2010. Subsequently, a decrease of 381.5 hm^3 or 42.10% registered between the initial capacity and the last bathymetric survey in 2010 despite the siltation management operations.

First phase (from the Impoundment until 1986)

The initial capacity of the 8 dams studied (906 Mm^3) was reduced to 675.14 Mm^3 with a siltation of 230.86 hm^3 in 1986 or 25.79 % of the total capacity (Fig 3). It is to high-light that the sedimentation is very variable among dams.

The Boughezoul dam is located in a watershed with a low vegetation cover rate and an area of 19724.76 km², recorded a silt volume of approximately 34.62 Mm^3 or 62.94% of the total capacity of the dam over a period of 52 years (from impoundment until 1986) , on the other hand, over 36 years, the Foum el Gherza dam has received 23.86 Mm^3 of sediment, i.e. 50.76% of the dam's total capacity is occupied this watershed showed a high specific slope index value which explains the importance of erosion and subsequently siltation, the Gharib dam produced a volume of 114.43 Mm^3 of silt, or 40.86% of its initial capacity in 47 years from impoundment until 1986, this dam has a very high drainage density (5.6 km/km²), and the highest solid load rate (37 hm^3) that favor the evolution of erosion despite morphological, hydro-logical and lithological disparities.

The three dams Boughezoul, Foum El Gherza and Gharib-produced 172.92 Mm^3 or 74.89% of the siltation of this phase and 17.86% of the siltation recorded during the all studied period (from the impoundment until 2010).

The lowest siltation rates compared to the total siltation of this first phase recorded respectively at: Zerdaza (4.42%), Chafia (4.52%), Bakhadda (4.57%), Ksob (6.31%) and SMBA (8.66%). Due to the effect of dense vegetation on the Chafia, Zerdaza and Bakhadda watersheds; the most important reforestation operations are carried out on the basin of the SMBA and Ksob dams.

Second phase (from 1986 to 2004)

The second phase totals a siltation volume of around 348.53 Mm^3 and a useful capacity of 554.47 Mm^3.

Figure 3 showed an increase in total measured siltation of 117.67 Mm^3 during the second phase , the siltation recorded in this phase constitutes 36.015 % of the total siltation (from impoundment until 2010), which shows the im-portance of the total siltation of the 8 dams in this phase.

The Gharib and SMBA dams have the largest areas and have the highest sediment volumes which are 164.70 Mm^3 and 55 hm^3 respectively, ie 62.82% of the siltation observed during this phase; by deeply analyzing this results we see that the Gharib dam experienced an increase in siltation between 1986 and 2004 by 50.27 hm^3 and an increase of around 35 hm^3 for the SMBA dam.

The two dam's Gharib and SMBA have the highest drainage densities, respectively 5.3 and 3.8 (Table 1). Then the other dams total a rate of 37.18% of the siltation noticed during this whole second phase and 13.31% of the total siltation (from the impoundment until 2010).

The third phase (from 2004 to 2010)

This last intense alluvial phase recorded a volume of silt estimated at 388.5 Mm^3, i.e. a percentage of 42.88% of the total siltation, which shows the accelerated behavior of the silting in this phase due to a characterized rainy phase. By intense torrential rains generating a series of floods preceded by another (2nd phase) relatively dry preparatory to soil erosion. This siltation is developing very quickly and reaches its maximum at SMBA (70 Mm^3) with an increase of 15 hm^3 compared to the previous phase and arrives at 49 hm^3 at Boughezoul whose difference in siltation between 2004 and 2010 is of the order of 12 hm^3 or 21.81% of the total capacity of the dam in 6 years.

Despite, the Gharib dam recorded a cumulative total of 168 Mm^3 but we can say that its evolution (difference between 2004 and 2010) remains low (3.30 Mm^3). However, the lowest silt accumulation in this phase is observed in the dam of Foum El Gherza with 0.87 hm^3 which approaches the annual mean siltation due to the lack of rain, around 150 mm on average. The siltation of the three dams constitutes 73.87% of that of the phase and 29.65% of the total siltation (accumulated in all the dams) since impoundment until 2010.

Behavior of the siltation of the studied dams

Table 2 has showed that the speed of siltation given by ANBT frome impoundment until 2010 was variable between dams, however, it approximates for some dams which offer similar

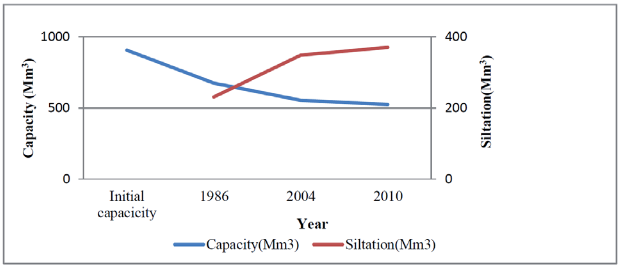

Fig. 3 - Temporal evolution of the capacity and siltation of the studied dams

conditions and are grouped into three categories:

- weak siltation show a value less than 0,50 hm^3 characterizes the dams: Zerdaza, Chafia, Bakhadda, Ksob; this remark is explained by the role of vegetation in limiting siltation, particularly in the first three dams (Table 1).
- average siltation is between 0.50 Mm^3 and 0.60 Hm^3 in this class there is Boughezoul and foum El Gherza dam, the effect of the surface, the slope and the average altitude help to increase the erosion and sedimentation of the two dams.
- high siltation: greater than 0.60 hm^3 was found in the Gharib and SMBA dams.

Finally, this increase in siltation would be controlled by the low rate of vegetation cover in the two dams: SMBA (30%), Gharib (41%), vulnerable lithology which contribute to the acceleration of siltation (53% for the SMBA watershed and 51.5% for the Gharib dam watershed) (Table 1).

Figure 3 shows the temporal variation of siltation and the capacity of the dams for different dates.

Figure 3 shows that a rapid decrease in capacity was recorded between impoundment and 1986 which moved from 906 Mm^3 to 554.47 Mm^3 followed by a rapid increase in siltation between 1986 and 2004 of approximately 348.53 Mm^3 and this increase reached its maximum in 2010 with 388.5 Mm^3 this cumulative siltation accelerated over time due to the increase in mean erosion during the last two phases of siltation.

	Silt (Mm^3). Frome Impoundment until 1986.	Silt (Mm^3). (2004)	Silt (Mm^3). (2010)
Accumulation of silt(Mm^3)	230.86	348.53	388.5
Alluvioning Phases	Silt 1986	Silt(2004)-Silt(1986)	Silt(2010)-Silt (2004)
Increase of the Silt(Mm^3)	230.86	117.67	39.97
Siltation / Number of years	4.6	6.53	6.6

Tab. 3 - Data on the behavior of siltation by phase

Table 3 shows that the cumulative sedimentation in 1986 reached 230.86 Mm^3 then the cumulative recorded in 2004 was 348.53 Mm^3 with an increase of 117,67 Mm^3 of silt in 18 years, in 2010 the total accumulation of silt became 388.5 Hm^3 on the other hand, the increase in sedimentation between 2010 and 2004 was 39.97 Mm^3; this difference can be explained by the difference in duration that characterizes each phase. When dividing the volume of siltation recorded during each phase by the corresponding number of years. It follows that the siltation is rapid in the last phase (6.6 Mm^3) then in the second phase (6.53 Mm^3) and seems relatively slow in the first phase (4.6 Mm^3).

Estimation of siltation as a function of time by empirical formulas

At the beginning, the calculation of the siltation by the empirical formulas aims to know how the siltation develops as a function of time then to take an idea on the future situation of the siltation and to take the results obtained in charge in the case of destination dams, under similar hydro-climatic and geomorphological conditions, especially in the absence of bathymetric surveys (Lahlou 1990; Kassoul 1999; Bouanani 2004).

It should be noted that the estimated values of siltation and capacity are very close to those observed in several dams and for all the phases, the similarity between the measured and calculated results shows the effectiveness of the model used in estimating siltation.

After having calculated the difference between the measured and simulated siltation in order to show the effectiveness of the estimate, this difference is classified into three categories as follows:

- < 2 this category contains 14 values; the measured and simulated data are very close together with 9 values less than 1;
- the class: 2 to 4 comprises 6 values in which the dams offer estimated and measured volumes which are close to which the Gharib dam expresses this situation well with two values for the years 2004 and 2010. While the other dams: Zerdaza, Chafia, Bakhadda and Foum El Gherza give a single value;
- > 4 this class matches the differences between the siltation values observed and simulated over the years:
  - 1986, 2004 and 2010 for Boughezoul
  - 2010 for SMBA.

On the other hand, the calculation of siltation by the model chosen has shown that the result obtained are overestimated for the Boughezoul dam which is located in a vast watershed with an area of around (19724.76 km^2), note that the difference greatly exceeds 4 hm^3 and reaches 17 hm^3.

Detailed examination of table 3, has shown that the estimated values of siltation are closely linked with the area of the watersheds as soon as the area is greater than 6000 km^2 the model gives acceptable results.

The application of the model gives very acceptable results in dams located in northern basins with a humid or sub humid climate (Zerdaza, Chafia, and in some dams in basins characterized by a semi-arid climate Ksob, Foum El Gherza, Bakhadda and SMBA) have shown values that belong to the first and second class (Table 3) While the dams (Boughezoul) which has a very large area (19724.76 km^2) is in the third class.

Figures 4 and 5 show good agreement between the observed and estimated capacities as well as for the estimated and observed values of siltation for all the dams. The difference between

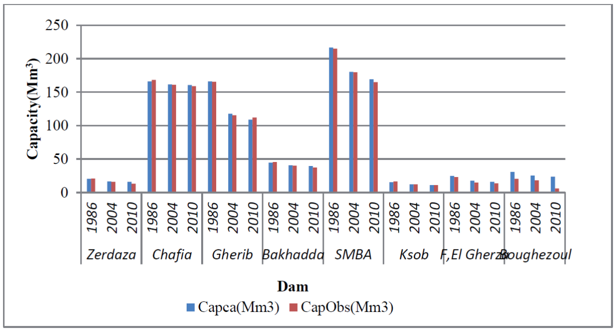

Fig. 4 - Estimated Capacity

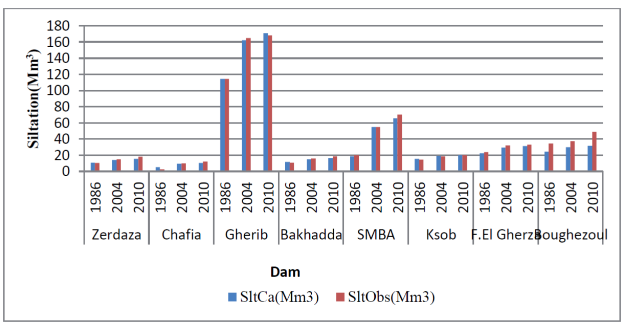

Fig. 5 - Estimated Siltation

the observed and estimated values remains very small, the acceleration of siltation observed for all the dams was during the autumn and spring, months concerned by this acceleration are September, October and april with a percentage reaching 60% of the general alluvium, knowing that this siltation corresponds with the torrential rains generating floods which mobilize and bring back large volumes towards the dams (MEBARKI, 2005; REMINI *et alii*, 2016; KHANCHOUL *et alii*, 2007). But, it is not always the increase in annual precipitation causes the greatest erosion in many cases the determining factors are lithology, plant density, density of drainage and other factors, however, the duration of the observation of siltation is different from one dam to another from the impoundment to the year of measurement or estimation.

The model chosen gives sufficiently acceptable results (Table 4).

Validation of the results obtained

Plus the difference calculated between the measured and simulated siltation which explains and clearly shows the efficiency of the model for all the dams and for all the phases studied, this conformity was also validated using the statistical test of Nash which remains largely used in this type of comparative studies:

$$Nash = [\,1 - \frac{(\sum(Sltca - SltObs)^2)}{(\sum(SltObs - \overline{Sltobs})^2)}\,] \qquad (4)$$

Dam	Year of Survey	Capca (Mm³)	SltCa (Mm³)	CapObs (Mm³)	SltObs (Mm³)	SltObs-SltCa (Mm³)
Zerdaza	1986	20.26	10.74	20.78	10.22	0.52
	2004	16.81	14.19	16	15	0.81
	2010	15.79	15.21	13	18	2.79
Chafia	1986	166.05	4.95	168.4	2.6	2.35
	2004	161.89	9.11	161	10	0.89
	2010	160.53	10.47	159	12	1.53
Gherib	1986	165.92	114.08	165.57	114.43	0.35
	2004	117.94	162.06	115.3	164.7	2.64
	2010	108.89	171.11	112	168	3.11
Bakhadda	1986	44.51	11.49	45.44	10.56	0.93
	2004	40.98	15.02	39.94	16.06	1.04
	2010	39.86	16.14	37.5	18.5	2.36
SMBA	1986	216.56	18.44	215	20	1.56
	2004	180.19	54.81	180	55	0.19
	2010	169.47	65.53	165	70	4.47
Ksob	1986	15.69	15.31	16.43	14.57	0.74
	2004	12.02	18.98	12.34	18.66	0.32
	2010	10.99	20.01	11	20	0.01
F.El Gherza	1986	24.56	22.44	23.14	23.86	1.42
	2004	17.75	29.25	14.89	32.11	2.86
	2010	15.93	31.07	14	33	1.93
Boughezoul	1986	30.8	24.2	20.38	34.62	10.42
	2004	25.19	29.81	18	37	7.19
	2010	23.56	31.44	6	49	17.56

Tab. 4 - Calculation of siltation as a function of time using the F.Orth equation

Sltca: calculated siltation
SltObs: Observed siltation
$\overline{Sltobs}$: Average siltation of bathymetric surveys taken.

According to NASH (1970) and GUPTA (2009):
- if the value of Nash = 1: perfect estimate of the observed values;
- if 0 <value of Nash <1: estimate is better;
- Nash <0: estimate minus.

The value obtained for all dams by applying the formula (4) gives a very good estimate. (the simulated values fit perfectly with the observed values).

The result obtained confirms the correlations made between the observed and calculated volumes.

Management of siltation

At the watershed level

Soil conservation as a means of minimizing the penetration of solid materials into a reservoir, two methods of soil conservation are used to curb erosion:

The establishment of anti-erosion structures.

The development of watersheds and rivers; This concerns the development of watersheds by carrying out the torrential correction of thalwegs, and the development of watercourses (REMINI, 1997).for all the watersheds, in particular those which attest to a strong erosion, a weak vegetation cover and a vulnerable lithology (wadi Labiod and Gharib basin).

Reforestation.

- Planting of crops along the contour lines and fixing the banks of

Dam	Years	SltCa	Sltobs	Nashe
		0.000	0.000	
	41	10.740	10.220	
Zerdaza	59	14.190	15.000	
	65	15.210	18.000	
	M		10.805	
	∑	40.140	43.220	0,992
	Years	SltCa	Sltobs	
		0.000	0.000	
Chafia	21	4.950	2.600	
	39	9.110	10.000	
	45	10.470	12.000	
	M		6.150	
	∑	24.530	24.600	0.977
	Years	SltCa	Sltobs	
		0.000	0.000	
Gharib	47	114.080	114.430	
	65	162.060	164.700	
	71	171.110	168.000	
	M		111.783	
	∑	447.250	447.130	1.000
	Years	SltCa	Sltobs	
Bakhadda		0.000	0.000	
	50	11.490	10.560	
	68	15.020	16.060	
	74	16.140	18.500	
	M		11.280	
	∑	42.650	45.120	0.994
	Years	SltCa	Sltobs	
		0.000	0.000	
	8	18.440	20.000	
	26	54.810	55.000	
SMBA	32	65.530	70.000	
	M		36.250	
	∑	138,780	145.000	0.998
	Years	SltCa	Sltobs	
		0.000	0.000	
	46	13.570	14.570	
Ksob	64	17.090	18.660	
	70	18.090	20.000	
	M		13.308	
	∑	48.750	53.230	0.997
	Years	SltCa	Sltobs	
		0.000	0.000	
	36	21.120	23.860	
	54	27.780	32.110	
	60	29.620	33.000	
Foum.Elgherza	M		13.308	
	∑	78.420	53.230	0.996
	Years	SltCa	Sltobs	
		0.000	0.000	
	52	24.2	34.62	
	70	29.81	37	
Boughezoul	76	31.44	49	
	M		30.155	
	∑	85.45	120.62	0.95

Tab. 5 - *Calculation of Nash criterion. M: Average siltation ($\overline{SObs}$), ∑: Summ of Siltation, SObs: Observed siltation, SCa: Calculated Siltation, N: Nash Criterion.*

the watercourse.
- Construction of upstream settling dams.
- The construction of hunting dams.

At the dam level

Withdrawal of density currents (Drawing off): a practical method which consists in evacuating the sediments drained by the density currents on the bottom of the reservoir by using drain slits (drain valves or bottom valve) from the dam; As soon as the roof of the sludge reaches the thresh-old of the valves, the turbid layer is above, and its with-drawal becomes easier (Remini *et alii*, 1997).

The sediment clearance operations and the extraction of density currents must be mastered in order to be able to remove the maximum amount of silt with a minimum of water (Saidi, 1991; Brambilla *et alii*, 2015).

According to Remini (2003) the racking technique can be an effective means of combating the silting up of reservoirs.

The elevation of the dikes

One of the techniques that can extend the life of a dam is elevation. The increase in the height of the dike makes it possible to compensate for the volume of water lost in depth occupied by the silt. Their operation is very encour-aging (Kassoul, 1997). This technique was carried out on the Zerdaza dams, Ksob, Boughezoul and Bakhadda whose dikes were respectively raised in 1975, 1977, 1960 and 1958 at following rapid filling of the reservoirs. All the over-breeding operations in Algeria made it possible to recover a capacity of 100 million m^3 until 2007.4 Mm^3 in Foum Gherza, 7 Mm^3 in Zerdaza (Hallouche & Remini, 2005; Remini & Bensafia, 2016).

Dredging dams

The factors that lead to consider dredging are linked either to hydraulic considerations or to the maintenance and restoration of the environment. Dredging can have several objectives including; recovery of storage capacity; Extract submerged sediments such as sand, gravel, clay, precious metals and fertilizers (Benblidia *et alii*, 2001).

CONCLUSIONS

In this work we have approached the processes of water erosion as well as the resulting siltation in reservoirs, this problem which remains a topical subject and which interests researchers, policy makers and citizens of all countries. Several researchers have tried to describe and quantify siltation using predictive models, these models adapted to specific conditions (Sogreah, 1989; Tixiront, 1960) in this context, we will try to apply the model of Orth which seems a more reliable model for the estimation of siltation in some Algerian dams despite the difference in the technical conditions of the dams and sometimes a large difference in the conditions. climatic, lithological and morphometric of the watersheds where the dams are installed. Solid transport in Algeria is characterized by rapid filling of dam reservoirs and a considerable decrease in storage capacity and consequently the reduction in the lifespan of dams (Hallouche *et alii*, 2005; Remini & Bensafia, 2016; Meddi *et alii*, 2014).

According to Khentouche & Dridi (2019). The evolution of siltation follows an accelerated path and in fact due to the extreme climatic, morpho-dynamic and hydrological conditions of the basins on the other hand we can say that the degradation of the forest cover worsens the flood regime by making it more violent due to lack of retention. (Remini, 2018; Hallouche, 2005). The results of specific solid transports are comparable to those found in several areas in Algeria and by many researchers the valus of sediment yield is varied between 450 and 1000 T km^{-2} y^{-1} but in different period.(Kassoul, 1999; Tebbi, 2014; Meddi, 2014).

The siltation remains variable and irregular between dam and other and takes an accelerated rate for Gharib and SMBA.

According to ANBT (2010). Certain dam which are practically silted (Foum el Gherza), it attests to the operations of devasement. 4 Mm^3 of the silt was removed by dredging for 48 months but the volumes of inflows that arrive after each flood can recover this sediment supply. In addition, the calculations of siltation at Gharib, Smba and Boughezoul dams have shown the high alluvial behavior due to the fragility of the lithological formations and the effect of certain morphometric and physical factors (Hallouche *et alii*, 2005; Bougamouza *et alii*, 2020; Remini & Bensafia, 2016). Certain dams were endowed with dense and varied vegetation cover which slows down the erosive force of the rains minimizes the quantities of sediments produced, while some dams (SMBA, GHARIB) presents only a weak cover dominated by the scattered maquis which develop on a clearly denuded soil which makes the particles of the soil very equipped to move quickly under the flow of the floods in particular of autumn and spring (Remini, 2018).

The acceleration of siltation in certain dams is primarily due to the intensity of erosion and the accentuation of certain morphometric and hydrological parameters (Benblidia *et alii*, 2001; Khentouche & Dridi, 2019; Mebarki, 2010). In addition, the calculations carried out by the Orth method are fully justified and confirm, all the more so the trend taken by the temporal evolution curve of the alluvium observed.

It is clear that Orth's model gives results close and comparable to those found by bathymetric surveys, which qualifies this model to be applicable in similar climatic, physical and lithological conditions and to put in the hands of engineers and decision-makers an effective alluvial forecasting tool that rapidly replenishes reservoirs and considerably reduces the lifespan of dams.

The evolution of siltation has been increasing to reach a very advanced stage.

This development is reflected in three phases depending on the extent of the phenomenon:

- weak siltation show less than 0.50 characterizes the dams: Zerdaza, Chafia, Bakhadda, Ksob.
- average siltation is between 0.50 and 0.60 in this class there is the Boughezoul and Foum El Gherza dam.
- high siltation: greater than 0.60 was found in the Gharib and SMBA dams, attests to accelerated siltation.

According to our analysis supported by the reports of ANBT (2010). We find that the rate of silting of dams in operation increases with the age of the dam. In this sense one can find some cases of dams for which the rate of silting is high, in particular: Foum El Gherza (1950) 68%, Boughezoul (1934) 63%, Ksob (1976) 60%, Gharib (1939) 59%, Zerdaza (1974) 40%, SMBA (1978) 36%, Bakhadda (1936) 28%.

The main goal of this study was focused on the diagnosis and evolution of siltation based on quantitative and analytical methods to arrive at possible and favorable recommendations and solutions (Remini, 2018; Tabbi, 2014). Finally. The Algerian climate is characterized by the abundance of torrential rains which generate aggressive floods carrying significant solid transport therefore a rapid silting up of the dams. It is becoming urgent to plan for the siltation of dams as precisely as possible so as to take the necessary economic and social measures but also and above all to develop certain study techniques to improve methods of controlling alluvial deposits. (Khentouche & Dridi, 2019).

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