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SUSTAINABLE DESILTING OF DAMS

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ABSTRACT

The recovery of mud is the only way to solve the problem of silting up dams. At the beginning of the 1990s, we studied the recovery of mud from a dozen dams in construction and agricultural fields. In the case where the destination of the silt is known thanks to the chemical, physical and mineralogical analyses, the desiltation is carried out in a continuous way; in this case, we speak of sustainable desilting. This is what this paper discusses for the first time. Sustainable desilting consists of equipping the dam with one or more dredges that continuously remove silt. Once the mud is discharged and then stored in basins built upstream of the dam, the water returns to the reservoir. Once dried, the mud is transported to its place of use, but preferably in the agricultural field.

Keywords: Dam, Siltation, Sustainable desilting, Valorisation of the silt, Hydraulic dredging.

INTRODUCTION

In arid regions, dam operators are confronted with a thorny hydraulic problem; this is the phenomenon of the siltation of dams. Due to the construction of a dyke (obstacle) on a watercourse, the sediments drained by the water settle at the bottom of the reservoir following the slowing down of the flow by the obstacle. Layer after layer, the fine particles torn from the slopes settle down and consolidate, thus causing clogging problems in the drainage sluices. Thus, over time, the useful volume shrinks following the lengthening of the dead volume. In this case, the dam becomes unable to meet the water demand for irrigation or drinking water supply. These cases exist in arid countries and more particularly in North African countries. The northern part of Algeria is known for the importance of the phenomenon of erosion, which degrades the four hydrographic basins. According to Demmak (1982), more than 180 million tonnes of fine particles torn from the slopes during a year flow into the sea. On average, 65 million m^3 of silt settles at the bottom of 74 dams in operation (Remini, 2017). We estimated the volume of mud deposited at the bottom of these dams to be 2 billion m^3. However, 20 dams are in a critical situation and can no longer meet domestic or irrigation water needs. It should be noted that Algeria has made great efforts to reduce the effects of siltation and therefore increase the life of dams. Algeria is among the rare countries in the world that have used all the technical means of combating siltation, whether preventive or curative means. After studies carried out on the siltation of Algerian dams since the nineties, it turns out that this phenomenon is complex and is not so simple to eliminate the deposits of sediments at the bottom of the lakes of the dams. However, the studies that we carried out on the recovery of silt from approximately ten dams at the beginning of the 1990s showed that this deposit (silt) can be used in agricultural and construction fields (Remini, 2006; Labiod et al., 2004; Remini and Kenai, 2000; Remini et al., 2018; Remini, 2020; Remini et al., 2019). However, despite the very encouraging results obtained in the laboratory, these results have not materialized in the field. Today, it is time for the silt to return to where it came from, that is to say to use the silt in the agricultural field. The recovery of silt is the key to the sustainable desilting of dams; this is the subject that we study in this article.

STUDY REGION AND WORK METHODOLOGY

Study area

Algeria today has a potential of 80 dams, 76 of which are located in the north, and 4 others are located at the entrance to the Sahara. Only 6 dams have been built recently and have not yet been silted up. The 74 dams in operation with a capacity of 8.6 billion m^3 have a total silt deposit equal to 1.7 billion m^3, i.e., a filling rate of 20% (Remini, 2017) (Fig. 1).

Methodology of work

This modest work on the sustainable desilting of dams is the result of research undertaken since 1987, when I started preparing for my Magister degree on the mechanism of siltation. At the time among the first to raise this problem of siltation in Algeria. Approximately one hundred articles and proposals on the technical means of combating siltation have been drawn up. However, curative means of struggle have always been a complicated subject that deserves to be studied. We deduced that once a dam is dredged or raised, it continues to silt up. Afterwards, we focused our work on the recovery of silt from dams. Several mud samples were taken from approximately ten dams (Zardezas, Beni Amrane, Foum El Gherza, Oued Lekhel, Bouhanifia, Ighil Emda, Sidi M'hamed Ben Aouda, etc.) for analyses carried out in the laboratory (Remini, 2006; Labiod and Remini et al., 2004; Remini and Kenai, 2000; Remini et al., 2018; Remini, 2019; Remini, 2020). Despite results deemed very satisfactory, we did not materialize this project in the field at the time. After thirty years, siltation persists, and approximately twenty dams are now in danger of disappearing if means of control are not taken in the short term. Going for sustainable desilting is the only way to extend the life of our dams. This is what we address in this paper.

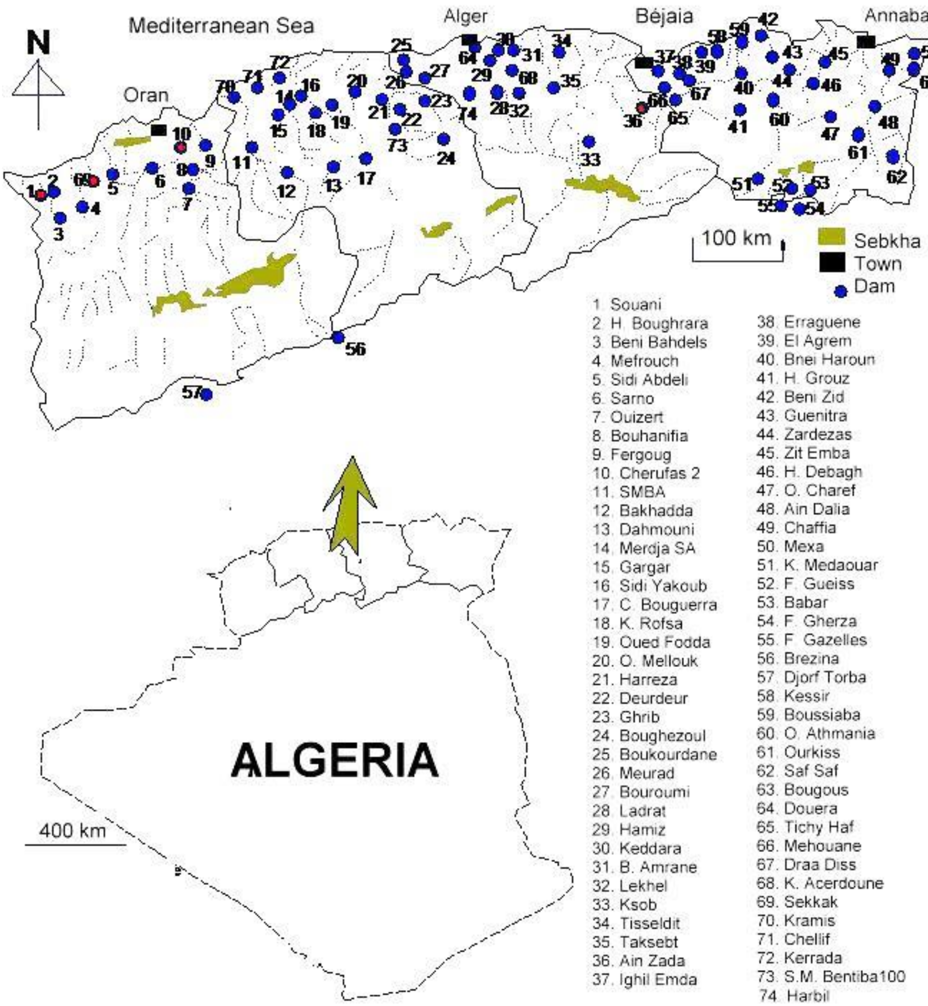


Figure 1: Geographical location of dams in operation in Algeria (Remini, 2017)

RESULTS AND DISCUSSION

Magnitude of the phenomenon of siltation in Algeria

As a natural phenomenon, the siltation of dams poses many problems for dam operators, such as the reduction of the useful volume and the clogging of the outlets. Due to the complexity of the mechanisms of siltation, it becomes difficult to solve this problem, especially with the disruption of the climate, further complicating this problem (Remini, 1997; Remini and Bensafia, 2016). The study we conducted in 2017 showed that the average annual siltation rate is approximately 65 million m^3 per year (Remini, 2017). Today, of the 74 dams in operation, 20 dams are seriously threatened by the phenomenon of siltation (Fig. 2 and Table 1). With a total capacity of 2370 million m^3, more than 1150 million m^3 of sludge drained by the floods is currently deposited at the bottom of these 20 dams. This is a filling rate of 48% of the total capacity. It must be admitted that despite the very advanced age of these dams, a capacity of 2.37 billion m^3 of water is in serious danger of disappearing in the short term if serious solutions are not taken immediately. In addition, favorable sites for the construction of new dams are increasingly rare.

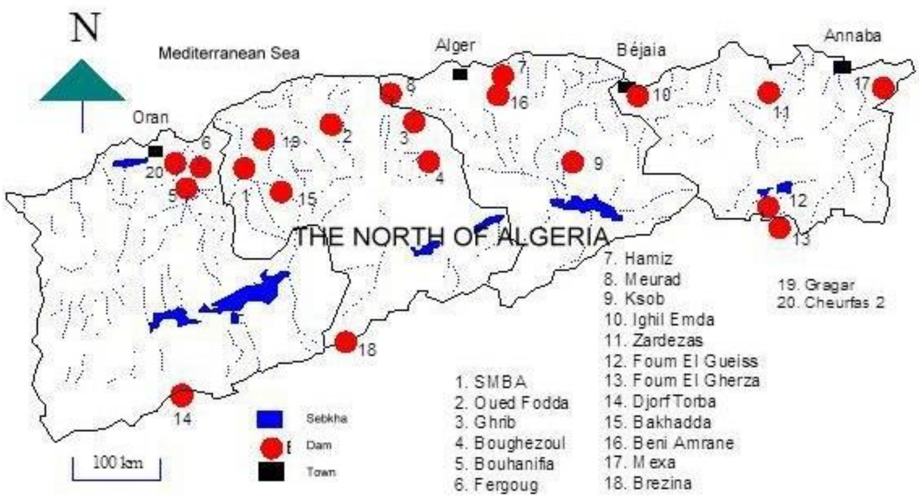


Figure 2: Location of the most silted dams in Algeria (Remini, 2017)

Table 1: Filling rate of dams threatened by siltation

N°	Dam	Year of dam impoundment	Initial capacity (million m^3)	Annual filling rate (%/year)	Year of full filling of the dam
1	SMBA	1978	235	1.7	2040
2	Oued Fodda	1932	228	1	2060
3	Ghrib	1939	350	1.15	2045
4	Boughezoul	1934	55	1.6	2025
5	Bouhanifia	1948	73	1	2055
6	Fergoug	1970	18	1.22	2017
7	Hamiz	1935	21	1.55	2045
8	Meurad	1860	1,2	0.6	2090
9	Ksob	1977	29,5	1	2045
10	Ighil Emda	1953	155	1	2070
11	Zardezas	1977	31	4,5	2020
12	Foum El Gueiss	1939	3	1.65	2017
13	Foum El Gherza	1950	47	1,2	2034
14	Djorf Torba	1969	350	0.9	2050
15	Bakhada	1963	56	0.72	2060
16	Beni Amrane	1988	16	6	2019
17	Mexa	1998	47	4,6	2019
18	Brezina	2000	122	2.9	2034
19	Gargar	1988	450	1.3	2065
20	Cheurfas 2	1992	82	1.35	2067
		Total	**2372**		

Among the 74 dams in operation, 8 dams recently put into operation are classified as vulnerable to siltation (Fig. 3 and Table 2). With a total capacity of 560 million m^3, more than 67 million m^3 of mud was deposited at the bottom of these dams in 2014. These dams could disappear in the short and medium term if measures to combat siltation are not taken in time. To obtain an idea of the extent of siltation on these new dams, we evaluated the lifetime of these dams (Table 2). For these new dams, preventive means are the priority of the National Agency for Dams and Transfers, as well as the development of watersheds by the realization of torrential correction, the realization of benches, reforestation and the stabilization of river banks.

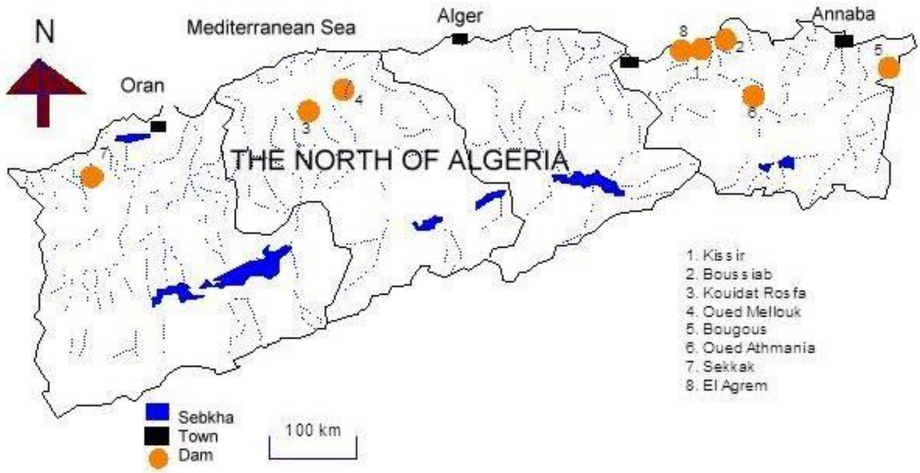


Figure 3: Location of new dams vulnerable to siltation (Remini, 2017)

Table 2: New dams vulnerable to siltation

N°	Dam	Year of dam impoundment	Initial capacity (million m^3)	Annual filling rate (%/year)	Year of full filling of the dam
1	Kissir	2009	76	4.2	2029
2	Boussiab	2010	120	2.3	2053
3	Kouidat Rofsa	2004	75	1.2	2087
4	Oued Mellouk	2003	127	2	2050
5	Bougous	2010	66	2.3	2054
6	Oued Athmania	2006	36	1	2106
7	Sekkak	2004	27	1.1	2094
8	El Agrem	2002	34	1.3	2079
		Total	**561**		

THE ALGERIAN EXPERIENCE IN THE FIGHT AGAINST THE SILTATION OF DAMS

Hydraulic dredging of dams

Algeria has deployed many efforts in the fight against siltation and, more particularly, curative means, particularly silting by hydraulic dredge and raising the dyke (Remini and Hallouche, 2004). Algeria has extensive experience in the desilting of dams by hydraulic dredging. Eleven dams were desilted by dredging (Fig. 4).

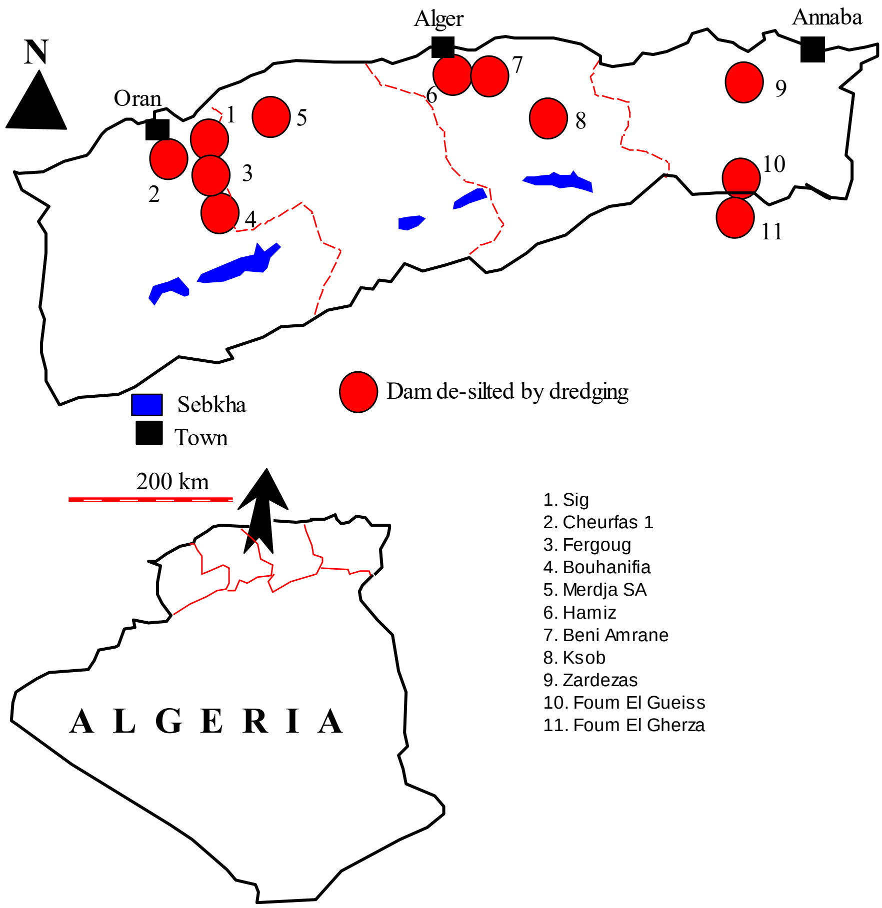


Figure 4: Location of dams desilted by hydraulic dredging in Algeria (Remini, 2022)

On the basis of a very thorough bibliographical research and the contribution of approximately twenty bathymetric surveys of the old dams, we have grouped in Table 3 all the data of the dredging operations carried out since independence (1962). It is interesting to note that a volume of 75 million m^3 of mud was removed by dredging at the level of the 11 dams with a total capacity equal to 380 million m^3 of water, i.e., a ratio of 20%.

Table 3: Volumes desilted by dredging in Algerian dams (Remini, 2019)

N°	Dam	Year	Initial capacity (10^6 m^3)	Year of desilting	Volume removed (10^6 m^3)	Current state of the dam
1	Sig	1846	1	1962-1964	1	Abandoned
	Fergoug	1871	30	1965-1966	3	Abandoned
2	Fergoug3	1970	18	1989-1992	7.1	
	Fergoug 3	1970	18	2005-5007	10	In use
3	Cheurfas 1	1882	14	1959-1962	8.5	Abandoned
4	Hamiz	1879	14	1967-1975	8.5	In use
5	Zardezas	1945	31	1993-2002	10	In use
6	Ksob	1879	29.5	2002-2004	4	In use
7	F. Gherza	1950	47	2004-2006	4	In use
	F.Gherza	1950	47	2015-2017	8 (operation in progress in 2019)	
8	Merdja	1984	55	2004-2006	5	In use
9	Bouhanifia	1940	55	2012-2015	4	In use
10	Foum El Gueiss	1939	2.5	2006	1	In use
11	Beni Amrane	1988	16	2004	0.28	In use

Algeria was among the rare countries that introduced the dredger in the sector of the stoppings and succeeded in clearing a volume of 75 million m^3 of mud; however, the hydraulic services encountered problems of the place of rejection of the mud (Remini and Hallouche, 2004). During the first dredging operations (1962-2000), approximately 40 million m^3 of silt was dumped directly into the rivers (Fig. 6a). Such a practice has caused many environmental problems, including pollution. Today, Algeria has made remarkable progress in terms of desilting by dredging. Suspension discharge operations directly into the rivers have been permanently suspended and replaced by a closed discharge system consisting of a series of storage basins dug upstream of the reservoir (Fig. 6b)

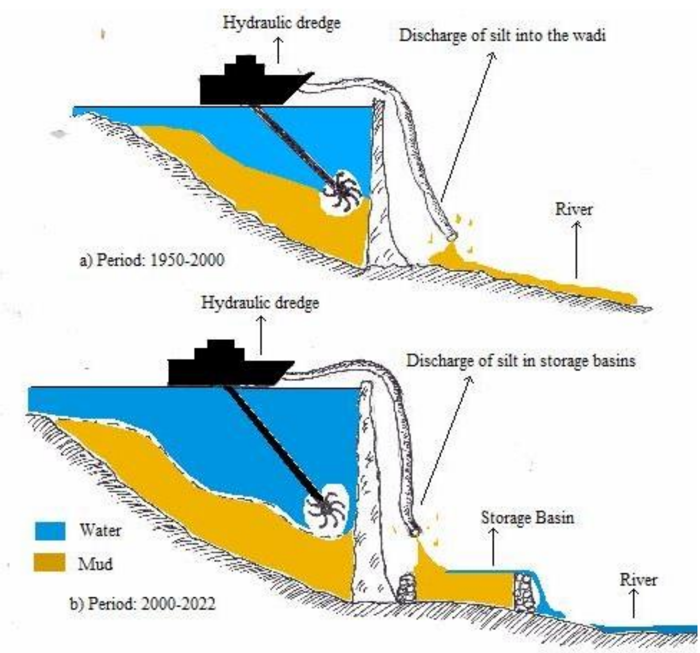


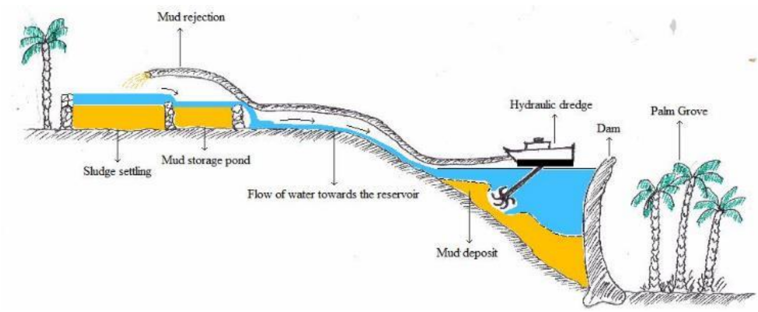
Figure 5: Diagram of the silt discharge site during dredging operations carried out on 11 Algerian dams (Diagram Remini, 2022)

a) Draping operation carried out on the reservoir of the dam of Foum El Gherza in 2006 (Photo. Remini, 2006)

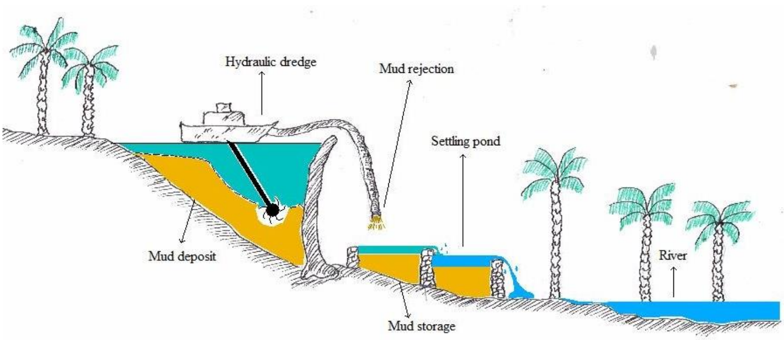
b) Dredging operation carried out on the Foum El Gherza dam reservoir in 2017 (Photo. Remini, 2017)

Figure 6: Discharge of silt in the storage basins built upstream of the Foum El Gherza dam

It should be remembered that deepening the bottom of a dam lake (dredging) consists of removing a quantity of mud deposited at the bottom of the dam during years of operation. The technique generally used is hydraulic dredging using a bucket dredge. For the success of such an operation, a significant quantity of water is needed in the reservoir to ensure a sufficient water depth at the dredge pump to easily suck up the loaded water. The dredge is equipped with a cutter to convert the sludge from the Bingham state to suspension (liquid in the Newtonian state). Such an operation is necessary to allow the pump to better suck up water containing fine particles. A series of basins must be constructed upstream of the dam reservoir to store the sludge discharged by the dedge. The number and dimensions of the basins are determined according to the amount of silt to be removed in the dredging operation. Using the floating discharge pipe, the suspension is filled basin by basin until the end of the desilting operation. Once the silt settles in the storage basin, the clear water returns by gravity, the silt returns to the ground, and the water returns to the reservoir. This mud storage and water recovery facility was implemented during dredging operations at the Foum El Gherza and Bouhanifia dams during the 2004-2019 and 2012-2015 periods. This closed circuit arrangement makes it possible to solve the problem of the place of storage of the mud and at the same time to recover the water lost during the desilting of the dams. Thanks to this development, the problem of discharging the suspension downstream of the dam into the river has been resolved but unfortunately only temporarily. The number of basins depends on the amount of sludge to be cleared. The silt cannot be dumped indefinitely in the peripheral areas of the dam. Discharge into the basins cannot exceed two to three dredging operations. This is the case with the desilting of the Foum El Gherza dam (Figs. 7 a, b, and 8).



a) Storage basins upstream of the dam



b) Silt storage ponds downstream of the dam

Figure 7: Approximate diagram of a dredging operation carried out on the Foum El Gherza dam during the period 2004-2017 (Drawing. Remini, 2022)

Figure 8: Basin filled with silt spilled during dredging of the Foum El Gherza dam reservoir (Photo. Remini 2017)

A quantity of silt estimated at more than 12 million m^3 was removed from the reservoir of the Foum El Gherza dam during the period 2004-2017. This volume of silt was stored in 13 basins covering an area of 1.3 km^2, of which 10 basins were developed upstream and 3 downstream of the dam. Despite these dredging operations, the Foum El Gherza dam silted up increasingly, and its useful volume became unable to satisfy its demand for irrigation of the palm groves of Sidi Okba and Garta of 300,000 date palms. To compensate for this lack of water from the dam, the services concerned have used borehole water. Today, it will be difficult to schedule other dredging operations due to the lack of an area for the digging of new basins. To further extend the life of this dam, raising the dike becomes an emergency exit. Otherwise, resorting to sustainable desilting remains the last solution. This is what we study in the rest of this article.

Raising of dams

The second option for curative means of control consists of leaving the mud at the bottom of the dam and raising the dike by a few meters to gain an additional volume of water (Fig. 9). However, such an achievement takes into account the geology of the site and the foundations of the dike. More hectares of land upstream of the dam will be occupied by the rising water level of the dam lake.

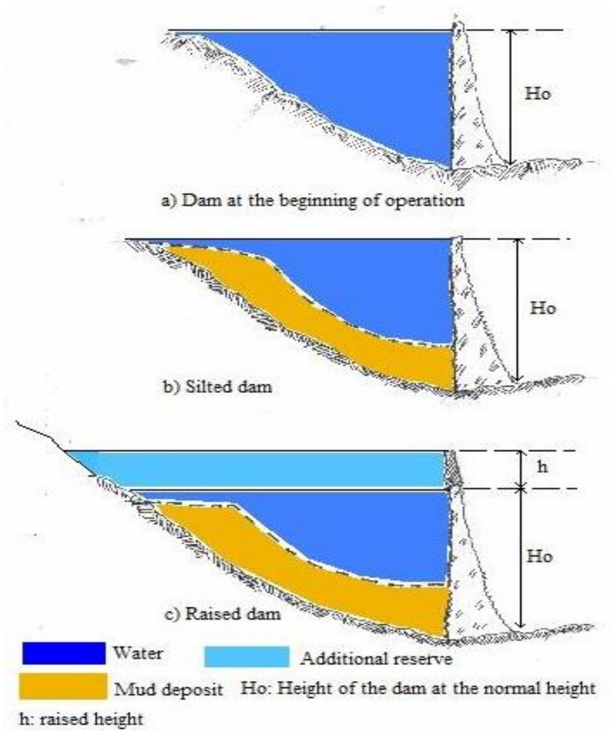


Figure 9: Schema of a raised dam (Schéma Remini, 2022)

This solution has been used by hydraulic services on 9 dams since the 1960s (Remini, 2008) (Fig. 10). However, during the last 10 years, the National Dams Agency has experimented with a new technique that consists of raising the spillway with fuse blocks, as is the case with the Ghrib and Beni Amrane dams. The last raised dam is that of Ghrib, which in 2007 underwent an operation to raise the spillway by 3 m using fusegates to gain an additional water reserve of 70 million m^3, i.e., a 25% increase in the total capacity of the dam (Fig. 11).

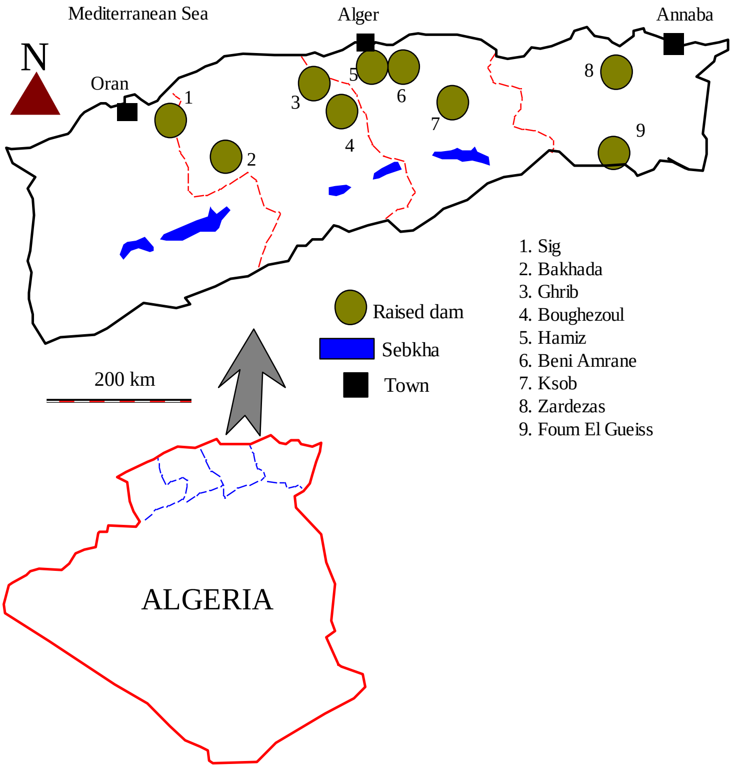


Figure 10: Location of raised dams in Algeria (Remini, 2022)

Figure 11: The Ghrib dam spillway equipped with fusegates (Photo. Remini, 2018)

The desilting paradox

In a dam in an advanced state of siltation, the useful volume decreases to the detriment of the dead volume, which gains space due to the successive deposits of sediments. We have defined that a dam is in a state of critical siltation when its filling rate exceeds 50% (Wv/Wo=50%). In this case, two solutions are available to increase the useful volume of the dam (Fig. 12):

- Deepen the reservoir by removing a quantity of silt using the hydraulic dredging technique.
- Extend the height of the reservoir while keeping the mud at the bottom of the dam. This technique consists of raising the dike by 2 to 3 meters to gain additional volume.

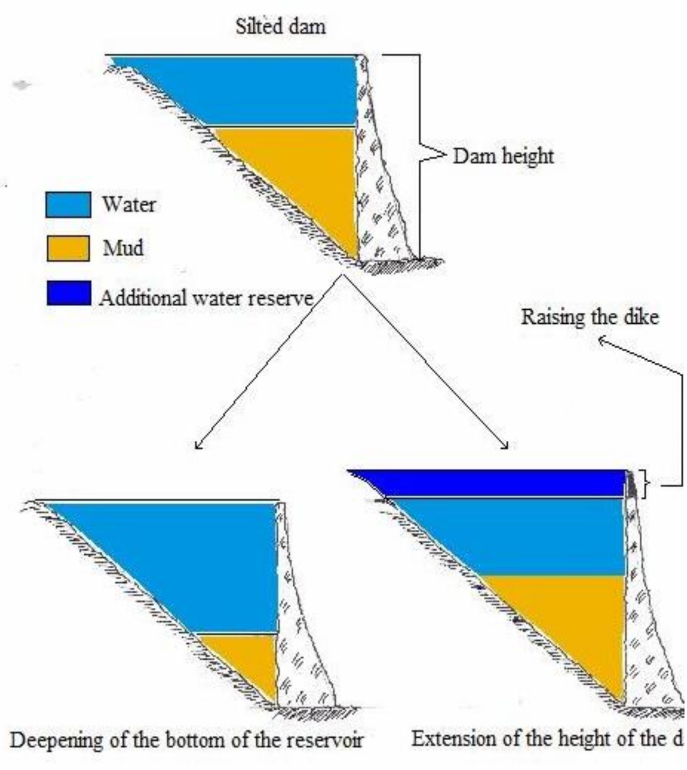


Figure 12: The two types of dam life extension (Remini diagram, 2022)

However, if the geometry of the reservoir and, more particularly, the depth is modified, whether by raising the dike or by digging the bottom of the reservoir (by hydraulic dredging of the reservoir), the solid contributions will increase even more after tank modification. Table 4 confirms this hypothesis since we observe that the rate of siltation after raising or dredging is higher than before. The evolution of the siltation is greater than after the modification of the reservoir.

Table 4: Average sedimentation velocities of raised dams (Remini, 2008)

Dam	Sedimentation rate	(10^6 m ^{3} / an)
	Before elevation	After elevation
Zardezas	0.30	0.70
Ksob	0.25	0.29
Boughezoul	0.34	0.50
Bakhada	0.05	0.15
Hamiz	0.06	0.33
Foum El Gueiss	0.006	0.04

Regarding dams desilted by hydraulic dredging, two cases have been studied in this paper. These are the Hamiz and Zardezas dams. We found that the rate of silting after desilting was higher than before; siltation accelerated after dredging. To give more weight to our study, the municipality of Tiout carried out dry desilting of the reservoir of the ancestral dam by mechanical means in 2017. It is reported that Tiout is an oasis located 750 km southwest of Algiers. It is known for its ancestral dam built more than 7 centuries ago on the Tiout River, which incidentally bears its name (Fig. 13).

Figure 13: A general view of the ancestral Tiout dam (Photo. Remini, 2008)

This dam, which is intended for the irrigation of the palm grove and the supply of the ksar, is filled with spring water. Today, it is silted up by sediments drained by the floods of the Tiout River (Fig. 14a and b). In 2017, the dam was desilted by mechanical means (Fig. 14 c and d). It was necessary to wait just a year after its desilting to observe a flood that appeared on the Tiout River. After the flood, the same quantity of silt that was desilted was again deposited in the reservoir, but this time, all the silt was brought back by a single flood (Figs. 14e and f).

a) Dam before the 2017-Silted Reservoir (Photo. Remini 2008)

b) Front dam 2017- Right bank of the reservoir (Photo. Remini, 2008)

b) Dam in 2018-Desilted reservoir seen from the dyke (Photo. Remini, 2017)

d) Dam in 2018 - Reservoir seen from upstream (Photo. Remini, 2017)

e) Dam after the passage of the 2018 flood-The silt is more important than before the desilting. The dike is hidden by mud (Photo. Remini, 2018)

f) Dam after the passage of the 2018 flood-The silt is more important than before the desilting. View from upstream (Photo. Remini, 2018)

Figure 14: Siltation process of the Tiout dam after mechanical desilting

Sustainable desilting of dams

A reservoir dam is the only hydraulic structure whose lifespan depends on an external parameter; it is water erosion. When a dam is built on a watercourse, it will be subject to siltation, the intensity of which depends on the phenomenon of erosion. Once the dam is totally filled with mud, it will be decommissioned. The initial capacity of a dam decreases over time to zero m^3, and in contrast, the successive deposits of silt increase over time until the volume of silt is equal to that of the dam. In arid zones, this phenomenon of siltation is much more aggressive; the lifetime of a dam of the same volume is very short than that of a dam located in a wetland. During its operation, a dam goes through two main stages: before and after the filling of the "dead" volume. At the start of operation, the evolution of siltation is linear, but as soon as it exceeds the dead volume, the evolution of siltation follows a parabolic law, and the rate of siltation tends to decrease over time. In this part, the useful volume decreases over time to the detriment of the "dead" volume, which increases to reach the threshold of 50% of the initial capacity. In this case, the dam becomes incapable of satisfying the needs for irrigation or drinking water supply. For dams to remain in service as long as possible, sustainable desilting must be adopted. However, before reaching this stage, the filling of the "dead" volume must be delayed as long as possible. This requires adequate management of the watershed and, more particularly, the use of torrential correction, which can reduce erosion and therefore keep the sediments at the level of the watershed (Fig. 14a). In a second stage, once the usable capacity begins to silt up, we start raising the dike so that the dam continues to play its role properly (Fig. 14b). In this case, the dam gains a few more years of age, but the deposition of the silt follows its rise, and the siltation will eventually reach the useful volume. Therefore, in this last step, we must move on to sustainable desilting, which consists of managing water and sediments in parallel (Fig. 14c). The dam becomes a supplier of water and sediment. In this case, at least two dredgers will be installed in the lake of the dam and work continuously.

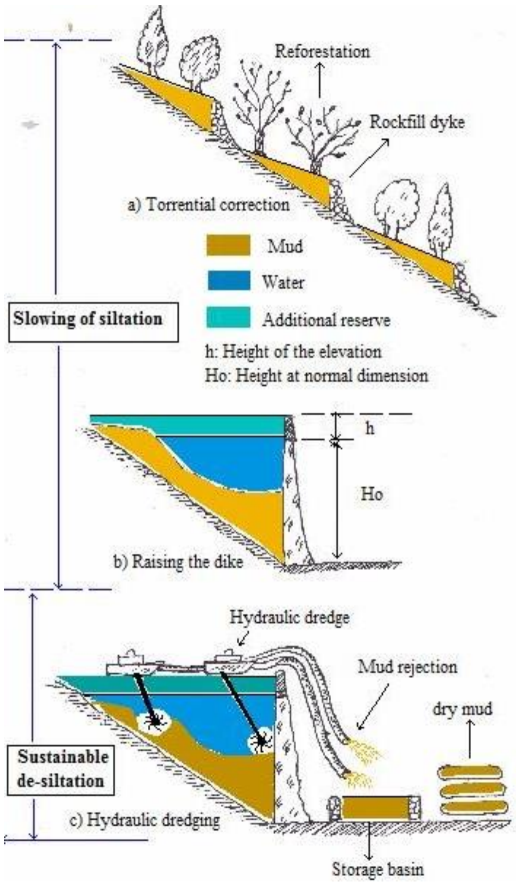


Figure 15: Steps to achieve sustainable desilting (Diagram, Remini, 2022)

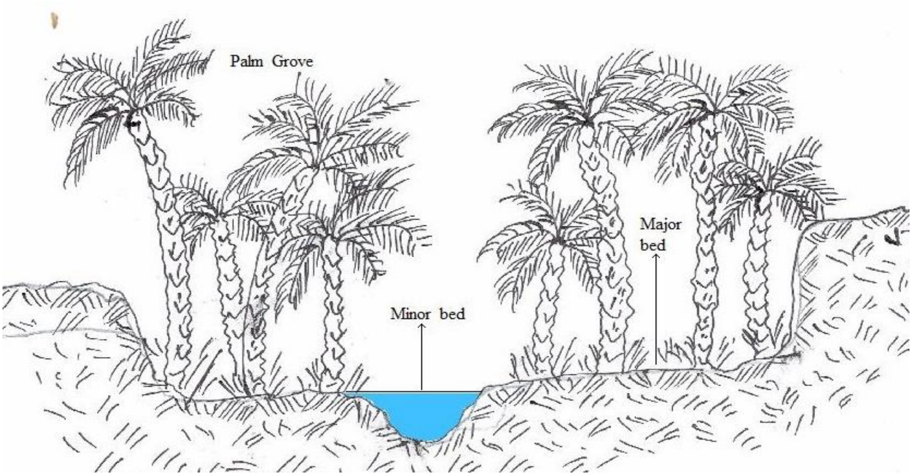
However, to ensure the lasting desiltation of a dam, we must know from the start the destination of the silt that will have to be removed. The results of the physical, chemical and mineralogical analyses of the mud determine the orientation of the mud between the agricultural and industrial domains. Once these conditions have been met, the dam is equipped with dredges, discharge pipes and a silt discharge site, which must serve as a silt distribution station. To know the number of dredges that must be installed in the lake, it is only necessary to check that the solid inputs into the reservoir are less than the amount of sludge removed per year. Once removed and dried, these quantities of silt can be used as raw material for construction products, but more importantly, these sediments can be used as an amendment to soils low in organic matter. Therefore, the best solution is for the sediment to return where it came from. The recovery of silt from a dam becomes an essential step in sustainable desilting. Moreover, at the beginning of the 1990s, we were the first to propose the reuse of silt in the agricultural and construction sectors. It was the only solution for us for the success of the lasting desilting of a dam. At the time, more than ten reservoirs were studied in the laboratory, but unfortunately, these very interesting results were not confirmed in the field (Figs. 16a and b).

a) Field of pottery

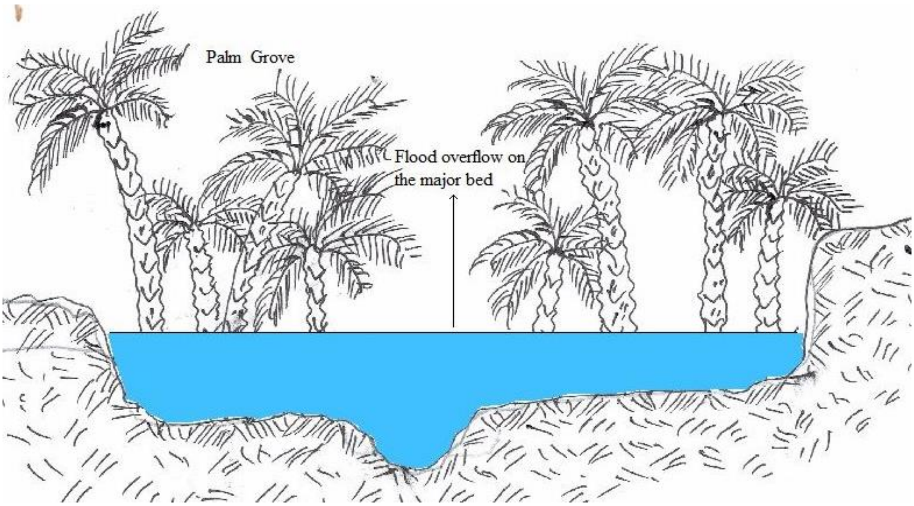
b) Area of construction

Figure 16: Pottery and construction products obtained with mud from the Foum El Gherza and Sidi M'hamed Ben Aouda dams (Photo. Remini, 2022)

However, the best option for silt is for it to come back where it came from (soil), i.e., silt should be used as an amendment for soils low in organic matter since the sediments that come from the erosion drain nutrients with them. For more than 7 centuries, oasis dwellers have developed their palm groves and their gardens on the major beds of the wadis since these regions bordering the minor beds are made up of sediment deposits drained by floods from the watersheds under the effect of the 'erosion. In addition, these gardens and palm groves are watered by floodwaters drained by the wadis (Figs. 17a, b; Fig. 18).



a) In the absence of floods



c) The arrival of a flood

Figure 17: Simple diagram of flooding of the major bed in an arid region (Diagram executed by Remini, 2022)

Figure 18: A view of a palm grove developed on the major bed of the Labiod wadi (Photo. Remini, 2021)

What Mozabites have achieved for more than 7 centuries in the Mzab Valley remains a very good example of water and sediment management in a region hostile to life. The Mzab Valley; a rocky plateau traversed by a wadi of the same name. Located 600 km southwest of Algiers. The Mzab valley extends over approximately 8,000 km^2 and is home to five ksour in Ghardaïa. The Mzab valley receives very little rain, but the life of the ksouriens depends on flash and sporadic but violent floods that occur on the Mzab, Zegrir and Ntissa Rivers. Thanks to a hydroagricultural development invented by the Mozabites and which we have baptized: IRS development. The water of a flood is divided into 3 parts according to the order of priority. Depending on the quantity of water drained by the flood, IRS development gives priority to the flooding of gardens and palm groves by flood water loaded with fine particles and nutrients (Fig. 19).

Once this task is accomplished, we move on to the artificial recharge of the water table, the only reservoir in the entire Mzab Valley. In the last stage, what remains of the flood water follows its course in the Mzab River without causing damage; in this case, we are talking about security, which consists of protecting the oasis. To this end, a hundred hydraulic structures have been built on the Mzab River and its tributaries. The entire population waits year round for the arrival of the flood of nutrient-laden waters. To this end, an engineering hydraulic system has been implemented to ensure the sharing of flood waters in an equitable and fair manner. This demonstrates the interest brought by the Mozabites to the sediments drained by the floods. In addition, the mud deposited in traditional dams (Ahbas) made in the valley is highly coveted by the population for use in agriculture and the construction of ksours.

Figure 19: Palm grove of Beni Izguen- The arrival of a flood in the Izguen wadi; priority is given to the flooding of the gardens by water loaded with sediments (Photo. Remini, 2013)

CONCLUSION

As we mentioned at the beginning of this article, when the dead volume exceeds these limits and threatens the useful volume, the desilted of the dam becomes a mandatory outcome. Two solutions emerge, namely, the hydraulic dredging of the reservoir and the raising of the dike. Only the two options present a paradox of siltation; each time the dam is desilted, the annual siltation rate increases in intensity. In addition, silt cannot be removed from a dam continuously until the destination of the silt is unknown. Similarly, for stability reasons, the dike cannot be lifted each time the “dead” volume gains height. To this end, the valorization of the mud of the dam in the fields of construction and preferably agriculture can solve the problem of siltation. In this case, we speak of sustainable desilting; the dam will be equipped with one or more dredges that continuously suck up the mud. The mud is discharged directly into basins fitted out on the periphery of the dam in such a way that a closed circuit is created; the mud settles in the basins, and the water returns to the reservoir. Once dried, the mud will be transported to its place of use.

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