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Environmental and socio-economic impacts of erosion and sedimentation in north Africa

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Abstract The increasing pace of water resource exploitation with the aim of developing water resources all over the countries of north Africa (Morocco, Algeria, Tunisia), brings with it a greater and greater need for a thorough knowledge (both in theory and in practice) of the widespread erosion of drainage basins, of the resulting transport of sediment, and of the silting-up of reservoirs. In north Africa, the high degree of climatic variability, the torrential nature of storm runoff, the low vegetation cover, and the excessive soil exploitation, have a great impact on erosion, sediment yield, and fluvial transport, on dam sedimentation and, consequently, on socio-economic conditions. An analysis of sedimentation data for 73 large dams in north Africa and of turbidity measurements at gauging stations, has been used to investigate relationships between sediment yields and basin area, dominant lithology and mean annual runoff; and to establish a series of formulae for predicting the rate sedimentation of dams before construction for various lithologies. In order to assist in the establishment of appropriate policies for reducing the negative impacts of erosion and sedimentation, through implementation of anti-erosive measures, existing methods are assessed and strategies to be adopted in the short, medium and long terms are reviewed in terms of both technology and legal and planning aspects. The analysis reported provides a contribution to the understanding and quantification of the complex factors associated with the erosion of drainage basins, the transport of sediment, reservoir siltation, and the environmental impact of these aspects, In north Africa, the need to develop improved models of sediment transport as well as of reservoir sedimentation is highlighted. The social, economic and environmental impacts of reservoir siltation in the short- medium- and long-term, as well the effects of sediment (particularly in drinking water reservoirs) on eutrophication, the stability of banks, and the risk of flooding caused by the rise in water level in rivers upstream from important north Africa large dams are also considered. The need to start to undertake multi-criteria and systematic economic impact studies, using a maximum number of parameters related to erosion, sediment transport and reservoir sedimentation, in order to demonstrate external losses due to such factors in corresponding analytical matrix inputs, is emphasized.

INTRODUCTION

In Morocco a vast dam building programme was launched in 1975 aimed at irrigating one million hectares before the year 2000. There are currently 84 large dams (meeting the ICOLD definition). Their total capacity exceeds 10×10^9 m^3 and they supply 772 000 ha of irrigated land. A current objective is also to reduce the countries dependence on external sources of energy. The present annual production of hydroelectricity is 2527 GWh $year^{-1}$, out of a total potential capacity estimated at 5100 GWh. Other objectives include the management of surface water resources for domestic and industrial uses. Demand is increasing at a rate of 8% per year and the dams currently supply 64% of the demand.

In north Africa (Morocco, Algeria, Tunisia), the total capacity of reservoirs exceeds 4.3×10^9 m^3 in Algeria and 2.3×10^9 m^3 in Tunisia. In 1991 the hydroelectric production was 1240×10^6 kWh in Morocco, 193×10^6 kWh in Algeria and 106×10^6 kWh in Tunisia. The increased development of water resources in north Africa increasingly demands an improved knowledge and understanding of the sediment generation, transport and deposition which seriously threatens the life of many reservoirs. Annual sedimentation rates can reach as much as 50×10^6 m^3 $year^{-1}$ in Morocco, 30×10^6 m^3 $year^{-1}$ in Algeria and 28×10^6 m^3 $year^{-1}$ in Tunisia. The total annual loss of storage due to reservoir siltation is 0.5% per year for Morocco, 0.7% for Algeria and 1.2% for Tunisia. Sediment yields in north Africa are as high as 5900 t km^{-2} $year^{-1}$ (Mbaek, Morocco), 7200 t km^{-2} $year^{-1}$ (Ighil Emda, Algeria) and 5070 t km^{-2} $year^{-1}$ (Kasseb, Tunisia).

Reservoir sedimentation rates

In the present study, sedimentation in 73 large north African dams, is analysed, as follows:

(a) *Moroccan large dams* (17 reservoirs): Nakhla, Mohamed V, Lalla Takerkoust, El Kansera, Mohamed Ben Abdelkrim Al Khattabi, Ibn Batouta, Moulay Youssef, Mansour Eddahbi, Bin El Ouidane, Hassan Eddakhil, Sidi Mohamed Ben Abdellah, Youssef Ben Tachfine, Oued El Makhazine, Hassan I, Al Massira, Idriss I, Abdelmoumen.

(b) *Algerian large dams* (39 reservoirs): Fodda, Boughzoul, Bakhadda, Beni Bahdel, Ghrib, K'sob, Bouhanifia, Zardezas, F. E. Gherza, Sarno, Ighil Emda, Mefrouch, Eraguene, Cheffia, Djorf Torba, Fergoug, S. M. B. Aouda, Guenitra, Merdja, Harreza, Deurdeur, Sly, Bouroumi, Lekhal, Ouizert, Ain Zada, Dahmouni, H. Debagh, Keddara, H. Grouz, S. Abdelli, Gargar, Souani, Ain Dalia, Ladrat, D. J. Dzioua, Bougara, Beni Amrane.

(c) *Tunisian large dams* (18 reservoirs): Beni Metir, Kasseb, Kebir, Mellegue, Nebhana, Bezik, Chiba, Lakhmess, Masri, Bir M'cherga, Bou Hertma, Houmine, Lebna, Rhezela, Sidi Saad, Sidi Salem, Siliana, Marguellil.

Studies of erosion, sediment transport and reservoir sedimentation in north Africa, have progressed substantially during the last 20 years because of the interest of decision makers, the improved understanding, and the development of various new techniques, and, finally, because of the cooperation with international organizations.

Many methods have been used to establish sedimentation rates. These include:

- Determination of the sediment yield from the upstream watershed.
- Measurements of fluvial sediment transport at gauging stations, including both bed load and suspended sediment.

Table 1 Sedimentation of principal Moroccan large dams.

Dams	Watershed area (km^2)	Initial capacity (10^6 m^3)	Last bathymetric survey date	Total sedimentation since the construction of the dam (10^6 m^3)	Average annual silting-up (10^6 m^3)	"Dead zone" (10^6 m^3)	Lost capacity (in %)	Actual capacity (10^6 m^3)
Nakhla	107	13	1987	6.08	0.23	1.5	46.80	6.92
Mohamed V	49 920	725	1990	256.91	11.17	60.0	35.44	468.09
Lalla Takerkoust	1 710	96	1988	26.50	0.50	4.0	33.97	51.50
El Kansera	4 540	330	1989	64.66	1.22	21.5	22.30	225.34
M. B. E. A. Khattabi	780	43	1989	6.96	0.87	4.5	16.19	36.04
Ibn Batouta	178	43.6	1989	5.60	0.56	2.51	12.84	38.00
My Youssef	1 440	198	1990	22.00	1.10	24.0	11.11	176.00
Mansour Eddahbi	15 000	592	1988	62.88	3.93	24.0	11.09	504.12
Bin El Ouidane	6 400	1 484	-	99.82	3.22	324.0	6.73	1384.18
Hassan Eddakhil	4 570	369	1990	20.96	1.31	20.0	5.68	348.04
Y. B. Tachfine	3 780	320	1989	16.49	0.97	20.0	5.15	303.51
S. M. Ben Abdellah	9 800	509	1985	22.97	1.77	100.0	4.51	486.03
Oued El Makhazine	1 820	807	1990	33.99	3.09	20.0	4.21	773.01
Hassan I	1 670	272	1990	10.00	3.33	40.0	3.70	260.01
Al Massira	28 500	2 724	1987	82.94	7.54	480.0	3.04	2641.06
Idriss I	3 680	1 217	1986	30.94	2.21	180.0	2.54	1186.06
Abdelmoumen	1 300	216	1987	1.38	0.23	10.0	0.64	214.62

- The regression obtained between mean annual silting-up (E) (10^6 m^3 $year^{-1}$), the watershed areas S (km^2) and the ratio [reservoir capacity (C)]/[inflow (A)] is as follows: $E = 10^{-2.228} . S^{0.699} . (C/A)^{-0.259}$. The regression coefficient is 0.758.
- The "dead zone" of the following large dams: Mohamed Ben Abdelkrim Al Khattabi, Ibn Batouta, Hassan Eddakhil, Mansour Eddahbi, El Kansera and Mohamed V, is already full of sediment.

Table 2 Sedimentation of principal Algerian large dams (annual sedimentation = 30 × 10^6 m^3).

No.	Dam	Construction	Initial total capacity (10^6 m^3)	First bathymetric survey date	Capacity of the dam after first bathymetric survey (10^6 m^3)	Second bathymetric survey date	Capacity of the dam at the second bathymetric survey	Annual sedimentation (10^6 m^3)	Actual capacity of the dam (10^6 m^3)
1	Fodda	1932	228	1986	132.7	1974	143.9	0.93	128.0
2	Boughzoul	1934	55	1986	55	1972	17.9	0.6	16.6
3	Hamiz	1935	23	1986	16.4	1974	45.4	0.11	15.8
4	Bakhadda	1936	56	1986	25.1	1974	56.5	0.03	44.9
5	Beni Bahdel	1938	63	1986	56.5	1974	177.8	neglible	56.5
6	Ghrib	1939	280	1986	165.6	1973	53.5	1.01	160.5
7	K'sob	1939/75	31	1986	26.4	1975	31.9	0.28	25.0
8	Bouhanifia	1948	73	1985	51.4	1974	21.7	0.16	50.6
9	Zardezas	1948/75	31	1985	20.1	1974	119.9	0.25	18.8
10	F. E. Gherza	1952	43	1986	26.5	1973	14.7	0.49	24.0
11	Sarno	1953	22	1986	17.6	1975	173.9	0.34	15.9
12	Ighil Emda	1954	155	1986	14.6	1974	12.7	3.19	69.7
13	Mefrouch	1962	15	1986	168.4			neglible	14.6
14	Eraguene	1963	200	1985	316.4			0.27	192.4
15	Cheffia	1965	171	1985	309			0.5	165.9
16	Djorf Torba	1969	360	1985	225.6			2.9	299.0
17	Fergoug	1970	18					0.73	8.0
18	S. M. B. Aouda	1978	235					1.34	221.2
19	Guenitra	1984	120					0.13	219.1
20	Merdja	1984	55					0.60	50.8
21	Harreza	1984	70					0.63	65.6
22	Deurdeur	1985	115					0.83	110.0
23	Sly	1986	285					1.86	275.5
24	Bouroumi	1986	220					0.90	215.5
25	Lekhal	1986	30					0.27	28.6
26	Ouizert	1986	100					0.47	100.0
27	Ain Zada	1986	125					0.10	122.6
28	Dahmouni	1987	41					0.54	40.6
29	H. Debagh	1987	220					0.17	217.8
30	Keddara	1987	146					0.45	145.3
31	H. Grouz	1988	45					0.66	43.8
32	S. Abdelli	1988	110					4.32	108.0
33	Gargar	1989	450					0	444.0
34	Souani	1989	13					0.90	13.0
35	Ain Dalia	1989	82					0.30	80.2
36	Ladrat	1990	10					0.06	9.7
37	D. J. Dzioua	1990	13					0.04	12.9
38	Bougara	1990	13					4.00	13.0
39	Beni Amrane	1990	18						14.0
Total (10^6 m^3)			4340					30.36	3856.8

- Bathymetric surveys (range-lines).
- Aerial surveys, especially after the drawdown of the water level (due particularly to the current drought period in north Africa). This is the best method used at present. It is possible to determine reservoir sedimentation with an error of 0.10 m (in the level).
- Radioisotope methods.
- Mathematical models for predicting reservoir siltation.

The results are presented in Tables 1, 2 and 3. The specific sediment yields estimated for a number of river basins in Morocco, Algeria and Tunisia, based on reservoir sedimentation surveys are presented in Table 4.

REMEDIAL MEASURES TO CONTROL EROSION AND RESERVOIR SEDIMENTATION

The following methods have been employed to control erosion and reservoir sedimentation.

(a) *Preventive methods*:
- watershed management;
- maintenance of river banks;
- reservoir management:
  * sediment transport diversion,
  * emptying and water supply management;
- legislative and regulation control.

(b) *Curative methods*:
- evacuation of sediments by appropriate management:
  * flushing at lower reservoir level,
  * flushing without bringing down the reservoir level;
- allocation of a "dead zone" for sediment storage;
- dredging of sediment;
- raising of dams and establishment of new sites.

The following consequences of reservoir sedimentation have been identified.
- capacity loss and reduction of regulated volume;
- economic implications of capacity loss:
  * reduction of drinkable, irrigation and industrial water,
  * reduced employment;
- height of the reservoir;
- security of the dam;
- flood flow lamination;
- annex management (valves, gallery-visit, spill-way);
- eutrophication;
- water quality;
- upstream watershed.

Further details of the potential economic consequences of loss of reservoir capacity due to silting in north Africa are presented in Table 5.

Table 3 Silting-up of principal Tunisian large dams.

No.	Dam	Start date	Watershed area (km^2)	Initial capacity (10^6 m^3)	Mean annual sedimentation (10^6 m^3 $year^{-1}$)	Specific sediment yield (t km^{-2} $year^{-1}$)
1	Ben Metir	1953	103	73	-	-
2	Kasseb	1969	101	81.9	0.427	5 070
3	Kebir	1925	271	26	-	844 (full)
4	Mellegue	1954	10 300	332	5.29	695
5	Nebhana	1965	855	86.4	1.64	2 300
6	Bezik	1960	84	6.46	0.164	2 430
7	Chiba	1965	64	7.86	0.225	4 220
8	Lakhmess	1966	127	8.0	0.313	2 865
9	Masri	1968	53	6.82	0.202	6 050
10	Bir M'cherga	1971	1 263	165.6	-	-
11	Bou Hertma	1976	390	117.5	0.5	1 600
12	Houmine	1983	418	130	0.5	
13	Lebna	1986	199	29	0.5	
14	Rhezela	1984	48	11.7	-	1 900
15	Sidi Saad	1981	8 950	209	5.4	160
16	Sidi Salem	1981	18 250	555	3.3	380
17	Siliana	1987	1 040	70	3.5	
18	Marguellil	1990	1 120	110	5.5	1 500

Sedimentation rates have been estimated using bathymetric surveys (and other methods) undertaken in 1975 and more recently in 1991-1992.
In 1975 the following reservoirs were surveyed: Nebhana; Bezik; Chiba; Masri; Lakhmess; Mellegue.
In 1991-1992 the following reservoirs were surveyed: Sidi Salem; Masri; Lakhmess; Sidi Saad; Bir M'cherga.

THE CONSEQUENCES ON EUTROPHICATION

The sedimentation of reservoirs can have an important impact on the eutrophication process characterized by increased nutrient levels (particularly phosphorus and nitrogen attached to sediment particles) and also by dissolved oxygen deficits and increased biological production. The high water temperatures, ion exchange, and photosynthesis promote eutrophication problems. This phenomena constitutes a great problem for impoundments used for drinking water. In north Africa, we find oligotrophic reservoirs (with low nutrient level), mesotrophic reservoirs (medium nutrient levels) and particularly eutrophic reservoirs (high nutrient levels). Furthermore anaerobic conditions lead to the formation of hydrogen sulphide (particularly under drought conditions). The dissolved oxygen content in the water is also changed due to increases in suspended sediment.

Many ecological models are being employed in Morocco, Tunisia, and Algeria through cooperation with UNDP (United Nations Development Programme) under

Table 4 Specific sediment yields for selected reservoirs catchments in Morocco, Algeria and Tunisia, based on reservoir sedimentation surveys.

Dam	Specific sediment yield ($t\ km^{-2} year$)	Number
MOROCCO		
S. M. Ben Abdelkrim	5900	1
M. B. A. Al Khattabi		
Ibn Batouta	4700	2
Nakhla	2500	3
Oued El Makhazine	2000	4
Moulay Youssef	900	5
Lalla Takerkoust	350	6
Idriss I	720	7
Bin El Ouidane	680	8
Hassan I	430	9
Mansour Ed Dahbi	400	10
Al Massira	320	11
El Kansera	330	12
Mohamed V	240	13
Youssef Ben Tachfine	385	14
S. M. Ben Abdellah	270	15
Abdelmoumen	260	16
ALGERIA		
Ghrib	110 (190)	17
Djorf Torba	85 (105)	18
Bouhanifia	60 (170)	19
S. M. Ben Abdellah	220 (500)	20
K'sob	200 (270)	22
Bakhadda	130 (310)	23
F. E. Gherza	440 (900)	24
Beni Bahdel	140 (260)	25
Fodda	2100 (2900)	26
Ighil Emda	2500 (7200)	27
Cheffia	270 (580)	28
Zardezas	290 (940)	29
Sarno	240 (700)	30
Foum El Gheiss	190 (500)	31
Hamiz	690 (2300)	32
TUNISIA		
Kasseb	5070	33
Kebir	844	34
Mellegue	695	35
Nebhana	2300	36
Lakhmess	2665	37
Masri	1100	38
Bir M'cherga	350	39
Sidi Saad	160	40
Sidi Salem	380	41

Maximum specific sediment yields observed in north Africa:
Ighil Emda (Algeria): = 7200 $t\ km^{-2}\ year^{-1}$
Mbeak (Morocco): = 5900 $t\ km^{-2}\ year^{-1}$
Kasseb (Tunisia): = 5070 $t\ km^{-2}\ year^{-1}$

Note that maximum erosion is observed in the northern (boundary of Mediterranean sea areas) of north Africa.

Table 5 Predictions of the silting of north African large dams and of environmental impacts on long-term economic development (to 2030).

Country	Yearly sediment transport (10^6 m^3 year^{-1})	Yearly sedimentation of large dams in 2030 (10^6 m^3 year^{-1})	Yearly reduction of hydroelectric production due to sedimentation (10^6 kWh year^{-1})[a]		Impact of sedimentation on annual reduction of potable water supply (10^6 m^3 year^{-1})		Annual reduction of irrigated area due to sedimentation (ha year^{-1}) (based on an irrigation requirement of 10 000 m^3 ha^{-1} year^{-1})	Annual economic loss in 2030 due to sedimentation (10^6 DH year^{-1})	Yearly reduction of employment due to sedimentation	
	in 1995	in 2030	in 2000	in 2030	in 2000	in 2030	in 1995	in 2030	in 2000	in 2030
Morocco	50	150	60	80	50	120*	5 000	800*	10 000*	30 000*
Algeria	38	60*	10*	14*	30*	75*	3 800	320*	7 600*	10 000*
Tunisia	30	50*	4*	6*	20*	50*	3 000	260*	6 000*	8 000*
Total	118	260*	74*	100*	100*	245*	11 800*	1 380*	23 600*	48 000*

Study Principle: Capacity Reduction → Reduction of Regularized Volume → Reduction of Hydroelectric Production

* Estimated values.

[a] In 1991, hydroelectric production was: 1246 × 10^6 kWh in Morocco, 193 × 10^6 kWh in Algeria and 106 × 10^6 kWh in Tunisia.
(1$ = 9 DH)

Project RAB80/011 and in Morocco through cooperation with the World Health Organization, Project MOR.

The settling of suspended matter in large reservoirs may also have serious adverse effects downstream by reducing the quantity of natural nutrients available to agricultural land or to coastal waters. This nutrient depletion can lead to increased fertilizer use and increases in coastal siltation. Additional effects are associated with increased erosion downstream of dams.

THE USE OF SEDIMENT PREDICTION MODELS FOR RESERVOIRS IN NORTH AFRICA

A number of sediment transport numerical models are currently in use in north Africa. These include:

(a) For permanent and uniform flows, the HEC-6 model of the US Army Corps of Engineers, based on the Toffaletti, Laursen, Du-Boys, and Yang models, with friction equations.

(b) For non-permanent flows:
- the Fluvial-11 model of Chang, based on the Du-Boys model,
- the MOBED model of Krishnappan (modified), based on the Ackers and White, Toffaletti, SADOK and Marche models with a mobile bed,
- the alluvial model of Karim and Kennedy, based on the Karim and Kennedy model, with a mobile bed,
- the Garichar model of IMG Grenoble, based on the Meyer-Peter equation, and taking into account armouring,
- the WENDY model of Delft.

For bed load sediment transport, the selection of models is complicated.

(c) The calibration and validation of models constitutes a great problem because great differences are frequently encountered between measurements and model prediction.

A CASE STUDY OF SEDIMENTATION MODELS IN TUNISIA

The University of Tunis has developed a numerical model based on the St Venant equation and employing a discontinuous two-layer system. The flow is assumed to be undimensional and the lower layer of deposited sediment inhomogeneous. Thus, for each step of time and space the height and speed of the turbid layer, the friction factor (normal and critical), the erosion rate, and the thickness of the eroded layer are calculated. It has been applied to a number of flood flows observed in the large Nabeur dam in Tunisia.

Other sedimentation models are being developed in north Africa, with the objective of forecasting the long-term silting of large dams. These models will reduce the need for expensive bathymetric surveys. They are based, principally, on the following equations: St Venant equation (for variation of liquid phase), equation of solid phase, and equation of bottom deformation of reservoirs and rivers.

There are also a number of integral, diffusive and differential models which describe sedimentation phenomena, and a particular difficulty currently exists in relation to limited understanding of turbulent flows (in the field of fluid mechanics) and knowledge of local erosion conditions on reservoir and rivers beds.

RECOMMENDATIONS AND CONCLUSIONS

(a) There is an important need for soil conservation in north Africa due to the high erosion rates.
(b) Training of specialists in anti-erosion management and also in river sediment transport is required.
(c) Erosion and anti-erosion management courses should be included at different levels of primary, secondary and higher education and both fundamental and applied research on erosion should be developed to reduce erosion.
(d) There is a need to integrate anti-erosion measures before dam construction.
(e) In response to the high rate of population growth and the associated pressure on vegetation cover, erosion is increasing exponentially in north Africa. It is necessary to reduce this trend using both biological methods (e.g. reforestation) and mechanical methods (eg. construction of debris dams).
(f) There are socio-economic constraints to combatting erosion, particularly in basins with high population densities.
(g) Basins subject to anti-erosion management will have different degrees of fertility and will be subject to different laws. Any management strategy will need to take into consideration the best approach to apply, the financial source, and other constraints.
(h) The objective of anti-erosion management is to increase the soil productivity and to protect the existing infrastructure.
(i) The participation of the local population in anti-erosion management is an important requirement and an equilibrium should be established between the upstream and downstream areas of a drainage basin. It is recommended that the population should me made aware of negative consequences of erosion problems.
(j) Because of the relationship between erosion and other erosion parameters, it is necessary to develop multicriteria economic analysis for assessing the economic impacts of erosion problems (and sedimentation) on environmental and social conditions. The sound environmental management of sediment projects should be orientated towards the establishment of a long-term dynamic equilibrium between sediment projects and their environment. It is necessary not only to assess but also to manage the environmental impacts of sediment projects on both a short and a long-term basis.
(k) After the establishment of anti-erosion management programmes, cost-benefit studies aimed at assessing the real efficiency of the programme and at developing the best methods and conservation systems for future programmes should be undertaken.
(l) There is a need to increase the frequency of bathymetric measurements, especially after large floods (bathymetric surveys at 2-year intervals) to provide more exact information on the magnitude of annual sedimentation.
(m) A special investigation of theoretical and practical aspects of suspended sediment and bed load measurement should be established. Such measurements are required, particularly in flood periods, to establish exactly the sediment loads of north African rivers.
(n) There is a need to implement sedimentation models to forecast reservoir silting.
(o) The complex phenomena of erosion, fluvial sediment transport and reservoir sedimentation in north Africa produces a need for both empirical data and for models describing relationships between upstream and downstream conditions in rivers.