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The silting of Moroccan dams

ABDELHADI LAHLOU

Hydraulic Administration, Avenue Hassan Ben Chekroun, Casier Rabat Chellah, Morocco

Abstract After analysing the various methods used in Morocco for the determination of the silting of dams, this study reviews a number of relationships between sediment yields from the watersheds and their surface area, their dominant lithology and their annual runoff. These have been used to establish a series of formulae for predicting the rate of siltation of dams constructed in any region of Morocco for various dominant lithologies.

L'envasement des barrages du Maroc

Résumé Après avoir analysé les diverses méthodes utilisées au Maroc pour la détermination de l'envasement des retenues de barrages, cette étude met en relief les lois obtenues, liant les dégradations des bassins versants à leurs surfaces ainsi qu'à leur lithologie dominante et aux lames d'eau écoulées. Elles débouche enfin sur l'établissement d'une série de formules de prévision du taux de comblement des barrages à implanter ultérieurement dans n'importe quelle région du Maroc et pour diverses lithologies dominantes du substratum.

INTRODUCTION

In 1929 the first large dam was built in Morocco. This was the Sidi Maachou dam. By 1966, 15 dams with a total capacity of 2×10^9 m^3 had been constructed. In 1967, King Hassan II gave a new impetus to the dam building programme by launching a vast and ambitious programme aimed at irrigating one million hectares before the year 2000. Today there are 34 large dams in operation. Their total capacity exceeds 10×10^9 m^3 and they supply 590 000 ha of irrigable land. A current objective is to reduce our dependence on external sources of energy. The present annual production of hydroelectricity is 2.100 GWh per year of a potential estimated at 5.100 GWh. A third objective is the management of surface water resources to satisfy the water needs of major centres of population for domestic and industrial use. Demand increases at a rate of 8% per year. The dams currently supply 60% of the demand.

The increased development of water resources in Morocco increasingly demands a full knowledge and understanding of sediment generation, transport and reservoir siltation. Silting seriously threatens the life of many reservoirs in Morocco. Annual sedimentation rates can reach as much as 40 to 50 × 10^6 m^3 $year^{-1}$ (Lahlou, 1987). The total yearly loss of storage in the 34 reservoirs due to silting is 0.5%. Sediment yields in Morocco vary to a great extent, from 100 t km^{-2} $year^{-1}$ to as much as 5900 t km^{-2} $year^{-1}$ (in the Nekor basin). Fortunately, the study of erosion, solid transport and dam silting in Morocco has progressed substantially in the course of the last ten years, as a result of the development of new techniques.

METHODS USED FOR THE DETERMINATION OF RESERVOIR SILTING

The various direct methods used for the determination of the rates of silting of reservoirs in Morocco include:

(a) the bathymetric method,
(b) sediment monitoring,
(c) the stereophotogrammetric method,
(d) the use of degradation prediction relationships for the upstream basins.

The bathymetric method

Direct measurements of water depth can give precise results but where water depths exceed 10 m they become laborious. Therefore we have recourse to bathymetric or indirect methods.

Sediment monitoring

Measurements are undertaken primarily during floods. During each flood we measure the level of water at the gauging station and the station calibration curve is used to derive the instantaneous flow Q_1. The concentration of suspended sediment in the water is measured by double weighing in the laboratory. By multiplying this concentration with the instantaneous flow Q_1, we obtain the sediment load. We draw the sediment load hydrograph and the area under this curve is used to derive the total suspended sediment load.

Examples of relationships between annual sediment transport V_{SA} (10^6 m^3) and annual runoff V_{LA} (10^6 m^3) established for the Tamellaht gauging station in the Nekor basin are listed in Table 1.

It is even more difficult to take bed load samples. The maximum ratio between bed load and suspended load is 0.3 for the Nekor basin. However, in other regions this ratio is affected by the geological characteristics, the watershed size and other factors. Bed load formulae, e.g. the Meyer-Peter formula and the Einstein-Brown formula, have been used to compute bed load transport rates (Table 2). The ratio annual bed load/annual suspended load varies considerably from 2% (Kansera Dam) to 29.5% (Idriss 1st Dam).

Table 1 *Relationships between annual sediment transport and runoff established for the Tamellaht gauging station in the Nekor basin*

Curve no.	*Relationship*	*Correlation coefficient*
1	$V_{SA} = -2.6 + 0.09\, V_{LA}$	0.98
2	$V_{SA} = -32 + 8.7 \log V_{LA}$	0.92
3	$V_{SA} = 0.94 V_{LA}^{0.015}$	0.84
4	$V_{SA} = 0.004\, V_{LA}^{1.597}$	0.88

V_{SA} = *annual sediment load* ($10^6\ m^3$);
V_{LA} = *annual runoff* ($10^6\ m^3$).

Table 2 *Application of the Meyer-Peter formula (bed load) in some rivers*

Reservoir	*Annual bed load (B) ($10^6\ t\ year^{-1}$)*	*Annual suspended load (S) ($10^6\ t\ year^{-1}$)*	*Ratio B/S (%)*
Lalla Takerkoust	0.050	0.750	6.7
El Kansera	0.030	1.875	1.6
Mansour Eddahbi	0.200	3.300	6.1
Mohamed Ben Abdelkrim Al Khattabi	0.500	4.050	12.4
Idriss 1st	0.950	3.225	29.5
Sidi Mohamed Ben Abdellah	0.060	0.810	7.4

The determination of annual siltation from aerial stereophotography

One of the best methods currently used to determine rates of silting employs aerial stereophotography. The degree of error associated with this method is low (*c.* 0.1 m) and this precision has allowed us to use this technique for measuring the level of mud in dams. This method has particularly been used during the dry conditions which have been experienced in Morocco from 1980 to 1985.

The extrapolation of degradation prediction relationships

The method has been widely used by consulting engineers to forecast rates of dam siltation. The large amount of data now available provides a basis for developing improved prediction relationships, as undertaken in a recent study.

Sediment yield data were assembled from 15 river monitoring stations and from 23 dams where sedimentation rates had been calculated. This provided estimates of sediment yield or degradation for 38 drainage basins. These represented a wide range of lithologies which made it possible to isolate the influence of basin lithology on sediment yield. Three major lithological formations have been identified (Fig. 1) and relationships between specific sediment yield and basin area and annual runoff have been developed for each formation. These prediction relationships have been widely applied by government bodies including the Ministry of Agriculture, the Office of Water and Forests, the Ministry of the Interior and the Department of Geology, as well as by agricultural and hydraulic engineers. Applications include roads (the landsliding in the Rif), ports (the silting and dredging of ports), drinking water (the eutrophication of dams), etc. The Directorate of Hydraulic Development now uses data on drainage basin area, annual runoff and dominant lithology to predict silting in all proposed dams.

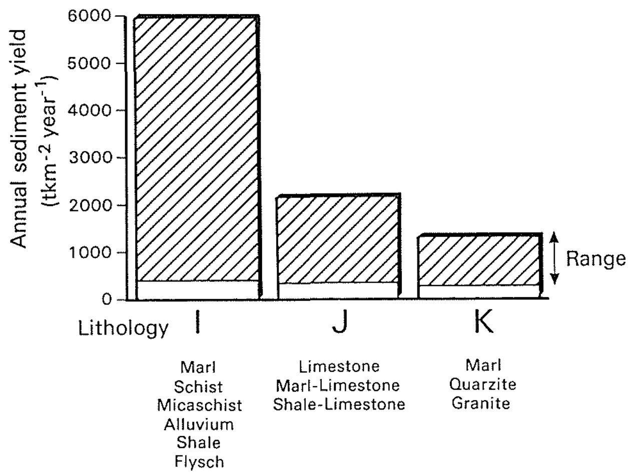

Fig. 1 *The influence of lithology on mean annual sediment yields in Morocco.*

THE SILTING OF MOROCCAN DAMS

Table 3 lists the characteristics of 16 dams for which sedimentation rates have been evaluated. These characteristics include the level of the thalweg, the initial capacity C, the surface of the watershed S, the annual silting E and degradation D (t km^2 year^{-1}) based on an average density of 1.2 t m^{-3} for the material, and an estimated trap efficiency, and the annual inflow A (10^6 m^3).

The annual degradation of these watersheds allows us to classify the degree of erodibility of the regions of Morocco as follows:

(a) The Occidental and Central low-Rif located on the highly erodible rocks;

(b) the Middle Atlas and High Atlas regions located on highly erodible rocks;

(c) The lowland regions of Rommani-Maaziz (Bou-Regreg), and the Issen River located on resistant rocks;

Table 3 *The silting of dams in Morocco and the annual degradation of upstream watersheds*

					(END OF 1986)			(END OF 1987)		
DAM	STARTING DATE	LEVEL (M)	INITIAL CAPACITY (10^6 M^3) C	WATERSHED SURFACE (KM^2) S	ANNUAL SILTING (10^6 M^3) E	ANNUAL DEGRADATION (T/KM^2/YEAR) D	ANNUAL INFLOW (10^6 M^3) A	ANNUAL SILTING (10^6 M^3) E	ANNUAL DEGRADATION (T/KM^2/YEAR) D	ANNUAL INFLOW (10^6 M^3) A
MED BEN ABDELKRIM AL KHATTABI	1981	26,3	43	780	2.7	5900	80	2.70	5900	88
IBN BATOUTA	1977	34,5	43,6	178	0,49	3900	65	0.65	3900	65
NAKHLA	1961	46	13	107	0.12	1680	68	0.07	2500	63
EL MAKHAZINE	1979	66,5	789	1820	1,8	1420	829	1,02	2700	854
MOULAY YOUSSEF	1970	100	198	1441	1,4	1400	386	0.59	1850	290
LALLA TAKERKOUST	1935	71	34,4	1707	0.5	425	165	0.50	350	163
IDRISS 1IER	1973	72	1217	3680	2	1200	577	2.15	3200	650
BIN EL OUIDANE	1953	132.5	1484	6400	3.3	740	1127	3.60	870	1144
HASSAN EDDAKHIL	1971	85	369	4400	1.75	570	147	1.0	260	143
MANSOUR EDDAHBI	1972	70	567	15000	4,7	450	400	2,2	210	394
AL MASSIRA	1979	82	2724	28500	9	450	2954	(7,5)	375	1400
EL KANSERA	1935	68	330	4540	1,4	440	372	1,25	330	400
MOHAMED V	1967	64	725	49920	14,5	420	768	10	240	930
YOUSSEF BEN TACHFINE	1973	85	310	3784	1.1	420	122	0.50	170	122
SIDI MOHAMED BEN ABDELLAH	1974	98	493	9800	2,5	370	936	0.54	200	880
ABDELMOUMEN	1981	94	216,3	1300	0,2	200	87	(0,8)	200	86

(d) the Middle Atlas and High Atlas regions located on coherent rocks principally the regions bordering the Atlantic;
(e) the central plateau regions, the Sai'ss and the Moulouya and the Oum er Rbia inferior basins, the Middle Atlas and High Atlas continental watersheds, and the Anti Atlas Atlantic Ridge;
(f) the Abda-Doukkala and Rhamna regions, the Tensift basin regions, and the Moulouya High plateau;
(g) the pre-Saharian and Saharian region.

PREDICTIVE RELATIONSHIPS

The relationships between annual degradation D (t km^{-2} year^{-1}) and the surface area of the basin S (km^2) for the different dominant lithological formations are as follows:
(a) for the 16 dams:

$$D = 33.7 \times 10^3 \; S^{-0.498} \quad (1)$$

(b) for all lithological formations (38 units, 23 dams + 15 river stations):

$$D = 5.3 \times 10^3 \; S^{-0.252} \quad (2)$$

(c) for the limestone formations, group J (11 units):

$$D = 6.3 \times 10^2 S^{-0.018} \quad (3)$$

(d) for the schist formations and the marl-schist formations, group I (17 units):

$$D = 2.9 \times 10^3 S^{-0.419} \quad (4)$$

(e) the low erodibility regions, group K (23 units):

$$D = 8.3 \times 10^3 S^{-0.094} \quad (5)$$

Relationships (c), (d) and (e) are portrayed in Fig. 2. The relationships between annual degradation D (t km^{-2} year^{-1}) and the annual runoff L (mm) for the different lithological groups are as follows:

(f) for all lithological formations (38 units including 23 dams and 15 river stations):

$$D = 1.9 L^{0.547} \quad (6)$$

(g) for the limestone formations, group J:

$$D = 2.2 L^{0.291} \quad (7)$$

(h) for the schist and marl-schist formations, group I:

$$D = 1.6 L^{0.732} \quad (8)$$

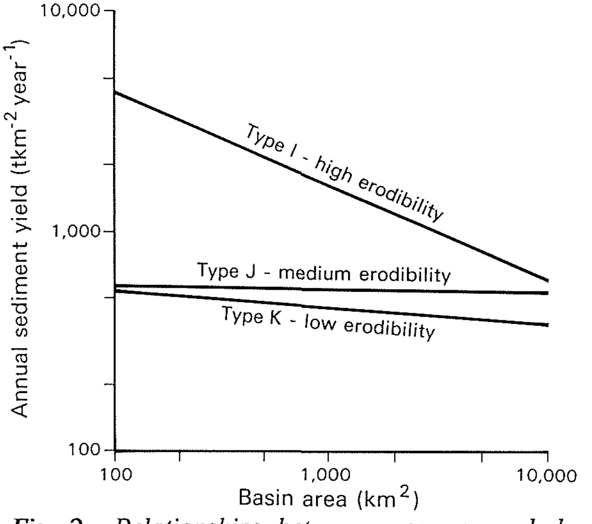

Fig. 2 Relationships between mean annual degradation and basin area established for the dominant lithologies in Morocco.

(i) for the low erodibility regions, group K:

$$D = 99\ L^{0.326} \tag{9}$$

(j) for the 16 dams:

$$D = 2.08\ L^{0.421} \tag{10}$$

For the 16 dams listed in Table 3, a multivariate relationship was established linking rate of silting E (10^6 m^3) to the basin area S (km^2) and the capacity inflow ratio (C/A) as follows:

$$E = 10^{-2.106}\ S^{0.661}\ (C/A)^{-0.078} \tag{11}$$

REFERENCE

Lahlou, A. (1987) Etude actualisée de l'envasement des barrages du Maroc. *Science de l'Eau* 6, 337-356.