The sediment budgets of hill reservoirs in small catchments in North Africa and the Middle East

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Abstract Global assessments place the loss of reservoir storage by sedimentation at 1% per year. The cost of recovering such storage may be prohibitive. In Mediterranean countries, the situation is worse due to widespread land degradation. Trapping the sediment that comes primarily from the upstream mountain zones in small and relatively inexpensive reservoirs is important. The construction of small dams at different points on the stream network also attenuates flood flows and reduces the erosion potential of storm events, which are often of high magnitude in the Mediterranean region. Within this framework, 32 artificial reservoirs situated in the Tunisian Atlas Mountains, the Rif Mountains of Morocco and the Homs basaltic plateau of Syria, were chosen to constitute a network for hydrological observations. This paper synthesizes the results obtained from this hydrological network. Guidelines relating to the effective assessment and management of the sediment budgets of small hill reservoirs in the Mediterranean region are provided.

Key words dam sedimentation; erosion; Middle East; North Africa; sediment budget; small dams

INTRODUCTION

In the countries of the Middle East and North Africa (MENA), there is a tradition of constructing small dams. These small dams provide not only valuable water storage, but also control erosion. The dams themselves are commonly between 5 and 15 m high (the lower limit for large dams established by the International Commission on Large Dams), constructed of earth and rocks and located in small rural catchments in areas of moderate relief. They have crudely designed lateral spillways with a discharge capacity of some tens of cubic metres per second or even in some cases slightly over 100 $m^3 s^{-1}$. Some, but not all, have a sluice gate. Their unit cost is around 500 000 Euros, sometimes far less. The reservoirs are relatively small in area (a few hectares) and have a holding capacity ranging from a few tens of thousands to one million cubic metres (Albergel & Rejeb, 1997).

In Tunisia, the construction of one thousand small dams in the northern part of the country between 1990 and 2000 was planned as part of the programme “Aménagement des terres en pente, mobilisation des ressources en eau, entretien et sauvegarde des aménagements" (Management of sloping land, water resource development, and maintenance and protection of hydraulic structures) and incorporated in the 8th State Plan. These projects have become the keystone of the national soil and water conservation strategy developed by the Ministry of Agriculture, Directorate of Water and Soil and Conservation. The objectives of the strategy are (Talineau *et al.*, 1994):

(a) to reduce losses of agricultural land (estimated at 10 000 ha year^{-1});
(b) to reduce dam siltation (25 Mm^3 year^{-1} in 1990);
(c) to increase groundwater recharge;
(d) to make use of as much as possible of the 500 Mm^3 of water lost to the sea or to the Sebkhas;
(e) to promote the development of irrigated agriculture.

In Morocco, the period of drought in the early 1980s, considered to be the longest ever experienced, marked the start of a policy of very labour-intensive small dam and hill reservoir construction (El Mohammadi, 1993). The works were primarily designed for irrigation, livestock watering, flood protection or the supply of drinking water to rural areas that had no readily exploitable underground water resources. Morocco established a large-scale hydraulic infrastructure in the 1970s and 1980s. Virtually all the large dams are now affected by significant sediment deposition. Numerous small dams have been built to reduce this siltation. For example, the largest dam in the Kingdom, the Al Wahda dam on the Ouergha River in the province of Sidi Kacem (88 m high, with a capacity of 3.8 10^9 m^3) is protected by numerous small dams located in the upstream part of the catchment and designed to retain the sediment load transported from the steep marly slopes of the Rif Mountains. Some have already been constructed while others are still at the project stage. Erosion from the Ouergha catchment, estimated at 98 t ha year^{-1} over an area of 6150 km^2 generates about 60 Mm^3 of sediment (MTPFPFC, 1991). The net deposition in the dam is estimated to be 15 Mm^3, taking account of the hydraulic works installed in the upstream areas of the watershed (MTPFPFC, 1991).

Small dams have been known in the Middle East since ancient times (HYDROMED, 2001), with the dam on the Nahr El Asi near Homs having been constructed in the reign of Seti I (1319–1304 BC). Many were built at the start of the Christian era (Badieh Dam on the road to Palmyra). Numerous ruins testify to their presence in the dry steppes. Some still exist, but are completely filled with sediment. The first small dams built using modern techniques were those constructed during the 1960s in the province of Swaida to supply drinking water to villages on a basalt plateau that has no underground water resources.

THE RESERVOIR STUDIES

Theory

A reservoir fed by a single tributary, or at least by one principal tributary, can provide as much information about the water and sediment budget of the upstream catchment as a classical hydrometric station (Albergel *et al.*, 1999a). To achieve this goal, certain conditions must be met, but these are often less difficult and burdensome than those required for the correct functioning of a hydrometric station. These conditions are:

(a) The water level, rainfall and daily evaporation in the reservoir are monitored.
(b) The spillway is arranged in such a way that the discharge can be estimated and sediment transport can be sampled.
(c) The bathymetry of each reservoir is measured at least once every hydrological year, making it possible to determine the rate of silting of the reservoir basin and to establish level-volume, level-surface and level-spillway discharges curves.

The bathymetry of a reservoir can be measured by surveying the bottom of the reservoir along transverse survey lines between its shores. The ends of each survey line should be levelled and positioned on the original plan of the reservoir. A digital model of the reservoir bottom is constructed and comparison of the reservoir volumes below the spillway level between measurement campaigns provides a means of estimating the volume of sediment deposited. The mean concentration of suspended matter, obtained by sampling, can be combined with the discharge volume to estimate the sediment outflow from the reservoir. The sediment load at the catchment outlet for the period between two bathymetric surveys can be estimated by adding the sediment outflow from the reservoir to the mass of sediment deposited in the reservoir, calculated as the product of its volume and its density, i.e.:

$$T = V_s \times d + \sum_{i=1}^{n} S_i C_i \qquad (1)$$

where *T* is the total sediment transport for the period between two bathymetric surveys (*t*), *Vs* is the measured volume of deposited sediment (m^3), *d* is the density of the deposited sediment, *n* is the number of floods that have produced overspill discharges between two surveys, S_i is the volume discharged during flood *i* (m^3), and C_i is the measured mean concentration of suspended sediment during flood *i* (t m^{-3}).

This easily implemented method provides a reliable estimate of the sediment yield at the outlet of a reservoir catchment. It incorporates the sediment output due to all three forms of water erosion, namely: (a) sheet erosion caused by surface runoff on the catchment slopes, (b) gully erosion caused by concentrated runoff on parts of the catchment slopes, and (c) bank erosion produced by variations in the runoff regime.

One important uncertainty relates to the conversion of the volume of sediment deposited in the reservoir into an equivalent mass. The apparent density of the material deposited on the bottom of the reservoir will vary over time, according to the degree of compaction of the deposits and their water content. In badly silted dams the sediment deposits will have a density approaching 2 t m^{-3}, whereas the density of surface silt commonly varies between 1 and 1.2 t m^{-3}. It is not easy to measure density during bathymetric surveys. Advantage is generally taken of the periods when the reservoirs are dry to take core samples and measure their densities.

The measurement programme

Thirty two artificial reservoirs were chosen to provide an observation network covering the Tunisian Atlas Mountains and also the Rif Mountains in Morocco and the Homs basaltic plateau in Syria. These reservoirs have highly diverse catchment areas, ranging from relatively uninhabited semi-forests, to areas that are devoted entirely to agriculture. Their watershed areas vary from a few hectares to several tens of square kilometres. They are also representative of the rainfall gradient of the Mediterranean area, covering the range (250–700 mm annual rainfall). The different geologies of the Mediterranean basin are also represented. The first reservoir was instrumented in 1993 in Tunisia and the network was fully operational from 1997. The data used in this paper cover the period from 1994 to 2001.

Each small reservoir is equipped with a water level gauge, an evaporation pan, a tipping bucket raingauge (resolution of 0.5 mm rainfall), and a submerged pressure transducer that measures the water level to within 1 cm. The spillway comprises a concrete weir lying in the immediate vicinity of the reservoir. This situation makes it possible to assume that the initial velocity is zero and to use the Bazin formula to estimate spillway discharges from the water level in the reservoirs. The water balance equation can then be used to compute the discharges coming in and out of the reservoir, event by event, for small (5-min) time steps (see Albergel & Rejeb, 1997).

The bathymetry of the reservoir has been surveyed each hydrological year for seven small dams. For the others it was surveyed twice during the measurement period. For example, Fig. 1 shows the bathymetry measurements for the small dam at Kamech (2.5 km^2 catchment), on the Cap Bon Peninsula in northeast Tunisia. Appropriate investigations were undertaken to estimate the budgets for the different erosion processes, according to land use. These included the use of rainfall simulators, topographic surveys of gullies or landslides, soil roughness surveys, and field erosion measurements.

The model

For a storm event that produces a flood in a small watershed, the total soil loss can be estimated using the Modified Universal Soil Loss Equation (MUSLE) or Williams equation (Hadley, 1985):

$$A = \alpha \times (Q_{\max} \times V_{\text{flood}})^{\beta} \times K \times (LS) \times C \times P \tag{2}$$

where A is total soil loss during the flood (t), $Q_{\max}$ is peak discharge (m^3 s^{-1}), V_{flood} is flood volume (m^3), K is a soil erodibility parameter, LS provides a measure of the local relief (slope lengthy and steepness), C is a coefficient expressing the degree of soil protection by land cover, and P is a coefficient expressing the degree of erosion reduction due to soil conservation practices. The terms α and β are constants.

In a first stage $\alpha \times K \times (LS) \times C \times P$ and β are considered constant and as having the same value for all α events on the same watershed. Values of these parameters are computed using an optimization method, by comparing the total amount of sediment transported between two bathymetric surveys with the equivalent estimate of sediment output provided by MUSLE. The results for the period between the first two bathymetric surveys are used to calibrate α and β. On catchments for which more than two bathymetric surveys are available, it is possible to validate the model (Albergel *et al.*, 1999b).

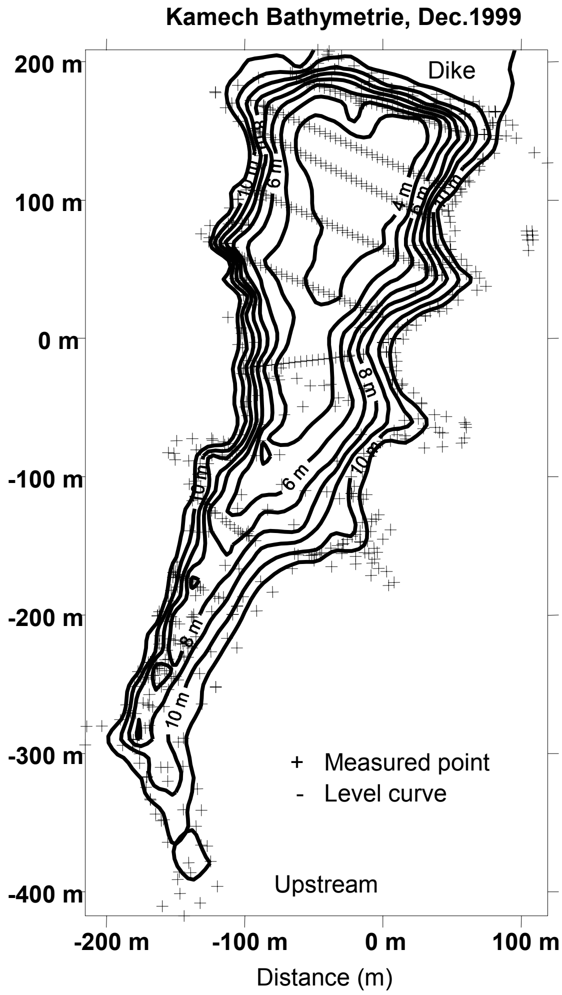

Fig. 1 Siltation measurement at Kamech (December 1999); the level curves are calculated from an arbitrary zero corresponding to the zero of the flood gauge installed in the dam.

RESULTS AND DISCUSSION

Sediment budgets on small dams catchments

Table 1 lists the volume loss for seven small dams in the network. Siltation rates relative to the area of the catchment, range from 1.1 m^3 ha^{-1} $year^{-1}$ (or 1.8 t ha^{-1} $year^{-1}$), for a fairly wooded piedmont catchment where erosion control work has been implemented (El Gouazine in Central Tunisia), to 31 m^3 ha^{-1} $year^{-1}$ (or 50 t ha^{-1} $year^{-1}$) for a small, marly catchment in the Pre-Rif hills of Morocco (the Saboun Dam). The equivalent estimate for the dam at Sindyaneh, on the basalt plateau of Homs, in Syria where the cultivated zones on the catchment slopes are terraced, with small stone walls to mark the boundaries of the fields is 2.4 m^3 ha^{-1} $year^{-1}$, (or 3.8 t ha^{-1} $year^{-1}$). It should be remembered that the USDA considers "normal" erosion of cultivated soil to be between 1 and 11 t ha^{-1} $year^{-1}$ (Roose, 1996).

Table 1 Siltation in seven small dams.

Dam	Catchment area (ha)	Year of construction	Date of the last bathymetry	Reservoir initial vol. (m^3)	Stoked sediment (m^3)	Siltation (m^3 ha^{-1} $year^{-1}$)
Fidh Ali (Tunisia)	413	1991	Sept1999	134 710	49 843	15.1
M'Richet el Anse (Tunisia)	158	1991	Sept 1999	42 400	9 609	7.6
El Gouazine (Tunisia)	1810	1990	May 1998	237 030	16 030	1.1
Es Senega (Tunisia)	363	1991	Jun 1998	86 420	27 778	10.9
Kamech (Tunisia)	246	1993	Dec 1999	142 100	29 441	20.0
Syndianeh (Syria)	359	1967	Oct 2000	433 300	28 370	2.4
Saboun (Morocco)	702	1991	Nov 1999	1 066 440	162 450	28.9

The same type of monitoring was conducted on 24 small dams in the Tunisian Dorsal and showed a total volume loss of 585 200 m^3 at the end of 1999 for an initial storage capacity of 2 634 000 m^3, i.e. a loss of 22% for an average life expectancy of 7.7 years. The average storage capacity depletion was thus 4.6% per year (similar to that quoted by Gazzalo & Bassi, 1969, for small dams in Italy). The average amount of sediment trapped by the small dams is thus approx. 16 t ha^{-1} $year^{-1}$. If we extrapolate this result to the thousand hill reservoirs provided for in the national strategy and attribute to them the average characteristics of the 24 reservoirs studied, we get 3.2 Mm^3 of storage per year, i.e. 13% of the current siltation of the large Tunisian dams, a not insignificant percentage. In Tunisia, where large dams represent a useable storage volume of 1612 Mm^3, the loss is estimated at 1.6% (Habaïeb & Albergel, 2001). This result does not of course take into account any dams that are completely silted up or those washed away by large floods, releasing their stored sediment.

The measurements of the solid transport retained by the small dam of Saboun (7 km^2 catchment)in the Western Rif Abdelhaoui *et al*, (2002) indicate a sediment yield of 50 t ha^{-1} $year^{-1}$. These very high erosion values contrast with the known erosion plot measurements for the region, the highest of which do not exceed 10 t ha^{-1} $year^{-1}$. There are two possible explanations for the major difference between the sediment yield estimated from the sedimentation data for the dam and that estimated from the erosion plot measurements:

(a) The dam data included all erosion events since its creation (1991), while the plots have been observed over only a few years and the exceptional events are often not recorded properly because the measurement device overflows.

(b) Gully erosion is widespread in the Saboun catchment, contributing a large quantity of sediment to the dam.

Using rainfall simulation experiments and applying a sediment production and transfer model, Hamed *et al.* (2002) examined the different types of erosion in the catchment of the small dam of Mrichet El Anse in Central Tunisia (erosion estimated at 12.5 t ha^{-1} $year^{-1}$). They showed that in dry years, sheet erosion is responsible for 90% of the sediment reaching the dam, whereas in rainy years only 65% of the erosion comes from the slopes. The rest is produced by gully erosion and the collapse of wadi banks.

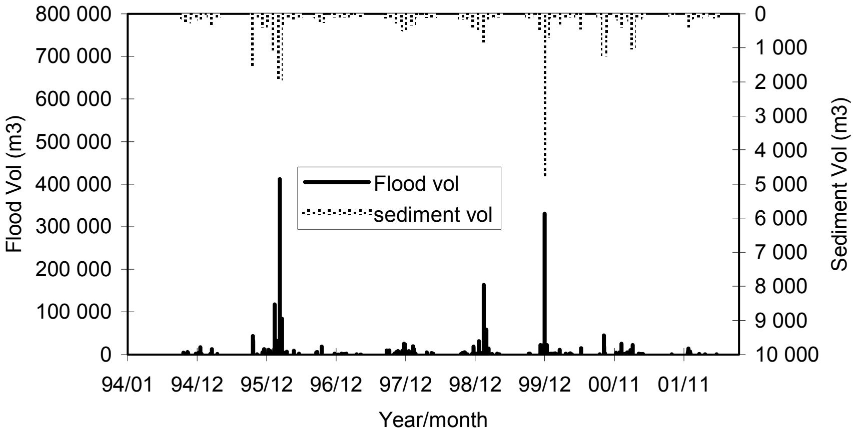

Fig. 2 Discharge and solid transport reconstituted flood by flood at the Kamech Dam over a nine-year period.

Table 2 Computed solid transport for each flood by MUSLE.

	Hydrological year	Rainfall (mm)	Flow volume (m^3)	Sediment volume (m^3)	Soil loss (t ha^{-1})
El Gouazine	1994–1995	298.5	226 073	4 536	3.01
(Tunisia)	1995–1996	575.7	481 331	5 962	3.95
	1996–1997	252.5	39 190	30	0.02
	1997–1998	387.0	80 050	80	0.05
	1998–1999	408.4	210 200	230	0.15
	1999–2000	303.5	469 265	7 321	4.85
Kamech	1994–1995	495.0	59 400	1 042	5.09
(Tunisia)	1995–1996	1036.5	943 040	8 794	42.98
	1996–1997	405.5	38 900	291	1.42
	1997–1998	750.7	176 020	2 070	10.12
	1998–1999	700.7	352 318	2 269	11.09
	1999–2000	769.1	469 265	7 321	35.78
M'Richet	1994–1995	349.5	8 686	497	3.77
(Tunisia)	1995–1996	744.5	55 812	4 021	30.54
	1996–1997	375.0	42 137	3 143	23.87
	1997–1998	533.0	14 400	563	4.28
	1998–1999	580.9	19 480	308	2.34
Es Sénéga	1994–1995	237.0	109 627	3 615	11.95
(Tunisia)	1995–1996	455.7	115 490	3 467	11.46
	1996–1997	244.5	120 232	3 329	11.00
	1997–1998	375.5	152 656	5 565	18.40
	1998–1999	292.5	66 270	1 472	4.86
	1999–2000	256.0	31 640	699	2.31
Fidh ali	1994–1995	206.0	234 740	4 574	23.06
(Tunisia)	1995–1996	495.5	469 172	6 015	30.33
	1996–1997	173.0	41 190	31	0.16
	1997–1998	369.5	80 050	80	0.40
	1998–1999	299.5	211 200	230	1.16
	1999–2000	184.0	13 913	10	0.05

Solid transport event by event

The MUSLE equation enables the sediment transport to be calculated for each flood since measurements were initiated. It can provide an improved understanding of erosion and its consequences for the siltation of the reservoirs of small dams. This model was applied to 18 small catchments where bathymetric measurements were available to calibrate and to validate the model. Each flood event is evaluated using the water balance equation in the small dam to determine its volume and its peak discharge.

Figure 2 shows the results of applying this model to the Kamech Dam in Tunisia. It emphasizes the importance of extreme events. Three floods were responsible for 50% of the sediment transport over this 9-year period (27 February 1996, 18 January 1999 and 29 November 1999). The last contributed 20% of the transport occurring over the period (Albergel *et al.*, 2003).

Table 2 reports the sediment transport for five dams and the reconstituted sediment loads for individual floods for each year. The sediment transport associated with the dam overflow is added to the sediment trapped by the dam. It shows that the sediment loads vary markedly from one year to the next, depending on the rainfall amount, intensity and the date of the event. Events occurring in the autumn generate more sediment than in winter or spring when land cover is denser.

CONCLUSION

In conclusion, it can be seen that a small artificial reservoir at the outlet of a catchment is an ideal location for observing the sediment transported by the river system. Eroded sediment transported by surface runoff is trapped in the reservoir, with only a small proportion being released when the reservoir overflows, which rarely occurs. It is relatively easy to estimate the sediment load by making regular bathymetric surveys, collecting samples of the overflow discharge and monitoring the water balance of the reservoir.

Since 1994, measurements of the sedimentation rate have been undertaken in 31 reservoirs where the water balance has also been monitored. This very important data set on small Mediterranean catchments must be further developed by more accurate studies of their geology, soils, land cover and agricultural systems. Such studies could lead to further work on the erosion processes and on erosion modelling in Mediterranean areas, as well as providing information on the areas where siltation is the most serious, thus helping to establish indicators that may be used as an early warning of siltation.

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