

Soil erosion and reservoir sedimentation in the High Atlas Mountains, southern Morocco

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Abstract In Morocco, for some reservoirs average annual loss of capacity reaches 1.6%. Assessments of erosion rates suggest sediment yields from drainage basins may be almost 5000 t km⁻² year⁻¹ in the Rif Mountains with mean rates of between 300-500 t km⁻² year⁻¹ in the High Atlas Mountains. In a study of the Aoulouz basin in the High Atlas Mountains factorial scoring methods founded on a GIS approach estimated that 46% of the sediment was produced by less than 25% of the 4446 km² catchment. The potential erosion rate of the most erosion susceptible sub-basin was estimated as 1592 t km⁻² year⁻¹. Field monitoring of actual erosion in the highest yielding sub-basin showed that gully sediment yields were in excess of 1000 t km⁻² year⁻¹ for individual storm events and exceeded rill erosion by two orders of magnitude. The study also emphasized the need to target soil conservation management strategies on gullied areas in the catchment.

INTRODUCTION

Reservoir sedimentation represents a major problem for the management of water supplies in many parts of the world and may have serious economic implications. In Morocco, Lahlou (1993) has estimated that by the year 2000 forty million m³ of sediment will be deposited in reservoirs each year. As a result, he suggests that each year 5000 ha of irrigated land will be lost to agriculture, electricity generation of 60 million kW h⁻¹ will be lost annually and as many as 10 000 jobs could be lost. In view of this, the accurate assessment of the spatial and temporal variation of erosion and ultimately sedimentation rates is of great importance, in order that effective soil conservation measures may be adopted. The significance of sediment sources and the relative erodibility of surface materials will be addressed in this paper which describes the results of a study carried out to measure sediment yields in the Aoulouz sub-basin of the Oued Souss in southern Morocco.

EROSION RATES AND RESERVOIR SEDIMENTATION IN MOROCCO

Many attempts have been made to estimate rates of erosion in Morocco at a range of scales and using a variety of methods. At the national scale, for example, Arnoldus (1977) produced a map of maximum potential average annual soil loss due to sheet and rill erosion using simple factorial methods based on the Universal Soil Loss Equation. This indicated maximum rates of erosion of up to 20 000 t km⁻² year⁻¹ for the Rif and Atlas Mountains. Suspended sediment yields for major rivers have been

used by a number of authors to produce estimates of actual erosion rates as opposed to potential sediment yields (e.g. Heusch & Millies-Lacroix, 1971; Snoussi, 1988; Probst & Amiote Suchet, 1992). Rates of erosion based on these suspended sediment yields ranged from $130 \text{ t km}^{-2} \text{ year}^{-1}$ to $3850 \text{ t km}^{-2} \text{ year}^{-1}$, with the highest yields reported from the basins draining the Rif Mountains of northern Morocco. A study of 16 Moroccan reservoir schemes by Lahlou (1993) produced an estimate of sediment yields based on sedimentation rates and this confirmed the spatial pattern of erosion rates produced by other workers (Fig. 1). As can be seen in Table 1 the rates of sediment yield are highest for Rif basins, with lower rates recorded for the less humid Middle and High Atlas regions. Analysis of natural lake sediment cores by Rippey (1982) suggests a sediment yield of $600\text{--}700 \text{ t km}^{-2} \text{ year}^{-1}$ for the Middle Atlas mountains, whilst most estimates of erosion in the High Atlas suggest rates of $300\text{--}500 \text{ t km}^{-2} \text{ year}^{-1}$ (Snoussi, 1988; Lahlou, 1993; El Kasri, 1995).

Lahlou's (1993) study also confirms the severe impact of sedimentation on reservoir capacity in Morocco. As can be seen, the percentage loss of capacity since dams have come into operation may be as high as 47% in a period of 30 years (Oued Nakhla) or 16% in 10 years (Oued Nekor) (Table 1). Average annual percentage loss of capacity ranges from 0.11 to 1.60, with an average figure for all 16 dams studied of 0.57%. Whilst these annual figures mask considerable variation from year to year due to the inherent variability of the climatic regimes, and hence runoff and sediment generation, they nevertheless illustrate the short life expectancy of some of the

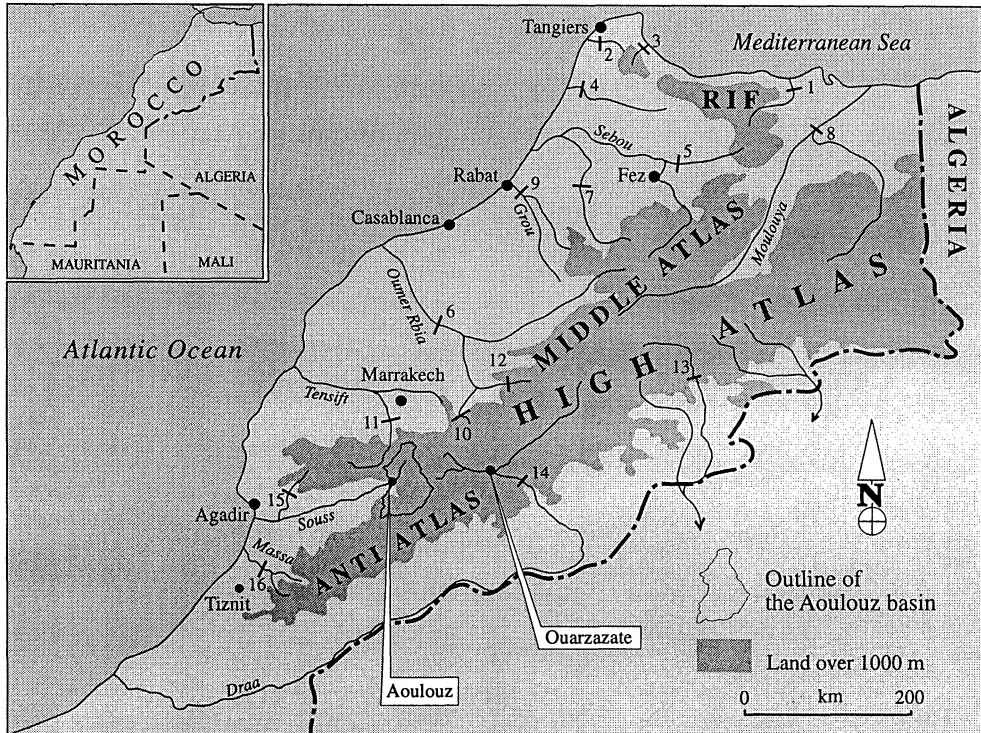


Fig. 1 Location map of the Aoulouz study area and the reservoirs listed in Table 1.

Table 1 Erosion rates and capacity losses for reservoir schemes in Morocco (adapted from Lahlou, 1993).

Barrage	River	Date of operation	Basin area (km ²)	Average erosion rate (t km ⁻² year ⁻¹)	Initial reservoir capacity (10 ⁶ m ³)	% Capacity lost to 1991	Average annual % loss of capacity
Mohamed Ben Abdelkrim El Khattabi (1)	Nekor	1981	780	1500	43	16	1.6
Ibn Batouta (2)	M'harhar	1977	178	4700	44	12.8	0.91
Nakhla (3)	Nakhla	1961	107	2500	13	47	1.57
Oued El Makhazine (4)	Loukkos	1979	1820	2000	807	4	0.33
Idriss 1 st (5)	Inaouene	1973	3680	720	1217	2.3	0.13
Average for Rif Mountains				2284	4125	16.4	0.89
Al Massira (6)	Our Er Rbia	1979	28500	320	2724	3	0.25
El Kansera (7)	Beht	1938	4540	330	273	20	0.34
Mohamed V (8)	Moulouya	1967	49920	240	725	35	1.46
Sidi Mohamed Ben Abdellah (9)	Bou Regreg	1974	9800	270	509	4.5	0.26
Average for Middle Atlas Mountains				290	1058	15.6	0.58
Moulay Youssef (10)	Tessaout	1969	14410	900	197	11	0.5
Lalla Takerkoust (11)	N'Fis	1935	1707	350	96	23	0.41
Bine El Ouidane (12)	El Abid	1953	6400	680	1484	7	0.18
Hassan Addakhil (13)	Ziz	1971	4400	430	369	6	0.3
Mansour Eddahbi (14)	Draa	1972	15000	400	592	11	0.58
Abdelmoumen (15)	Issen	1981	1300	260	219	0.6	0.11
Average for High Atlas Mountains				503	493	9.8	0.35
Youssef Ben Tachfine (16)	Massa	1972	3584	1300	320	5	0.26
Aoulouz ^a	Souss	1992	4446	480	103	4.9	1.3

Numbers in parentheses refer to dams in Fig. 1.

^aThis study.

schemes. Once again the greatest impact of sedimentation on reservoir capacities is to be found in the Rif mountains.

THE AOULOZ BASIN STUDY

The Aoulouz basin forms the headwaters of the Souss river and straddles the High Atlas and Anti Atlas Mountains in southern Morocco (Fig. 1). It has an area of 4446 km². The northern watershed rises to over 4000 m in the High Atlas mountains, but over most of the catchment elevations are lower. The catchment is underlain principally by volcanic rocks in the north and east, granitic rocks in the central part of the basin and limestones and sandstones in the south. Soils in the basin are generally shallow and skeletal except on alluvial footslopes and vegetation is typically low and sparse, with 90% of the basin land surface comprising bare soil or rock. Mean annual precipitation for the period 1949-1970 was 360 mm (El Hebil, 1970) but, as with many semiarid or sub-humid regions, the principal characteristics

of the precipitation are its unreliability and its temporal and spatial variability.

In 1992 the Aoulouz reservoir was put into service in order to recharge falling groundwater levels in the important agricultural area of the Souss Plain. In an effort to assess the erosional environment of the Aoulouz basin and to develop and implement a management plan for erosion control, a GIS based factorial scoring method was used by the Département des Eaux et Forêt et de la Conservation des Sols (El Kasri, 1995). Superimposition of basin maps for each of four factors produced a map of potential susceptibility to erosion. The sub-basins with the highest potential yields are located in the northern part of the catchment where slopes are steep, the parent material is defined as resistant and the rainfall erosivity is high.

The susceptibility map was then used as a basis for the assessment of the contribution to reservoir sedimentation from each sub-basin through the application of a sediment delivery ratio. The ratio was derived from the difference in height between each sub-basin and the reservoir and the length of the watercourse linking the two and was applied to an estimated sedimentation rate in the reservoir of 2 154 441 t year⁻¹. The study showed that the overall mean erosion rate for the

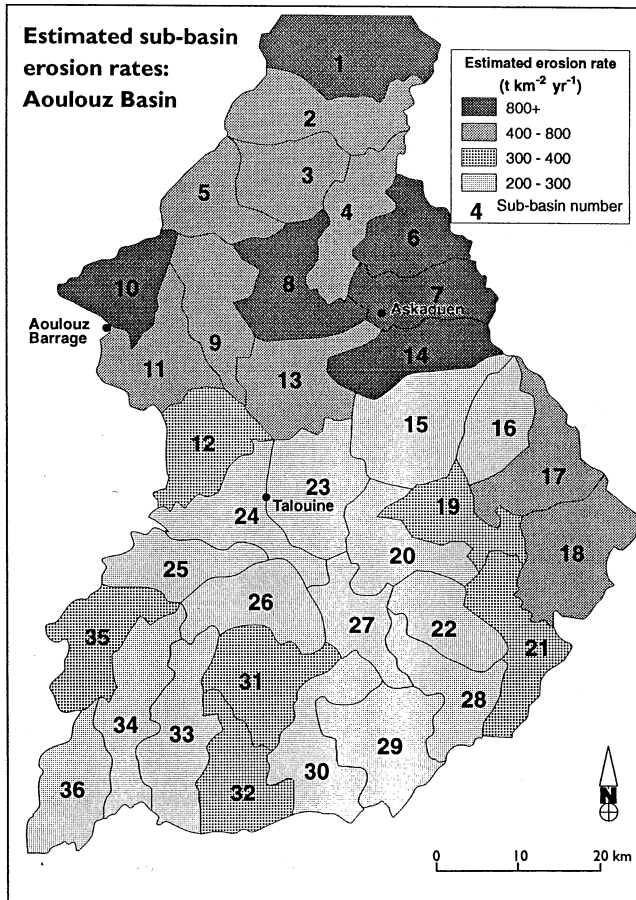


Fig. 2 Estimated sub-basin erosion rates: Aoulouz basin.

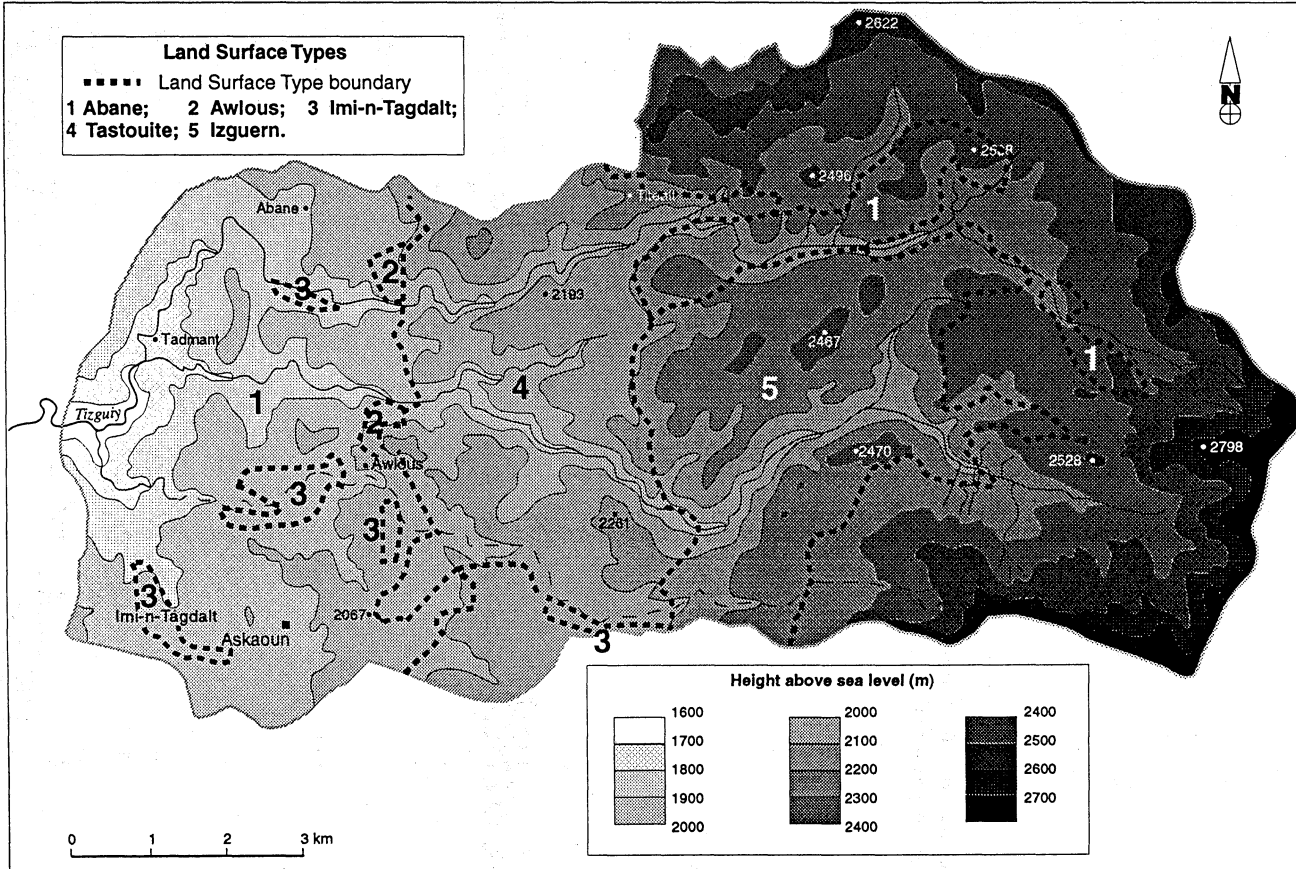


Fig. 3 Land surface types Askaouen sub-basin.

Aoulouz basin was approximately $485 \text{ t km}^{-2} \text{ year}^{-1}$ and that over 46% of the sediment was produced by less than 25% of the catchment. Sub-basin 7, the Askaouen sub-basin (Fig. 2), was calculated to have the highest contribution to sedimentation at 7.15%, which corresponded to a specific yield of $1592 \text{ t km}^{-2} \text{ year}^{-1}$. Sub-basin 29 on the other hand contributed only 1.32% to reservoir sedimentation with a specific sediment yield of $232 \text{ t km}^{-2} \text{ year}^{-1}$. Despite the seemingly accurate estimates of sub-basin sediment yield, they are nevertheless predictions of potential sediment supply based upon simple descriptors of the main factors influencing the processes of erosion and sediment delivery. In an effort to evaluate predicted erosion values and to describe the pattern and process of erosion, field measurements of soil erosion were made in the Askaouen sub-basin over the period 1993 to 1995. The 97 km^2 sub-basin was subdivided into a number of land surface types and pedogeomorphic toposequences using air photograph cover and field survey (Fig. 3). Gerlach troughs were used to monitor soil loss caused by surface wash and rill erosion in the land surface types and gully erosion was measured with a check dam.

The results of these measurements confirm the importance of gully erosion in the sediment production system. For the season 1994-1995, for which the most complete records are available, mean annual sediment yields for rill erosion and slopewash ranged from $9.0 \text{ t km}^{-2} \text{ year}^{-1}$ to $16.3 \text{ t km}^{-2} \text{ year}^{-1}$ for the lower slope units of five different land surface types (Table 2). This compares with a sediment yield in excess of $1030 \text{ t km}^{-2} \text{ year}^{-1}$ produced by a single rainfall event of 36 mm for a monitored gully system. Analysis of the frequency of such storm events for the sub-basin suggests that the annual sediment yield from gully affected land may be over $2050 \text{ t km}^{-2} \text{ year}^{-1}$. This is a figure comfortably in excess of the predicted potential yields of 1592 t km^{-2} for the sub-basin. The two orders of magnitude difference between rill erosion and gully sediment yield corroborates the findings of Heusch (1970) in the Rif Mountains of Morocco and the study by Roose (1991) in northern Algeria.

Gully texture in the five monitored land surface types ranged from 2 to 5 channels per km. Flow in the main badland area at Abane (Fig. 3) was activated by precipitation events in excess of 16 mm and occurred in seven out of 16 storm events during the monitoring period 1993-1995. Strong links between lower slope units of adjacent catenary sequences mean that sediment delivery to gully channels is very high and hence overall sediment yield from this gullied area is also high.

In terms of reservoir sedimentation in the Aoulouz reservoir and the contribution of the Askaouen sub-basin, the Abane badland area probably accounts for a significant proportion of the total sediment yield. This is not only because it is an area of high sediment production, but also because it is close to the sub-basin outlet in the Oued Tizguiy (Fig. 3). Other land surface types in other parts of the sub-basin have lower gully textures, weaker slope channel connections and are at greater distances from the basin outlet giving greater potential for deposition and storage within the sub-basin. Consequently any efforts to reduce sedimentation rates through control of sediment supply from the Askaouen sub-basin should be focused upon the Abane gully system.

Many workers have drawn attention to the importance of lithology in determining erosion rates. Probst & Amiotte Suchet (1992) and Lahlou (1993) produce multiple regression relationships describing the significance of varying

Table 2 Sediment yields from different land surface types (lower slope units) Askaouen sub-basin.

Land surface type	Lithology	Sediment yield 1994-1995 (t km ⁻²)	Mean rill density (rills 100 m ²)	Mean rill cross section area (cm ²)	Slope (°)
Abane	Granite (weathered)	16.30	8	625	10.5
Aoulouz	Granite	12.25	10	140	10.3
Imi-n-Tagdalt	Granite	13.47	9	470	4.5
Tastouite	Volcano-sedimentary siltstone and schist	15.23	44	70	5.0
Izguern	Andesitic tuff	13.97	18	135	9.5

lithology to rates of sediment yield. However such relationships are not simple and as noted by Gerrard (1989) and Fox & Moore (1993) similar lithologies may have quite different susceptibilities to erosion due to their physical and chemical make-up and past denudational history. Hence whilst igneous rocks are generally regarded as being amongst the least erodible lithologies, in the case of the Askaouen sub-basin erosion rates are high. The sub-basin is underlain principally by granites and volcanic lithologies, but the erodibility of these materials is determined by the degree of weathering to which they have been subjected. Where weathering depths reach several metres, as at Abane, gully systems have developed and as noted rates of sediment yield are at minimum in excess of 1000 t km⁻² year⁻¹.

Where relatively unweathered rock outcrops at the surface, gully development is restricted and consequently sediment yields are lower. Rill erosion rates were also higher on the weathered granite areas of Abane in comparison to the lower pedogeomorphic units of the relatively unweathered granite catenary sequences (Table 2). Rill densities were in fact lowest on the Abane weathered granite, but the rills developed were deeply incised into the colluvial footslope. Much smaller rills occurred on the other lithologies. Erosion on the less weathered granite areas was similar to that on the tuffaceous volcanic rocks and siltstone schist, volcano-sedimentary formation of the other land surface types.

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REFERENCES

- Arnoldus, H. M. J. (1977) Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco. *FAO Soils Bull.* **34**, 39-48.
- El Hebil (1970) Etude hydrogéologique du haut bassin versant du Souss. Thèse Univ. Montpellier -Rapp. Inéd. MTPC/DH/DRE.
- El Kasri, M. (1995) Project d'Aménagements du Bassin Versant du Barrage d'Aoulouz. Ministère de l'Agriculture et de la Mise en Valeur Agricole. Mai 1995 (unpublished).
- Fox, H. R. & Moore, H. M. (1993) Discussion: fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa). *Hydrol. Sci. J.* **38**(6), 1-4.
- Gerrard, A. J. (1989) The nature of slope materials on the Dartmoor granite. *Z. Geomorphol. N.F.* **33**, 179-188.

- Heusch, B. (1970) L'érosion du Pré-Rif- Une étude quantitative de l'érosion hydraulique dans les collines marneuses du Pré-Rif occidental. *Ann. Recherches Forestières de Maroc* **12**, 9-176.
- Heusch, B. & Millies-Lacroix, A. (1971) Une méthode pour estimer l'écoulement et l'érosion dans un bassin. *Mines & Géologie* **33**, 21-39.
- Lahlou, A. (1993) *Envasement des Barrages au Maroc*. Wallada, Casablanca.
- Probst, J. L. & Amiotte Suchet, P. (1992) Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa) *Hydrol. Sci. J.* **37**(6), 621-637.
- Rippey, B. (1982) Sedimentary record of rainfall variations in a sub-humid lake. *Nature, Lond.* **296**, 434-6.
- Roose, E. J. (1991) Conservation des sols en zones méditerranéennes. Synthèse et proposition d'une nouvelle stratégie de lutte antiérosive: la GCES. *Cah. ORSTOM sér. Pédol.* **26**, 45-181.
- Snoussi, M. (1988) *Nature, estimation et comparaison des flux de matières issus des bassins versants de l'Adour (France), du Sebou, de L'oun-er-Rbia et du Souss (Maroc)*. Memoire de l'Institut de Géologie du Bassin Aquitaine, no. 22, Université de Bordeaux, France.