# Effects of the construction of dams on the water and sediment fluxes of the Moulouya and the Sebou Rivers, Morocco

Maria Snoussi · Souad Haïda · Saïd Imassi

**Abstract** The sediment fluxes of the Moulouya and the Sebou Rivers – the two largest rivers in Morocco – were estimated on the basis of suspended sediment loads carried by these rivers towards the coastal zone. The high rate of the specific sediment yield of the Sebou (995 t $km^{-2}$ $year^{-1}$), which is one of the highest in Africa, is probably due to the fact that the drainage basin is characterized by young mountains, extended erodible sedimentary rocks, irregular and often stormy precipitation and scarce vegetation. Recently, the construction of dams and changes in rainfall have drastically reduced these sediment load and water discharges. It is estimated that the construction of dams has reduced the water discharge of the Sebou and the Moulouya rivers by 70 and 47% respectively, and their sediment fluxes by nearly 95 and 93%. The damming of rivers has also had a profound effect on the coastal zones, which reacted by reaching a new sedimentary equilibrium. The forcing induced by the estuarine behavior of the lower stretches of both rivers downstream of the dams has greatly disturbed the mouth topography and coastal stability.

**Keywords** Sediment yield · Moroccan rivers · Damming · Siltation · Coastal morphology

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## Introduction

River inputs are by far the main source of continental materials exported to the ocean. They can be seen as integrators of natural processes occurring on the land surface, since water and sediment fluxes in large rivers reflect nature as well as natural or man-induced changes in their watersheds. Since the beginning of the nineteenth century, human activities such as vegetation clearance, changes in land use and construction of dams have extensively increased or reduced natural river sediment fluxes (Ward and Stanford 1979; Walker 1985; Barrow 1987; Davey et al. 1987; Xu 1996; Vörösmarty et al. 1997).

In addition, river sediment fluxes constitute one of the main components of the coastal sedimentary budget. Any change in these fluxes could significantly alter the physical environment of the coastal systems (Hay 1994; Poulos and Chronis 1997; Simeoni and Bondesan 1997; Barusseau et al. 1998). Like all semi-arid regions with contrasting climatic seasons, Morocco periodically faces a rainfall deficit caused by recurrent droughts. In order to better manage these shortages, over the last decades a large-scale program for the construction of dams has been carried out to provide drinking water, irrigation and hydroelectric power (Direction de la Recherche et de la Planification de l'Eau 1994). However, these reservoirs have suffered from siltation due to the hinterlands' high rate of natural and accelerated erosion. According to Lahlou (1996), the annual sedimentation rate in Moroccan reservoirs reached 50 million $m^3$ $year^{-1}$. This huge siltation has a serious environmental and socio-economical impact, since it reduces the reservoirs' capacity, and could affect the morphological equilibrium of the coastline.

This paper provides data on the water and sediment fluxes of the two largest rivers in Morocco: the Moulouya and the Sebou Rivers, which flow into the Mediterranean Sea and Atlantic Ocean respectively. The main objectives are to determine the impact of the construction of dams on the water and sediment discharges of these rivers and to examine the coastline's potential geomorphologic response to human dam activity.

## The river systems

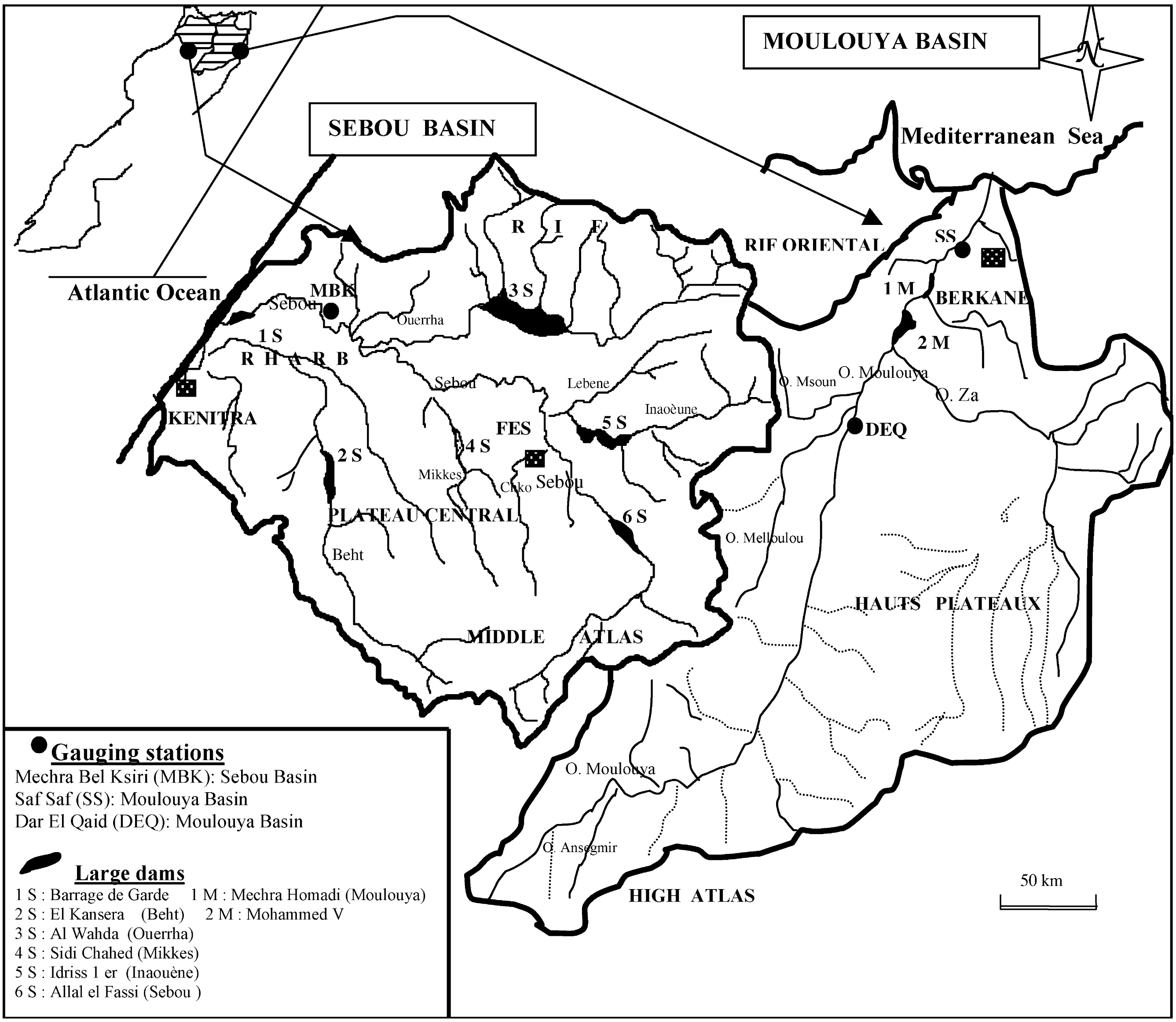
### The Moulouya River

The Moulouya River is the largest river in Morocco, draining approximately 53,500 km$^2$ in the eastern Morocco between 32–35°N and 2–6°W (Fig. 1). It rises in the Atlas Mountains at an altitude of 1,770 m and flows into the Mediterranean Sea. Topographically, about 3% of the drainage basin is mountainous (altitude >2,500 m), 15% is hilly (1,500–<2,500 m), 71% is foothills and a plateau region (500–<1,500 m), and 11% is plains and valleys. The slopes of the streams gradually decrease from about 0.56% in the upper part of the basin, 0.32% in the middle part, and 0.19% in the lower floodplain. The upper basin is separated from the lower floodplain by the large Mohamed V reservoir which traps most of the sediment delivered from the upstream region. The bedrock consists predominantly (97%) of sedimentary rocks (calcareous rocks, marls, sandstone, conglomerate, etc.); crystalline and metamorphic rock outcrop at only 3% of the basin area. The climate is typically Mediterranean, with the average precipitation ranging from 200–600 mm. Most of the rainfall is concentrated in only a few days. The mean annual temperature ranges between 9 and 20 °C. The main human activities in the Moulouya basin are agriculture (138,000 km$^2$ of irrigated lands), industry, mining, and grazing. Agriculture is developed mainly in the lower Moulouya, where the soil is fertile and water sufficient. The main crops grown are cereals, vegetables, and sugar beet. In the more arid zones, the land is used mainly for livestock grazing. Forests are developed on the slopes of the Atlas and Bni Znassen mountains.

### The Sebou River

The Sebou River is also one of the largest Moroccan rivers, draining approximately 40,000 km$^2$ between

**Fig. 1**
Geographic situation of the Sebou and Moulouya watershed, showing major dams and gauging stations where data were collected



33–35°N and 4–7°W. It stretches about 600 km from its source in the Middle Atlas to the Atlantic Ocean. The physiography of the watershed is strongly influenced by the altitude distribution between the north and the south. The Sebou basin can be divided into three distinct geomorphic regions: the upper, mid, and lower Sebou. The upper Sebou rises over 2,800 m in the Middle Atlas mountains and is underlain mainly by calcareous rocks. The mean annual precipitation is over 1,000 mm and at high elevations winters are snowy. The mid-Sebou basin is located in the Rif and the Prerif mountains which are characterised by an average altitude of 2,000 m, very steep slopes, a strong rainfall gradient across the basin averaging 2,000 mm, and a substratum composed of shale, marls, and sandstone. Ouerrha and Inaouene are the major tributaries of the Sebou draining the Rif and the Prerif mountains. At the lower basin, the Sebou opens into a wide valley where it meanders through a floodplain. The mean annual rainfall is about 600 mm in the west and 450 mm in the southeast.

The Sebou basin is one of the most populated regions of Morocco. By 1990, its population totaled about 5 million, of which 61% live in rural zones. It represents the country's most important agricultural region (19,200 $km^2$ of irrigated lands) and has a relatively well-developed social and economic infrastructure. Natural vegetation covers only 25% of the drainage basin's total area. Since the lower basin consists of a coastal plain, large-scale irrigation schemes have been developed in the Rharb Plain. The main crops grown are cereals, vegetables, sugar cane, rice, and cotton. The basin encompasses several large reservoirs as well as small ones built over a period of 70 years. The El Kansera reservoir was constructed on the Beht River in 1935. It was initially used to retain floods but now also stores water. By 1973, there were at least 15 dams with 5 large reservoirs and 10 small dams. These reservoirs are now a major source of irrigation and drinking water and strongly regulate the flow in the upper, mid, and lower catchments. The Al Wahda dam, constructed on the Ouerrha River between 1991 and 1996, is the second most important dam in Africa after the High Aswan dam. It has a storage capacity of $3.8\times10^3$ $km^3$ and a height of 88 m. This reservoir will provide long-term storage, irrigate 100,000 ha, generate a hydroelectricity potential capacity of 400 GW h $year^{-1}$, transfer a water capacity of $600\times10^6$ $m^3$ towards the southern regions, and protect the Rharb Plain from high floods.

# Data and results

Data on water flows and suspended sediment concentrations used in this study were obtained from four gauging stations operated by the Water Planning and Research Directorate (DRPE) which also kindly provided us with information on the status of dams. This latter is summarized in Table 1. Sediment fluxes were calculated by the stochastic method based on the product of suspended sediment concentrations weighted by the corresponding water discharges at each outlet station and for each flood period, and the water volume obtained by integrating water flows for the same period. All results on sediment discharges were based on suspended sediment only; no bed load sediment data were available.

Data on the annual water inflows (A) and the storage capacity (C) of the reservoirs were used to calculate the residence time ($\Delta\tau_R$) and the trap efficiency (TE) of each reservoir according to the following equations (Vörösmarty et al. 1997):

$$\Delta\tau_R = C/A \qquad (1)$$

$$TE(\%) = 1 - (0.05/\Delta\tau_R^{1/2}) \qquad (2)$$

The life-span of the reservoirs was calculated according to Hay's formula (1994; Eq.(3), where LS is the life-span (in years), W the mean bulk density of sediments (t $m^{-3}$), C the storage capacity ($m^3$), Qs the average suspended sediment load at a nearby gauging station (t $year^{-1}$), and TE the trapping efficiency (%).The bulk density used for calculations is of 1.56 t $m^{-3}$ (Sahalash 1982):

$$LS = (W \times C)/Qs) \times TE \qquad (3)$$

# Water and sediment fluxes

### Water fluxes

Table 2 presents for each river the drainage basin area, the river runoff, and the mean annual water discharge at the most-downstream flow-gauging stations, namely Mechra Bel Ksiri (MBK) for the Sebou and Saf Saf for the Moulouya. The average annual discharge varies from 5.10 $km^3$ $year^{-1}$ (1940–1972 period) to 1.49 $km^3$ $year^{-1}$ (1996–1997) for the Sebou River (Haïda 2000). For the Moulouya River, the mean annual flow ranges between a low of 0.173 $km^3$ $year^{-1}$ during the driest period (1980–

**Table 1**
Main characteristics of the dams constructed on the Sebou and the Moulouya Rivers. *T* Transfer of water; *HE* hydroelectricity; *I* irrigation; *R* regulation; *P* potable water

| River | Tributary | Dam | Year of completion | Surface area ($km^2$) | Capacity of reservoir ($km^3$) | Use |
|---|---|---|---|---|---|---|
| Sebou | | Allal El Fassi | 1990 | 5,400 | 81.5 | T |
| | Ouerrha | Al Wahda | 1996 | 6,190 | 3,800 | HE/I/R |
| | Inaouene | Idriss 1er | 1973 | 3,680 | 1,800 | HE |
| | Beht | El Kansera | 1935 | 4,542 | 266 | HE/I/P |
| Moulouya | | Mohamed V | 1967 | 49,920 | 490 | I/HE/P |

**Table 2**
Drainage basin area, mean annual water discharges and specific water flow at the downstream gauging stations on the Moulouya and Sebou Rivers

| River (gauging station) | Gauged drainage basin | | Period of data | Mean annual discharge | Mean annual flow | Annual runoff |
|---|---|---|---|---|---|---|
| | ($km^2$) | (%) | | ($m^3\ s^{-1}$) | ($10^6\ m^3$) | (mm) |
| Moulouya (Saf Saf) | 49,920 | 93 | 1970–1996 | 13 | 410 | 8.2 |
| Sebou (Mechra Bel Ksiri) | 26,100 | 65 | 1940–1994 | 131 | 4,127 | 158 |

1985) and a high of 0.945 $km^3\ year^{-1}$ in the wet period (1995).

Figure 2 shows the seasonal variations of water discharges during a mean hydrological year (1978–1979) downstream of the Moulouya and Sebou Rivers. The highest discharges occur between autumn and winter for the former, and between winter and spring for the latter. During the summer, water discharge is low for both rivers. These seasonal variations reflect a preponderant Mediterranean influence for the Moulouya basin and an Atlantic one for the Sebou basin.

Since the rainfall occurs mostly as short and heavy storms, flood events contribute extensively to the water fluxes of the rivers. For example, during the 1963 floods, the maximum water discharge of the Sebou River reached 8,000 $m^3\ s^{-1}$ (approximately 61 times greater than the mean annual value) and of the Moulouya River 5,200 $m^3\ s^{-1}$ (nearly 240 times greater than the mean annual discharge).

As Mediterranean rivers, the Sebou and the Moulouya are subject to interannual variations (Haïda et al. 1999). The available hydrological data (1940–1995) were used to calculate the hydroclimatic coefficient, Ec (Eq. 4):

$$Ec(\%) = [(Q_{ma} - Q_{mi})/Q_{mi}] \times 100 \quad (4)$$

where $Q_{ma}$ is mean annual flows and $Q_{mi}$ is mean interannual flows.

The long-term variation of Ec (Fig. 3) shows similar patterns for both basins, with a slight downward trend between 1977 and 1990. This decrease reflects the dryness Morocco faced during that period. (Belkheiri et al. 1987; Direction de la Météorologie Nationale 1993; Stockton 1993). Between 1990 and 1994 the trend for the two rivers diverges; the impact of the drought is less severe in the Moulouya River basin.

## Impact of dams on water fluxes

As outlined above, the Sebou River system is heavily regulated, thereby significantly altering the flow regime. Haïda (2000) estimated the water discharges before and after the construction of the dams. (Fig. 4). Between 1940 and 1972, the water discharge of the Sebou River and its tributaries was about 2.55 $km^3$. The construction of the Idriss 1^er^ dam on the Inaouene River in 1973 reduced the inflow volume supply by 55%. In 1990 the Allal El Fassi reservoir was built upstream on the Sebou River; the water discharge measured at the Azib Es Soltane station was down 70%. Recently (1996), construction of the Al Wahda dam on the Ouerrha River was followed by a decrease of the Ouerrha's average flow from 2.93–1.2 $km^3 year^{-1}$. Considering all dams, we can estimate that the water discharge of the Sebou River and its tributaries was reduced by approximately 70%.

Construction of Mohamed V reservoir reduced the water discharge at the Moulouya River by about 47%. In order to better show that the water flux reduction is due more to the construction of dams than to the dryness, we compared the relationship between the annual water discharge and the annual precipitation of the two rivers before and after damming (Fig. 5). For both rivers there is a high correlation for the period before the construction of the dams. After damming the water discharges vary independently of precipitation. This indicates that dams regulate the rivers' water flow. This trend could, however, also be

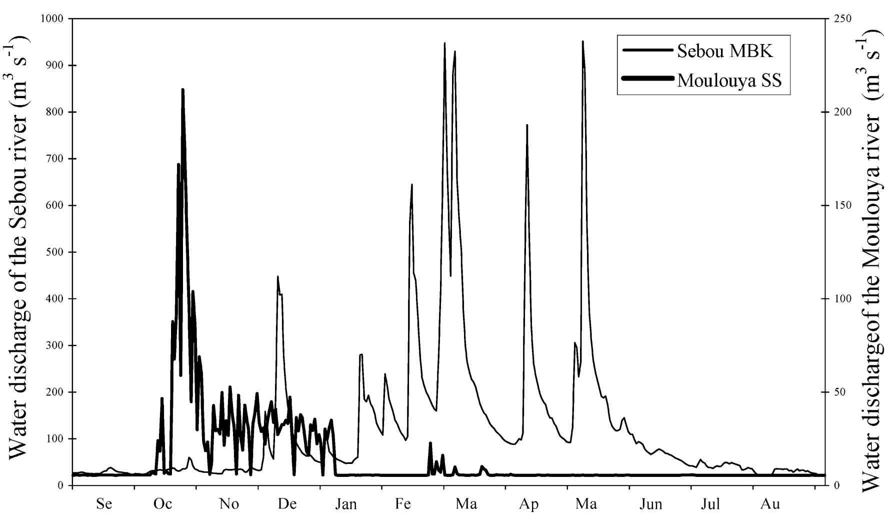



**Fig. 2**
Daily fluctuations of the water discharges in the Moulouya and Sebou Rivers respectively at the Saf Saf (*SS*) and Mechra Bel Ksiri (*MBK*) gauging stations

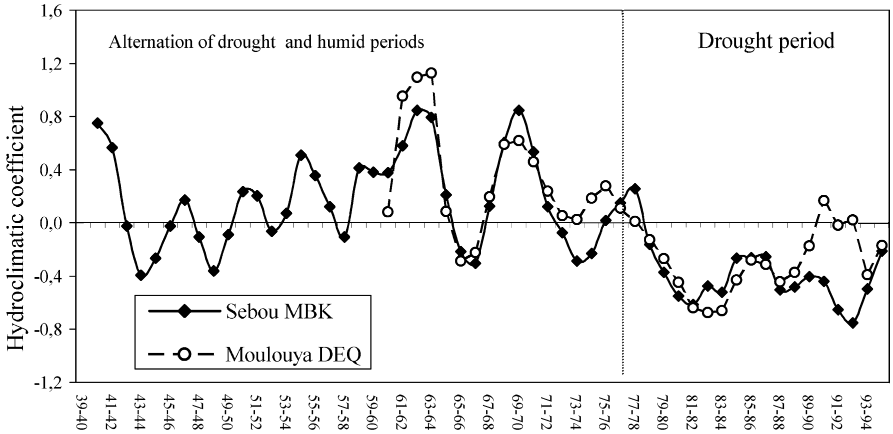



**Fig. 3**
Comparison of the hydroclimatic fluctuations of the Moulouya and the Sebou Rivers at respectively Dar El Qaid (*DEQ*) and Mechra Bel Ksiri (*MBK*) gauging stations

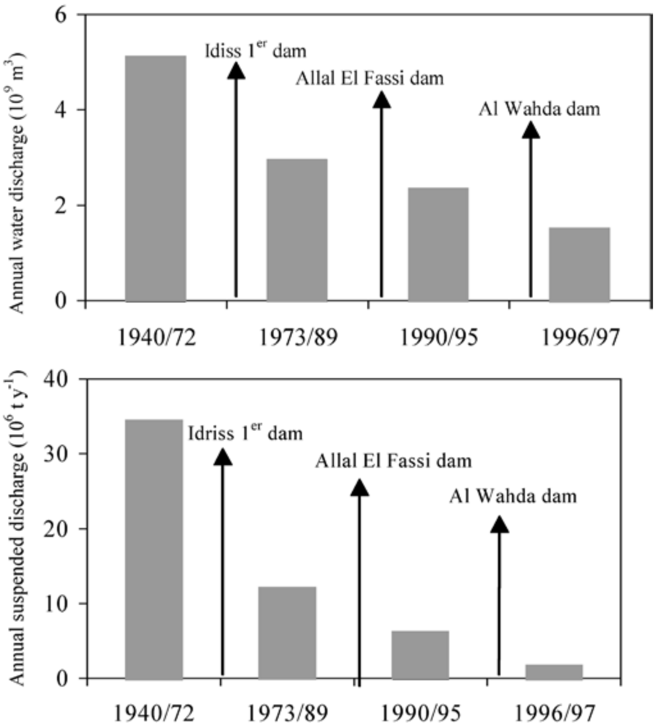



**Fig. 4**
Variation of the annual water (*above*) and suspended sediment (*below*) discharges downstream of the Sebou River before and after the construction of dams

caused by the excessive use of water for irrigation during the drought period, the increase of evaporation caused by higher area of surface water, and the transfer of water to other regions.

### Sediment fluxes before construction of dams

Available data of suspended sediment in the Sebou basin are relatively abundant and cover a long period, but are far more fragmentary and discontinuous for the Moulouya River. The annual suspended sediment discharges and yields and the corresponding water discharges are summarized in Table 3. As this table shows, the mean specific suspended sediment yield of the Sebou River (995 t km$^{-2}$ year$^{-1}$) is four times higher than that of the Moulouya River (240 t km$^{-2}$ year$^{-1}$). This value is also higher than that estimated by Snoussi et al. (1990) for the Moroccan Atlantic rivers (750 t km$^{-2}$ year$^{-1}$) and by Probst and Amiotte-Suchet (1992) for the whole Maghreb region (610 t km$^{-2}$ year$^{-1}$). The Sebou River's exceptionally high sediment yield is the combined result of steep slopes that cause landslides and mudflows (Heusch and Milliès-Lacroix 1971), the erodible sedimentary rocks of its drainage area (Haïda 2000), as well as precipitation rates that are higher than in the Moulouya River. Thus, while it is clear that land degradation is in many ways a product of human activity, it is also significantly amplified by physical factors such as climate (Langbein and Schumm 1958; Fournier 1960; Wilson 1973; Janson and Painter 1974; Walling 1987; Snoussi et al. 1989), topography (Pinet and SouriSouriau 1988; Milliman and Syvitski 1992; Harrison 1994; Summerfield and Hulton 1994), soil erodability (Milliman et al. 1987; Hay 1998), and the local vegetation status (Douglas 1972).

### Impact of dams on sediment fluxes

The Sebou River basin provides an interesting case study for examining the effects of the construction of reservoirs on river sediment fluxes. Before the dam's construction (1940–1972), the average suspended sediment input of the Sebou River to the Atlantic Ocean was about 34×10$^6$ t year$^{-1}$. After construction of the Idriss 1$^{er}$ and Allal El Fassi dams (1973–1995), the suspended sediment flux was reduced by about 73%. In 1996, when the Al Wahda dam was completed, the sediment discharge measured at the downstream gauging station was no greater than 1.6×10$^6$ t year$^{-1}$. Hence, considering all the reservoirs (Fig. 4), more than 95% of the total sediment load has been trapped. In fact, the trap efficiency (TE) calculated for the dams built on the Sebou and its tributaries (Table 4) ranges from 85–99%, and their life-span (LS) from 42–540 years (Haïda 2000).

For the Moulouya River, construction of the Mohamed V reservoir and the increased frequency of droughts since 1980 has also led to a drastic reduction in sediment supply to the coast. Prior to the dam's construction, the Moulouya transported an average sediment load of 12×10$^6$ t year$^{-1}$ that could reach the coast. Unfortunately, no suspended sediment data below the dam are available. Nevertheless, assuming that the trap efficiency (TE) of the Mohamed V

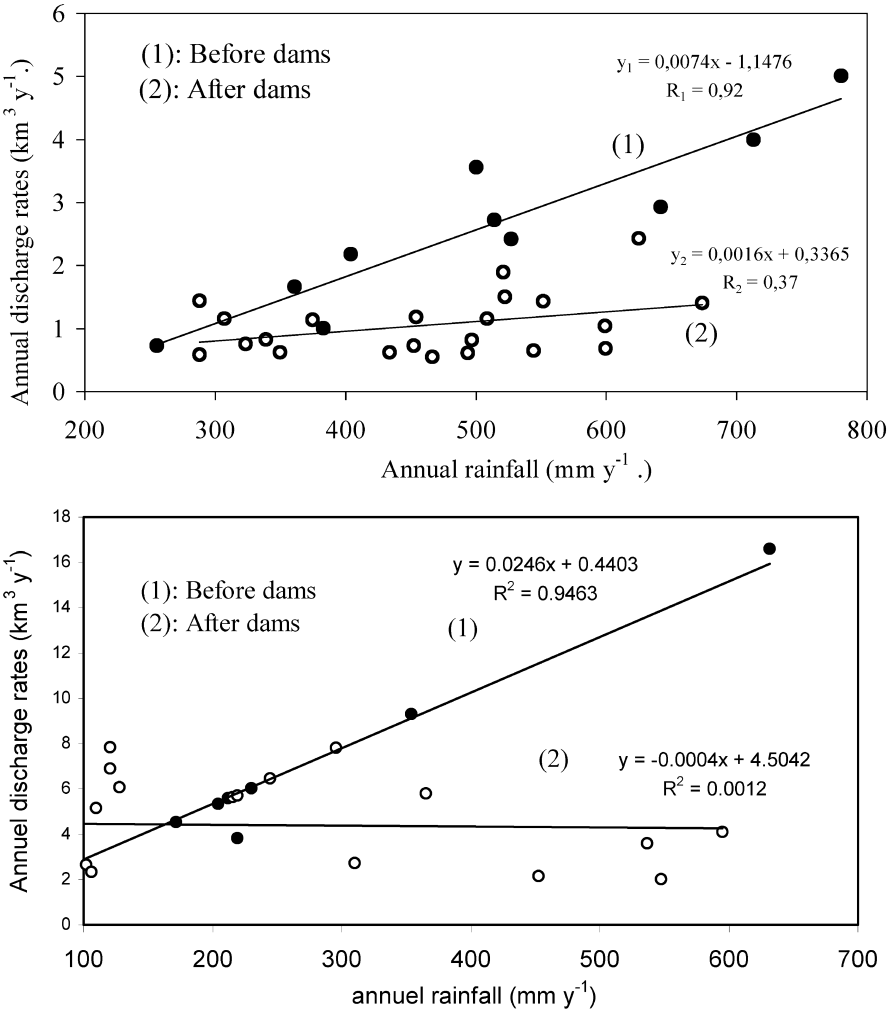



**Fig. 5**
Relationship between the annual water discharge and annual rainfall on the Sebou (*above*) and Moulouya (*below*) Rivers before (*solid circles* ) and after (*open circles*) the construction of dams

**Table 3**
Mean annual water and suspended sediment fluxes in the Sebou and Moulouya drainage basins

| River | Gauging station | Area (km$^2$) | Period of data | Mean annual w ater discharge ($10^6$ m$^3$) | Mean annual suspended sediment load and yield ($10^6$ t year$^{-1}$) | (t km$^{-2}$ year$^{-1}$) |
|---|---|---|---|---|---|---|
| Sebou | Mechra Bel Ksiri | 26,100 | 1940–1994 | 4,127 | 26 | 995[a] |
| Moulouya | Dar El Qaid | 24,422 | 1950–1988 | 700 | 7 | 287[a] |
| | Mohamed V dam | 49,920 | 1961–1990 | 1,000 | 12 | 240[b] |

[a]From measured values
[b]From the reservoir sedimentation rate

dam is about 93% (Table 4), we can estimate that today the Moulouya River delivers to the Mediterranean Sea only 7% of the load transported before it was dammed. However, this value is certainly an underestimation, because the calculations do not take into account the different flows released downstream during the flooding periods. The estimated time it takes to fill the reservoir with sediment is only 59 years. Indeed, between 1967 and 1991 the dam lost 35% of its storage capacity (Lahlou 1996). The high rate of dam siltation is a result of a high denudation rate that also causes a serious loss of arable lands. In the Moulouya River basin, it is estimated (Ministère de l'Agriculture 1997) that by the year 2030, 70,000 ha of irrigated land and 300 million kWh of electricity will be lost.

The short life-span of all the reservoirs means that soil erosion and dam sedimentation are serious problems in Morocco.

## Potential changes in coastal morphology in relation to the construction of dams

Sediment trapping by reservoirs can also affect the morphological evolution of the coastline. A comparison of two sets of aerial photographs (1958–1988) of the Moulouya

**Table 4**
Trapping efficiency (*TE*), residence time ($\Delta\tau$) and life-span (*LS*) calculated for the reservoirs. *D* Date of hydropower dam operation; *S* surface area regulated by dam; *C* reservoir capacity; *A* inflow volume

| Rivers | Dams | D | S ($km^2$) | C ($km^3$) | A ($km^3\ year^{-1}$) | $\Delta\tau$ (years) | TE (%) | LS (years) |
|---|---|---|---|---|---|---|---|---|
| Sebou | Allal El Fassi | 1990 | 5,400 | 81.5 | 750 | 0.11 | 85 | 42 |
| Ouerrha | Al Wahda | 1996 | 6,190 | 3,800 | 2,564 | 1.48 | 96 | 374 |
| Inaouene | Idriss 1[er] | 1973 | 3,680 | 1,800 | 700 | 2.57 | 99 | 540 |
| Beht | El Kansera | 1935 | 4,542 | 266 | 372 | 0.71 | 94 | 195 |
| Moulouya | Mohamed V | 1967 | 49,920 | 490 | 903 | 0.54 | 93 | 59 |

coastal plain (Zourarah 1994; Zarki 1999) lead to the examination of the potential effects of the construction of the Mohamed V dam on the shoreline morphology.
Before the dam was constructed (1958), the lower Moulouya River pattern was sinuous to meandering and the river's mouth was much wider than it is today (Fig. 6). The fluvial load was significant enough to lead to the progradation of deltaic deposits in the eastern part of the river's mouth. After construction of the Mohamed V dam, the river's mouth and the coastline reacted with remarkable adjustments. Indeed, given the weak fluvial hydraulic power, the marine influences have been reinforced, leading to the reworking of the shoreline sediments, narrowing of the mouth area, and the accumulation of mouth bars.
According to Zourarah (1994), the most effective waves and the induced sand transport are directed westwards. The net littoral transport was estimated at approximately 165,000 $m^3\ year^{-1}$. The sand transported was responsible for the accretion of the west coast, whereas the east coast retreated because it was not fed by fluvial inputs.
Regarding the evolution of the Sebou coastal plain, it is more difficult to link the shoreline's evolution to the river damming activities, since the causes of this evolution are manifold and affect the coast at different rates and times. Indeed, besides the fact that the Sebou River is heavily regulated (78%), the huge population moving from the country to the coastal towns, the development of beach tourism, sand extraction for construction purposes, the construction of the port and related defensive structures, combined with the presumed sea-level rise have all interfered with the river basin activities and deeply altered the natural evolution of the coast.
According to investigations conducted for the Sebou (Project Sebou 1970) (i.e. before the large dams' construction), it is estimated that an average of 700,000 $m^3$ of fluvial sediments were deposited annually within the estuary, considerably constricting navigation and necessitating costly dredging operations. Nowadays, due to dams impoundment, the fluvial competence has become very weak and the estuary is not flushed as frequently as before.

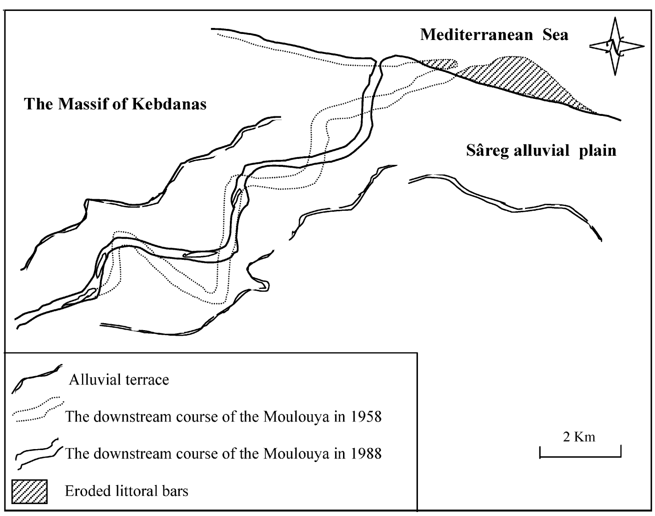



**Fig. 6**
Historical evolutions of the lower course of the Moulouya River and of the coastal morphology. (Modified from Zourarah 1994)

## Conclusion

Dams obviously have many socio-economic benefits for Morocco, since rainfall is scarce and concentrated over a few days and agriculture constitutes a large percentage of the Moroccan economy. However, due to the high rate of natural and man-induced soil erosion, and given their reduced design capacities and short life-span, doubts have been raised as to the long-term sustainability of these dams. A consequence of the damming activities is the sharp reduction of water and sediment fluxes of rivers to the coasts. It is estimated that the water discharge of the Sebou and the Moulouya Rivers has been reduced by 70 and 47% respectively, and their sediment fluxes by nearly 95 and 93%.
During the last decade, the recurrence of droughts has exacerbated the reduction of water flows into and below the reservoirs. By reducing the supply of rivers, dams may also affect the shoreline's morphological equilibrium. It seems that the coastal erosion/sedimentation is mainly due to the impoundment of flow discharges that modify the estuarine circulation and strengthen the marine influence. This behavior was also noted by Barusseau et al. (1998) for the Senegal River after the construction of Diama dam.

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