I - Executive Summary

This synthesis, outlined during the meeting, is based on inputs received thereafter from all the workshop participants, with particular mention to Wolfgang Ludwig, John Milliman, Michel Meybeck, Michael Collins, Serafim Poulos and Oya Algan. The final editing was carried out by Maria Snoussi and Frédéric Briand, with Valérie Gollino overseeing the physical production process.

1. INTRODUCTION

This workshop, the 30th in a long series, took place from 29 March to 1st April 2006 in the historical city of Trogir on the Dalmatian coast. Fourteen scientists from eleven countries attended the meeting at the invitation of CIESM. They were warmly welcomed by Frederic Briand, Director General of the Commission, and by Maria Snoussi, Chair of the Committee on Coastal Systems, who presented the main objectives of the seminar, and expressed their appreciation to Goran Kniewald, Croatian Representative of Croatia on CIESM Board, for his valuable logistic assistance.

1.1. Peculiarity of the Mediterranean and Black Sea rivers

The 30th CIESM Workshop focused upon the rivers of the Mediterranean and Black Seas and their roles in the formation and maintenance of coastal zone areas that are directly and/or indirectly influenced by riverine water/sediment fluxes. Special emphasis was given to medium and small rivers, that is those rivers that drain catchments <5,000 km^2. In the past, many investigations have concerned catchments >10,000 km^2. Because of their relative abundance, their strong relief in their hinterlands (Figure 1), as well as their highly variable runoff (from arid to humid watersheds) and response to episodic events, medium and small rivers play particularly crucial roles in the overall material transport to the Mediterranean Sea.

Fig. 1. Terrestrial drainage basin of the Mediterranean Sea (modified from Poulos and Collins, this volume).

The importance of medium and small rivers in the Mediterranean region can be illustrated by Figure 2a, in which it can be seen that global rivers with drainage basins <50,000 km^2 account for only 30% of the global area, whereas in the Mediterranean (excluding the Nile River, whose discharge has been effectively blocked by the Aswan Dam) they account for 70% of the cumulative drainage area. Reliable budgets for the overall inputs of riverborne materials to the Mediterranean Sea are, hence, more difficult to obtain than for the world oceans. It requires the monitoring of numerous small rivers, in order to obtain representative shares of the overall drainage basin covered by the observations. Moreover, the smaller basins are less represented in compilations of river data (Figure 2b), meaning that extrapolations to regional scales can be biased towards larger basins. This limitation can considerably influence sediment budgets, since small mountainous rivers often have high sediment yields, seasonal freshwater fluxes, and are more responsive to episodic flooding events (Milliman and Syvitski, 1992). Moreover, discharged sediment is more likely to escape the narrow shelves and deposited into the deeper basins (see also Ludwig *et al*., this volume).

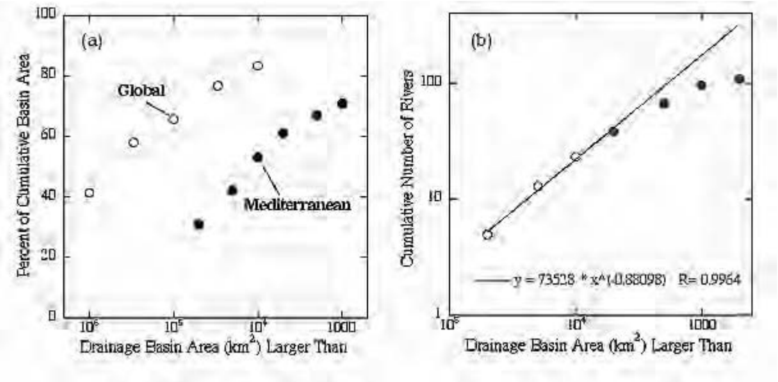

Fig. 2. Percentage of cumulative basin area (a) and cumulative number of rivers (b) towards decreasing minimum basin size for Mediterranean rivers (compilation of 125 rivers based upon data of the Workshop Participants). In b), the black trend line is based upon the cumulative number of rivers with 50, 20, 10 and 5 thousand km^2 basin areas. The trend begins to differ from the data set for rivers <5,000 km^2. Using the equation in the graph one can estimate how many Mediterranean rivers have basin areas greater than any particular number. Basins greater than 1,000 km^2, for example, should be about 167, whereas the data set only includes 99.

1.2. Formation and evolution of the coastal zone, in relation to rivers

River systems play a major role in the formation and evolution of the coastal zone, as they are the principal sources of sediment. Their importance depends primarily upon their sediment fluxes and the oceanographic conditions of their receiving basin. River-influenced sections of coastal zones are related to the seaward progradation of land, which can involve delta formation. However, their effect can be extended many kilometers from their mouth area, thereby influencing much of the continental shelf.

The coastal zone is defined as a strip of land and sea territory of varying width, formed by the interaction of terrestrial, marine and atmospheric processes (Carter, 1988). Furthermore, the role of the coastal zone has been recognized as a buffer in: (a) providing a filter, to remove pollutants and other material transported from the hinterland, before they enter the coastal ocean; and (b) protecting the upland areas from storms and flooding, originating from the sea. Finally, the natural boundary between the terrestrial and marine coastal zones (the coastline) changes constantly, in response to terrestrial and marine processes, incorporating any anthropogenic interference. However, within the context of the present investigation, the broader term coastal system is introduced (IGBP, 1993; Briggs *et al*., 1997); this is in order to accommodate a much larger geographical area (i.e. river catchment), where terrestrial environments (terrestrial sub-system) influence marine environments (oceanic sub-system), and vice-versa. The terrestrial sub-system acts mainly as the provider, e.g., water and sediment fluxes, whilst the marine sub-system plays primarily the role of the receiver. The terrestrial environment is related to the weather conditions of the region, as they are affected by climatic conditions (precipitation, air temperature); these, in turn, determine vegetation cover and the type of weathering of the hinterland. Furthermore, the oceanic sub-system is involved in the morphometric formation and evolution of the coastline, by: (a) affecting the seaward dispersion and deposition of the riverine suspensates (near shore current and wave activity); (b) participating in the formation and preservation of the estuarine and lagoon environments; and (c) being the controlling influence on the fate of the coastal aquifers (Poulos *et al.*, 2000; Poulos *et al.*, 2002).

2. Spatial and temporal variability of the Mediterranean fluvial and coastal systems

2.1. Geography and regional sub-units

The Mediterranean Sea covers about 2.5 million km^2, with an average water depth of about 1.5 km. It is divided commonly into ten sub-basins, which are shown in Figure 3 and listed in Table 1. The length of the Mediterranean coastline totals about 46,000 km, of which 19,000 km represent island coastlines. The entire coastal region covers an area of nearly 1.5 million km^2, that is 17% of the total area of the bordering countries: Spain, France, Monaco, Italy, Slovenia, Croatia, Bosnia and Hercegovina, Montenegro, Albania, Greece, Turkey, Cyprus, Syria, Lebanon, Palestinian Territories, Israel, Egypt, Libya, Malta, Tunisia, Algeria and Morocco.

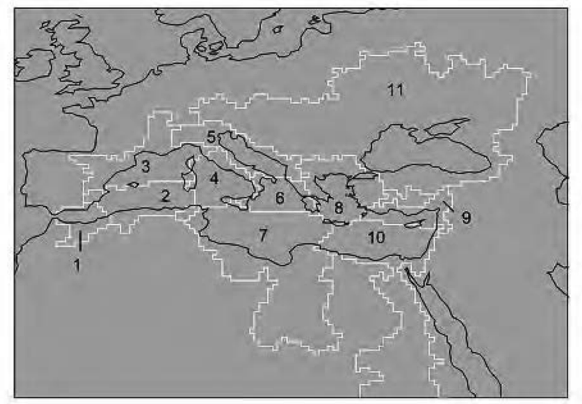

Fig. 3. Drainage basins of the 10 Mediterranean sub-basins, in comparison with the drainage basin of the Black Sea (derived from Doell and Lehner, 2002). For the basin names corresponding to the numbers, see Table 1.

Excluding the Nile River drainage basin, which accounts for nearly 3 million km^2 but is almost completely disconnected from the Mediterranean Sea since the construction of the Aswan High Dam in 1964, the cumulative terrestrial watersheds draining into the Mediterranean Sea represent ~2.5 million km^2. Subtracting also the area of the Central Basin, which is a potential drainage basin and nowadays almost entirely arheic, this value reduces to about 1.4 million km^2. The ratio of the terrestrial over the marine basin area is, hence, about 0.55. This ratio, which provides a rough idea about the potential influence of the terrestrial inputs on the functioning of the coastal and marine systems, is highly variable on the level of the individual sub-basins (Table 1). The greatest value is observed for the Adriatic Sea (1.80), whereas the lowest value is found for the Ionian Sea (0.37).

For the Black Sea, the ratio of the terrestrial over the marine basin area is greater than 5 and therefore very different. Its drainage basin is much larger than that of the Mediterranean (without the Nile), although its sea surface covers only about one-fifth (Table 1). This may explain in part why biological productivity in the Black Sea ecosystems is so much greater than in the Mediterranean.

2.2. Large-scale circulation and basin internal water exchanges

The Mediterranean receives oceanic water from the Atlantic Ocean through the Strait of Gibraltar and into the eastern Mediterranean through the Sicily Straits (Robinson *et al.*, 2001). Because evaporation exceeds precipitation, the Atlantic Water becomes progressively warmer and saltier as it flows eastward into Eastern Levantine Basin, where it becomes Modified Atlantic Water (Malanotte-Rizzoli *et al.*, 1996). Intense evaporation in winter and heat loss under surface winds

Table 1. Terrestrial drainage basin and sea surface areas in the Mediterranean and Black Seas, according to Figure 3 (W. Ludwig, pers. comm.).

basin name	abbrev.	no.	drainage basin area (106 km2)	ocean basin area (106 km2)	land / ocean ratio
Alboran	ALB	1	111	76	1,46
South-Western	SWE	2	129	270	0,48
North-Western	NWE	3	311	252	1,23
Tyrrhenian	TYR	4	112	242	0,46
Adriatic	ADR	5	235	131	1,80
Ionian	ION	6	68	184	0,37
Central	CEN	7	1135	606	1,87
Aegean	AEG	8	286	202	1,42
North-Levantine	NLE	9	131	111	1,18
South-Levantine	SLE	10	3010	436	6,91
Total Western	WMED		662	840	0,79
Total Eastern	EMED		4864	1669	2,91
Total	MED		5526	2508	2,20
Black Sea	BLS	11	2398	460	5,21

change this Modified Atlantic Water into the Levantine Intermediate Water, which is more saline and denser, causing it to sink to depths of 300 to 500 m. This dense water then moves westward from the Northeastern Levantine, crossing the entire Mediterranean, and exiting the Strait Gibraltar as dense bottom water. As the water masses formed in the northwestern Mediterranean (e.g., Gulf of Lions) are confined in the western basin in the layers below 2,000 m, the Eastern Levantine Sea is the "engine" that drives the upper Mediterranean water system (Malanotte-Rizzoli *et al*., 1996). The Aegean Sea provides a warmer, more saline, and denser deep-water mass than the previously existing Eastern Mediterranean Deep (and bottom) Water (EMDW), of Adriatic origin (Robinson *et al*., 2001). Its overall production was estimated for the period 1989-95 at more than 7 Sv, which is 3-fold higher than that in the Adriatic. In the southern Aegean, warmer and more saline Cretan Intermediate Water is formed and exits the Aegean mainly through the western Cretan Arc Straits and spreads in the Levantine Intermediate Water horizons, blocking the westward route of the LIW (Robinson *et al*., 2001).

Two marginal/land-locked seas, the Black and the Marmara Seas, constitute the eastern, extension of the Mediterranean Basin. The Black Sea has an approximate surface area of 435,000 km^2 and a volume of 537 km^3. The Danube River contributes about 200 km^3 of water discharge, which is more than the entire freshwater supply to the North Sea (Mee, 1992; NATO-CCMS, 2000). This large amount of freshwater input (~350 km^3/y) and precipitation (~300 km^3/y vs. evaporation of ~350 km^3/y) maintains a low-salinity surface layer in the Black Sea. This leads to greater outflow through the Istanbul Strait than the mass of saline Mediterranean water entering northward as an undercurrent inflow into the Black Sea (Ünlüata *et al*., 1990). The average fluxes at the Black Sea end of the Istanbul Strait are about 600 km^3/yr (outflowing from the Black Sea) and 300 km^3/yr (inflowing into the Black Sea), respectively. Approximately 650 km^3/yr of Black Sea water enters the Marmara Sea from the Istanbul Strait and 550 km^3/yr of Mediterranean water enters from the Çanakkale Strait. About 25 % of the Mediterranean water influx is entrained into the upper layer at the Istanbul Strait, whilst about 7 % of the Black Sea water is entrained into the lower layer. 45 % of the Mediterranean inflow is entrained into the upper layer in the Çanakkale Strait, and another 45 % of the amount reaching the Marmara is lost to the upper layer, by basin-wide entrainment (Beiktepe *et al*., 1994).

The water budget of the Mediterranean Sea is in deficit and is estimated at about 1.6 Sv (Bethoux and Gentili, 1999). The saline and warm Mediterranean outflow is about 0.7×10^6 m^3 s^{-1} (Bryden and Kinder, 1991). Black Sea outflow constitutes 20 % of the freshwater input into the eastern basin (0.11 m) (Bethoux and Gentili, 1999). A change in the Black Sea outflow thereby could change the water budget of the Aegean Sea, together with dense water formation in that area.

2.3. Climate and water resources

Climatically, the Mediterranean is characterised by generally warm temperatures, winter-dominated rainfall, dry summers, and a profusion of microclimates, reflecting local environmental conditions. Lowest temperatures of <5 °C are found in the higher parts of the Alps, whereas temperatures of >20 °C are typical for Libya or Egypt. Mean annual precipitation also shows a north to south gradient, with decreasing values towards the south. However, orography is a dominant factor. Precipitation exceeding 1,500-2,000 mm/yr is seen in the Alpine and Pyrenean headwater regions of the Po, the Rhone and the Ebro Rivers; it is common also in the mountains bordering the Dalmatian coast, from the Istrian Peninsula down to Albania. As a result, these countries are the most humid regions in the entire Mediterranean area.

The strong summer-winter rainfall contrast is one of the major characteristics of the Mediterranean climate. This contrast becomes increasingly pronounced to the south and to the east. Precipitation falls mainly during winter and autumn, being often less than 10% of the annual precipitation occurring during summer. This pattern contrasts starkly with the continental climate in the drainage basin of the Black Sea, where most of the precipitation occurs during summer (Ludwig *et al*., 2003). During spring, the rainfall contribution to the mean annual precipitation is quite homogenous throughout the entire Mediterranean region. High precipitation during autumn is typical for the coasts of Spain, France, Italy, Slovenia, Croatia, Bosnia and Hercegovina, Montenegro, Albania and Greece. Farther east, such as in Turkey and in Lebanon, autumn precipitation is much less important, with most of the rainfall occurring in the winter.

In certain regions, precipitation - especially in autumn - can occur as heavy downpours, leading to violent flash-floods. The most likely areas for flash-floods are the Côte d'Azur, east Pyrenees, Cevennes and Corsica in France, the north-western areas of Italy, and Catalonia and Valencia in Spain (Estrela *et al*., 2001).

2.4. Hydrological regimes

Due to the strong seasonal contrast of climate as well as their generally small drainage basins, Mediterranean rivers exhibit a rather unique hydrologic character. In the southern part of the Mediterranean, the differences between low and high water discharges can be extreme, with most water discharges often occurring during short floods. In some areas along the Mediterranean coast, the recorded maximum daily rainfall is near the mean annual rainfall (Estrela *et al*., 2001). In contrast, in the larger river basins in the north, wide-ranging and continuous precipitation is commonly the main factor in flood generation, associated often with snowmelt.

As a consequence, the ratio of peak discharge to mean annual discharge in drainage basins of 1,000 to 10,000 km^2, is frequently about one order of magnitude greater than for rivers in non-Mediterranean areas. This relationship represents also a major difficulty in the monitoring of these rivers, as gauging stations must be calibrated for extreme events and the equipment also must resist violent flash-floods. Monitoring of water quality parameters, as far as they can be used in calculating fluxes, is even more difficult; this is so since almost all of the transfer occurs during these floods. As a result, flash-floods often escape regular sampling programs.

Most Mediterranean rivers have their lowest discharge values during summer (July to September), the result of strongly reduced precipitation and elevated temperatures. Maximum discharge normally occurs between February and May. The February maximum is typical for the rivers that are precipitation-dominated (such as the Tiber and Arno Rivers), since precipitation is strongest in winter (see above). When the headwaters are in higher elevations, which often is the case, snowmelt discharge becomes dominant. This delays the maximum discharge to April or May (e.g., the Drini or Ceyhan Rivers). It also should be pointed out that the accentuation of the seasonal contrast towards the south and the east has, naturally, also a strong impact on the rivers in these areas. Almost all of the discharge occurs during the first half of the year, whereas the second half is very dry (e.g., Moulouya and Ceyhan Rivers).

2.5. Water and sediment discharges

Water discharge plays a key role in the transport of riverine matter to the sea. Summing up the overall freshwater inputs that are brought to the Mediterranean and Black Seas by rivers, yields a value of about 1,000 km^3/yr (see Poulos and Collins, this volume); 40% is discharged by the Black Sea rivers. However, these values rather reflect potential values, since they do not take into account the steady decline in water discharge due to climate change and anthropogenic water use (Figure 4a). Present-day freshwater discharge to the Mediterranean Sea may be only half that what it was 100 years ago (Ludwig *et al*., 2003). The decrease was accentuated especially after the 1970s, with strongest reductions in the Alboran and Aegean Seas (Figure 4b).

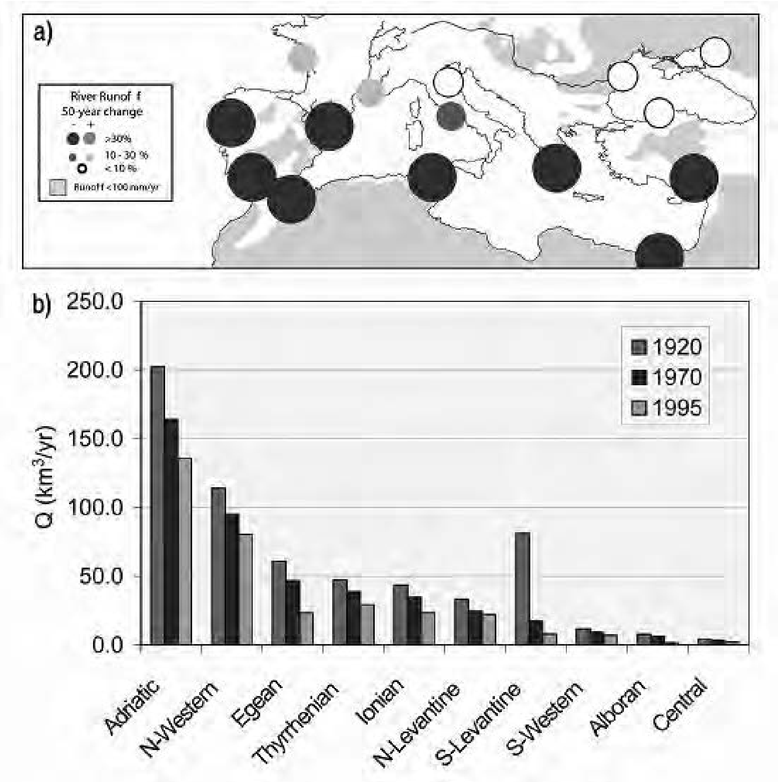

Fig. 4. Evolution of freshwater inputs to the Mediterranean Sea, during the 20th century. a) reduction of water discharge in some Mediterranean rivers – see Milliman, this volume; b) estimated freshwater inputs according to Ludwig *et al.* (2003).

Sediment fluxes are the second key parameter controlling the riverine transfer of terrestrial matter to the sea. Because of the strong seasonality in climate, the presence of elevated mountain ranges, the relative small basin sizes, the wide dominance of younger, softer rocks, and a long history of human activity, Mediterranean rivers tend to have high natural sediment yields, compared to global averages. Collins and Poulos (this volume) estimate that the natural sediment discharges by rivers may be in the range of 1,000 Mt/yr for the Mediterranean Sea, and about 300 Mt/yr for the Black Sea. Because of the massive construction of reservoirs, however, not all of these sediments reach the sea and at least ~45% (Mediterranean) and 30% (Black Sea) of these sediments might be retained behind dams or extracted from the river beds, for sand and gravel.

In Table 2, small (<500 km^2) and medium (500-5,000 km^2) catchments are shown to represent >40% of Mediterranean's drainage basin, when the catchment of the Nile is excluded. Even before damming, however, the Nile provided only 16% of the annual water budget and only 10% of the sediment load, due to its very low precipitation and low sediment yield (42 tons/ km^2). In contrast, the small and medium-sized catchments provide annually >40% of the freshwater inputs and >50% of the total sediment load; the latter is due to the high sediment yields (1,500-2,200 tons/ km^2, on average).

Table 2. Different sized drainage basins of the Mediterranean river systems.

	Catchment (10^3 km^2)		Water discharge [(a)] km^3/ year	Sediment yield [(b)] tons/km^2
Size	Including Nile	Excluding Nile		
<0.5	460 (36.8%)	460 (11.2%)	250.5 (43.9%) [(c)]	1554 (8)
0.5-5	70 (5.6%)	70 (1.7%)		2200 (18)
5-50	380 (30.4%)	380 (9.2%)	101.2 (17.8%)	570 (22)
50–500	340 (27.2%)	340 (8.3)	128.3 (22.5%)	251 (4)
Sub-total:	1,250 (100%)	1,250 (30.3%)	480.0 (84.2%)	
>500 (Nile)		2,870 (69.7%)	90.0 (15.8)	42 (1)
TOTAL:		4,120 (100%)	570.0 (100%)	

Keys: (a) Poulos and Collins (this issue); (b) for the rivers >500 km^2 data are abstracted from Ludwig *et al.* (2003) and for those with catchment <500 km^2, from Poulos and Collins (2002b). In parentheses, the number of rivers used for the calculations is given. The value given in (c) corresponds to rivers with catchments <5,000 km^2 (small and medium).

3. HUMAN IMPACTS ON THE CATCHMENT-COAST *CONTINUUM*

Coasts and river basins, small or large, incorporate important natural environments; they are used also intensively by mankind. Indeed, Mediterranean civilisation has always flourished beside the sea and in nearby river basins. The increasingly intensive human presence over almost 10,000 years has changed radically the landscapes around the Mediterranean. Although these changes vary between the countries, because of differences in geography and in socio-economic conditions, they have altered the flux of materials to the coast, with impacts on coastal morphology (sediments) or the ecosystems (nutrients and contaminants) (Poulos and Collins, 2002b; Ludwig *et al*., 2003; Meybeck *et al*.; Milliman; Simeoni *et al*., this volume).

This alteration is more visible in small and medium-size catchments, than in the large catchments, where the “buffer capacity“ against land-based change is higher.

3.1. From natural to impacted river-basins

Figure 5 represents, schematically, (i) a catchment-coast system under natural conditions, a system impacted by (ii) climate change and sea-level rise and (iii) by human activities.

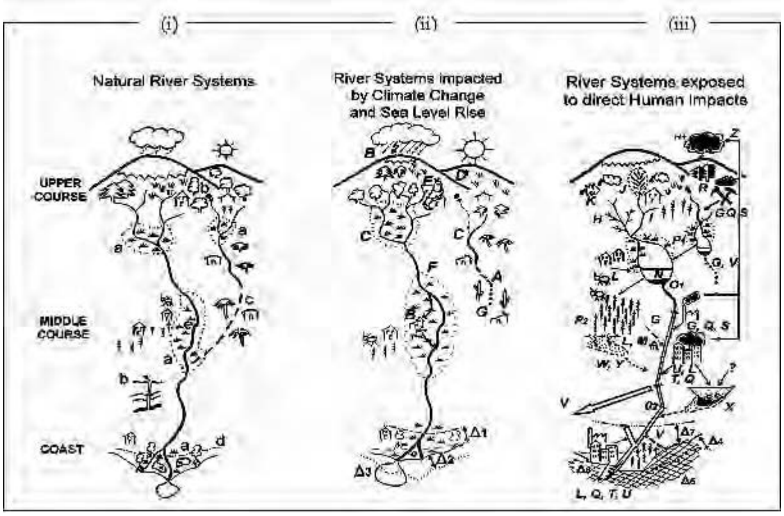

Fig. 5. Schematic analysis of the evolution of river systems under Climate Change and Sea Level Rise and under direct Human Impacts (Meybeck, 2006a) (for explanation, see text).

Under natural conditions, headwaters generally provide most of the riverborne material, particularly the suspended particles; this is eventually processed and/or deposited in wetlands (a), floodplains (e) and deltas. If part of the Mediterranean drainage basin is under a dry climate (c), this leads to seasonal drought. In the estuarine zone, water quality issues are linked mostly to the natural salt-wedge intrusion (d).

Under changing climate conditions, two main scenarios may occur. If the climate is more humid, wetlands (C) and extension of floodplains (F) may increase, threatening crops (B). Erosion and river sediment transport can be affected by increased landslides (E). If the climate is dryer, vegetation and land cover changes (D) will affect river chemistry and solid transport; this is particularly true if the precipitation regime is more irregular. Some tributaries can be cut-off from the main river course. In the estuarine zone, the sea level rise may lead to coastal erosion (Δ2), and to increased salt intrusion (Δ1). Increased upstream erosion could favour higher river solid transport to the sea (Δ3). These long-term changes have actually been observed in southern Mediterranean river systems, from the Maghreb to Turkey, over the last 6,000 years (when the Lower Nile tributaries were still active).

In an anthropogenically-influenced system, forest cutting (K) in the upper river catchments favours land sliding and gullying (J) whilst land use change is associated with moderate water quality issues under rural conditions (I). Wetland drainage (H) is common and may limit these natural filters. Mountain reservoirs (N) may store river particulates, or be exposed to nutrient loadings (L) and become eutrophicated. They may also be part of important water transfers (P), from one catchment to another, particularly for irrigation. Urban, industrial and mining emissions (G, Q, S) to the atmosphere may result in important pollution sources to the catchments soils and to the coast and to acid rainfall (Z) as well, which lead to forest die-back (R). Weathering and erosion of mine tailings, of various ages, may release slowly heavy metals into the aquatic systems. Other pollution sources include: agricultural soil leaching (L, M) and polluted ground waters inputs (W, Y); industrial urban wastewaters, discharged into rivers systems or to the coast (L, Q, T, U); and leakage of old waste dumps (X). The river course is also very much modified, through channelisation (O1-O2), sluice construction, dredging and artificialisation of river courses, from the middle river courses to the estuarine zone (V). Coastline erosion (Δ4) and salt wedge intrusion (Δ7) can be enhanced. The coastline can be artificialised (Δ6) and coastal sediments be contaminated (Δ5).

This diagram shows the complexity and the spatial interaction and inter-connectivity of all parts of the catchment-coast system. Coastal impacts are related generally to more than one pressure, either on the adjacent drainage basin, or directly on the coast.

Differentiating human-induced changes from naturally-forced changes is often difficult (Crossland *et al.*, 2005). It is more difficult in the Mediterranean catchment, as the human activities are among the oldest in the world (Meybeck *et al.*, this volume).

The main coastal impacts related to river-drainage changes and to climate change are presented in Table 3.

3.2. Coastal impacts related to river-basin changes

3.2.1. Deforestation / forestry, agriculture

The largest human modifications to vegetation cover and consequently sediment transport to the ocean, are from deforestation; this, in the Mediterranean region, dates from two millennia before present (Liquete *et al.*, 2004). According to the FAO (Food and Agriculture Organization, 2001), in recent years the overall deforestation rate in North Africa and the Near East has been greater than that of the tropical world (more than 1%, compared with 0.6%). In the European countries (excluding the Russian Federation), with a few rare exceptions such as Albania, due to very strict regulations the forest areas have increased over past decades. The annual growth rate did reach, or even exceeded, 1% for those countries in the Mediterranean area.

Many small and medium-size river catchments, especially those located in semi-arid regions, are presently undergoing important erosional problems; these are caused by the combination of insufficient vegetation cover, soil composition, steep slopes, and inappropriate agricultural

Table 3. Main impacts of river drainage changes and climate change on the coastal areas (Meybeck, 2006a).

A) River drainage changes	**Coastal impacts**		
	Morphology	**Food webs**	**Users**
Enhanced river fluxes			
Increased sediment supply	Increased siltation Accretion of deltas	Increased siltation	Need for channel protection and maintenance
Increased toxic fluxes		Degraded food webs	Loss of marine bioresources
Increased Nutrients		Eutrophication (harmful algal blooms)	Threats to tourism and food security
Episodic coliform inputs			Short-term beach access closure
Increased Organic Carbon		Increased heterotrophic food webs	Loss of seawater transparency
Changes in Redfield ratios		Food web changes (diatom loss)	Loss of bioresources
Retention of river material			
Sediment retention	Sediment starving Coastal erosion		Unsustained beaches and need for protection
Water flow reduction		Oligotrophication of estuarine food webs	Lack of water for delta/coast users Salt intrusion
River/habitat destruction		No migrating species	Loss of bioresources
Delta			
Water/gas extraction	Delta subsidence		Inundation (human safety) Salt intrusion
Artificial delta/habitat destruction	Loss of vegetal protection, against coastal erosion Dune loss/Movement	Limits to aquatic species	Loss of biodiversity
B) Climate changes			
Sea level rise	Coastal erosion maximum in deltas		Inundation Sea salt intrusion
Precipitation regime change/ Dryness	Long term changes in sediment supply	Long term changes in C and nutrient supply	Summer heat waves Floods
Global warming	?	Invasive species	
Sea storminess changes (wave pattern)	Coastal erosion		Risk of inundation and destruction of coastal infrastructures

practices (Ben Mammou; Boumeaza; Touaibia, this volume). It has been estimated that around 75% of the average sediment yield of the Mediterranean headwater river basins may be attributed to human activity (Dedkov and Mozzherin, 1992), mainly deforestation and intensive agriculture. These activities, over hundreds of years, have increased the sediment supply to the coast, prograding most of the deltaic coasts around the Mediterranean.

3.2.2. Damming and irrigation

Globally, more than 3500 small (height >30m) and high (height >60m) dams, devoted to hydroelectrical power production, irrigation, and flood control, together with millions of small hill reservoirs, are in operation in the Mediterranean catchment; they reduce the original natural drainage basin area by some 78% (Poulos and Collins, 2002b). According to the conclusions of Ludwig *et al*. (2003), the overall reduction of the riverine sediment discharge to the Mediterranean Sea may as great as 75% in comparison with the beginning of the 20th century. This means that probably only 25% of sediments actually enter the marine realm every year.

Even if the most impressive cases reported in the literature are those of the large rivers, such as the Nile and the Ebro, where dams trap respectively nearly 98% (Abdel Moati, 1999) and 99% of the solid discharge (Ibañez *et al*., 1996), some smaller rivers show the same percentage of sediment reduction, due to dams (e.g. the Moulouya 95%, Snoussi *et al*., 2002) and Tunisian rivers (Ben Mammou, this volume).

Moreover, due to the high rates of natural and man-induced erosion that characterise many Mediterranean hinterlands, the rapid silting up of reservoirs limits their storage capacity and their lifespan (e.g., dams in Algeria have lost a quarter of their original capacity (www.planbleu.org), whilst the Mohammed V dam on the Moulouya River will fill with sediments within 59 years, having lost nearly 50% of its storage capacity (Snoussi *et al*., 2002). The sediment trapped is abstracted from the coastal budget, leading generally to coastal retreat. Coastal erosion linked to damming is reported in many Mediterranean catchment-coast systems (Ben Mammou; Boumeaza; Simeoni *et al*., this volume). Pressures on water resources will increase significantly in the South and East of the region. Under such conditions, the construction of more dams is likely to have serious environmental and related societal impacts on the coastal zone.

3.3. Coastal impacts related to global/regional changes

3.3.1. Climate change

Climate change will affect the hydrological cycle and sea level, which in turn can be leading factors on shoreline morphology such agriculture, ecosystems and biodiversity. Most of the present climate models in the Mediterranean area indicate increased dryness occurring more often, or longer-lasting dry spells under doubled CO_2 conditions (UNEP/MAP, 2001). Impacts on water resources will be stressed in Southern Europe, North Africa and the Near East where water availability is low. These impacts include: increase of pollutant concentrations, due to decrease of run-off; reduction of the auto-purification capacity of the small rivers; increase of lakes and groundwater salinity, due to global warming; and higher evaporation and sea-level rise. In contrast, over the northern part of the Mediterranean basin, increases in rainfall patterns, during winter and spring, may lead to some extreme events, whereas summer heat waves can have severe implications on forest fire occurrence.

Within the marine realm, Mediterranean ecosystems are also very vulnerable to global warming. Changes in sea-surface temperature, salinity, chlorophyll and nutrient concentration interact with the thermohaline circulation which, in turn, induce significant local changes. Sea-level rise and increased storminess could cause impacts such as: submersion of sensitive deltas and low-lying lands; erosion of fragile coastlines; and salinisation of ground waters and soils, causing severe losses to agriculture.

3.3.2. Population growth and coastal urbanization

The Mediterranean coastal area is one of the most heavily populated regions of the world. The population of Mediterranean countries is expected to follow significant growth rates, from 356 million in 1985 to 520-570 million in 2025. Likewise, the coastal population is expected to increase, from 133 million to 195-217 million, in 2025. It should be noted that future projections show major differences between the North and the South, with the European countries having a nearly stable population, whilst the southern and eastern countries are expected to experience significant population growth (Figure 6).

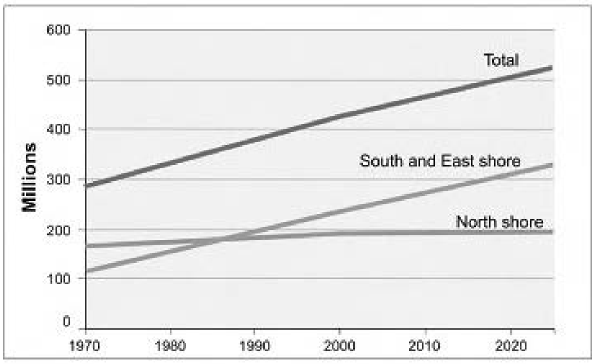

Fig. 6. Population growth in the Mediterranean northern- and southern-rim countries, 1970-2025 (Attané and Courbage, 2001).

The baseline scenario of the Blue Plan (www.planbleu.org) projects by 2025 significant increase in coastal pressures with:

– coastal city populations rising from 70 million in 2000, to 90 million in 2025;

– 312 million tourists in the coastal areas compared with 175 million in 2000, a density per km of coast which could triple in the South and East; and

– the most significant risk is the saturation of coastal areas and the additional artificialisation of 4,000 more km of coastline (reaching 50%, in 2025).

These projected pressures will lead to an increasing competition for space and natural resources, both on land and at sea. Conflicts and interferences between different uses will be reinforced by the seasonal variation in human pressures, with the highest number of people generally present in summer. At this time, the local populations are multiplied by millions of external tourists, when the water availability is at it lowest.

In summary, it is likely that changes in land cover and use, combined with changes in climate conditions and population growth, will have more visible impacts in small to medium Mediterranean catchments; this is due to the shorter time frames which they need to translate these catchment changes into coastal response, compared to large catchments.

4. Recommended needs and research agenda

– Creation of a Mediterranean Database on river fluxes, delta morphology, human impacts, dams, water uses, etc.

– Establishment of a network of Case Studies, based upon the availability of terrestrial and marine long-term data sets/including human impacts and existing national expertise. A network of medium-sized catchments in which the complex human-river relationships can be deciphered, and possibly, modelled is presented tentatively in Table 4. This network encompasses all kinds of Mediterranean river regimes and human impacts, for different sea basins and countries. These rivers are already studied by multiple national and international research teams, but this information is not yet collected, archived and synthesised.

– Definition of key indicators which required a DPSIR framework.

Table 4. Medium-sized Mediterranean rivers suggested for a network of case studies.

River	MED-Basin(1)	Country(2)	Basin Area $(10^3$ km$^2)$	Drainage Intensity (mm/yr)(4)	Present Runoff (km^3/yr)	Human Pressures
Têt	NW	FR	1,4	(291)	0,3	reservoir; agriculture (irrigation), major city
Moulouya	SW	MAR	51,0	(31)	1,6	reservoirs; agriculture; mining; tourism
Cheliff	SW	ALG	43,7	(29)	1,3	reservoir, cities
Tevere	TYR	IT	16,6	446	7,4	major city (Rome), agriculture
Krka	ADR	CRO	2,0	1015	2,0	none, exceptional pristine river
Neretva	ADR	CRO	17,7	780	13,8	limited pressures, limited damming; high erosion
Reno	ADR	IT	3,4	412	1,4	multiple impacts (agriculture, industries, river flow regulation)
Majerda	ION	TUN	21,8	(44)	1,0	reservoir cascade, agriculture
Acheloos	ION	GR	5,5	1023	5,7	reservoirs, agriculture, industries
Ceyhan	NLEV	TR	20,0	(346)	7,1	multiple reservoirs
Axios(3)	AEG	GR	24,7	(198)	4,9	urbanisation (Skopje); industries
Aliakmon(3)	AEG	GR	9,5	(123)	1,17	reservoirs, agriculture

Keys: (1) NW: Northwest, SW: Southwest, TYR: Tyrrhenian, ADR: Adriatic, ION: Ionian, LEV: Levantine. (2) Country of river mouth. (3) Common Delta. (4) In parenthesis runoff values already affected by water uses, with present-day figures likely to be lower.

The following questions and responses could be addressed, in a future research programme:

1) How to deal with exceptional events?

– Definition of extreme events for each type of hydrological regime.

– Gauging stations must be calibrated for extreme water levels with the necessary equipment designed to resist to violent flash-floods.

– Automatic samplers, or intensive field measurements.

– Response time is reduced, for smaller rivers.

– Sampling in response to sea storm or rain storm events.

– Interrannuel, long-term monitoring at selected sites should be consolidated.

2) How to deal with the spatial dimension of fluxes?

– Spatial and temporal relationship of river inputs to the coastline, i.e. impact scale.

– Remote sensing of marine waters, for surface plumes.

– Development of more coupled studies, between the drainage basin and the coastal waters.

– Extension of temporal studies on surficial sediment deposition, in offshore waters.

– Delta processes, i.e. between the most downstream river station and the first marine station, should be considered.

3) How to deal with ungauged catchments?

– Build-up typologies of catchment-coast interactions (hydrodynamics, sediment dynamics, etc.), in natural conditions, targeted to the Mediterranean Sea.

– Select representative catchments as a first approach.

– Extrapolate the representative catchments results to the ungauged catchments within each type.

– Extend the monitoring to small and medium catchments, possibly on the basis of the importance of their overall contribution to the Mediterranean Sea.

4) How to deal with human interactions?

– In-depth analysis and mass balances of contaminants, carbon and nutrients sources should be carried out on the selected sites.

– Sediment production, transfers and deposition (i.e. enhanced erosion vs enhanced reservoir retention) should be addressed.

– The impact of decreased water runoff linked to irrigation on riverine fluxes should be considered over long periods (>30 years if possible).

– Human interactions in deltas (wetland filling, channelisation, fertilisation, pollution, aquaculture, etc.) should be assessed in terms of: (i) modifications of river to coast filtering capacity; (ii) new sources/sinks of material; and (iii) regulation of the coastline.

– A typology of human interactions can be developed in parallel to the typology of catchment-coast interactions (developed in step 3).

Water and sediment delivery from Mediterranean rivers: regional, global and temporal perspectives

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ABSTRACT

Rivers discharging into the Mediterranean Sea drain primarily relatively small (1-5 thousand km^2) watersheds; runoff from these rivers, however, varies from less than 20 m in parts of northern Africa and the Middle East to more than 1,000 mm/yr in the north. Because of historic landuse practices throughout much of the Basin, land erosion and sediment delivery to the coastal ocean have had far greater impact in the Mediterranean than in most other coastal regions. Changes in landuse, decreased rainfall (particularly in northern Africa), and increased river damming and diversion over the past 50-100 years, however, have resulted in major decreases in sediment discharge in northern rivers and both water and sediment discharge in the south. These changes in river-ocean exchanges are certain to affect such important environmental and economic considerations as coastal evolution, coastal pollution and fisheries throughout much of the Mediterranean Sea.

INTRODUCTION

The Mediterranean Sea is bordered by perhaps the most diverse variety of watersheds of any inland sea in the world. To the east and south, Middle Eastern and North African rivers drain largely arid basins, with the mean annual runoff of some rivers (e.g., Chellif in Algeria, Miliane in Tunisia, Besor in Israel) being at or below 20-50 mm/yr. In contrast, rivers draining mountains in southern Europe (e.g., Mat in Albania and Acheloos in Greece) have runoffs that exceed 1,000 mm/yr, 20-to 50-fold greater than many North African and Middle Eastern rivers.

Superimposed on the climatic signal are physiographic, geologic and anthropogenic factors that collectively have resulted in different fluvial sedimentary regimes. Considering southern Europe, for instance, the combination of high mountains, erodable rocks and periodically intense rainfall, together with historically poor land-use practices, has resulted in a disproportionate sediment flux compared to rivers draining northern Europe. The rivers draining the southern slopes of the Alps discharge an order of magnitude more sediment than northern European rivers. Prior to damming, for instance, Semani River in Albania had a mean annual sediment load (Simeoni *et al*., 1997) greater than the collective annual loads of the Loire, Seine, Rhine, Weser and Oder rivers.

Similarly, the historic sediment loads from rivers draining the mountains of North Africa have had impressively large sediment loads, the Agrioun (a small mountainous river in Algeria), for instance, having a sediment yield (~7,000 t/km^2/yr) 12 times that of the Rhone (~600 t/km^2/yr), 35 times that of the Po (200 t/km^2/yr), and 180 times that of the Garonne (40 t/km^2/yr). Walling and Webb (1983) have estimated that (until recently) North African rivers discharged about 250 mt of sediment annually, an order of magnitude greater than all the rivers draining northern Europe (excluding Scandinavia). How do these impressive sediment yields and loads of

Mediterranean rivers correspond to other global rivers, particularly with respect to physiography, geology, climate and human impact?

GLOBAL PERSPECTIVE

Physical erosion and thereby fluvial sediment loads are functions of physiography of the watershed, geologic and lithologic character, climate (particularly precipitation and river runoff), and human activity. The rate of denudation (and thereby sediment yield within a river) increases in direct response to elevation of the watershed (which also serves as a proxy for such gradient-related phenomena as landslides and earthquakes), lithology (e.g., mudstone vs. granite), and precipitation (Milliman and Syvitski, 1992; Syvitski, 2003). Sediment yield also tends to decrease with increasing watershed area, smaller basins being more responsive to flooding and also providing less storage capacity for eroded sediments (Milliman and Syvitski, 1992). As such, rivers draining wet young mountains, although only occupying about 15% of the total land area, account for about 60% of the sediment delivery to the global ocean. The rivers draining the island of New Guinea, for example, are calculated to discharge about 1.8 billion tons of sediment annually, about 10% of the global load and 1 1/2 times that of the Amazon River (Milliman, 1995).

As seen in Figure 1, relative to their individual basin areas, Mediterranean rivers discharge relatively small sediment loads, their yields often being an order of magnitude smaller than those of wet young mountainous rivers, most of which are located in southern Asia and northern South America. However, this comparison is biased, since, as mentioned previously, many Mediterranean rivers have runoffs less than 100-200 mm/yr whereas wet young mountainous rivers shown in Figure 1 are defined as having runoffs exceeding 750 mm/yr. If we therefore limit our discussion to rivers with drainage basins between 1,000 and 5,000 km^2 in area, and then compare sediment yield to runoff for those mountainous rivers draining relatively young lithologies, we find that Mediterranean rivers tend to have significantly higher yields than do rivers with similar runoffs draining Oceania (New Zealand, Taiwan, Indonesia) or the western Americas (Figure 2). Low-runoff (~80-300 mm/yr) Mediterranean rivers, in fact, often have an order of magnitude greater yield than do global rivers with similar runoff characteristics. The reason for this disparity seems to be the much greater influence of human activities throughout the Mediterranean watersheds (Turner, 1990; Syvitski *et al*., 2005). Therefore, when one takes into account the size of the watershed and mean annual discharge, Mediterranean rivers are seen to have some of the highest sediment yields in the world.

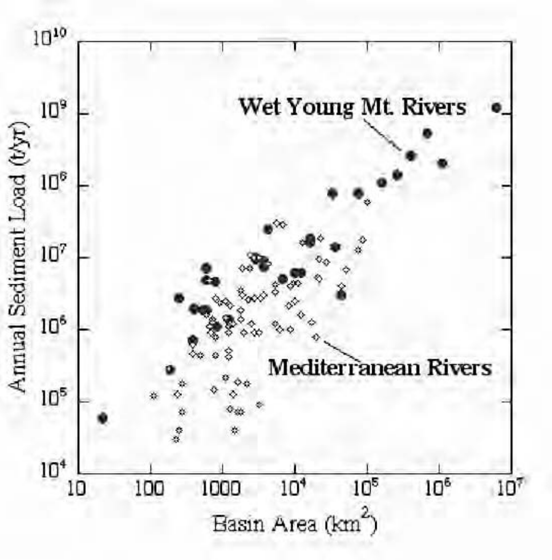

Fig. 1. Comparison of annual sediment loads for wet young mountainous rivers and rivers draining into the Mediterranean Sea. Data compiled by J. Milliman and K. Farnsworth.

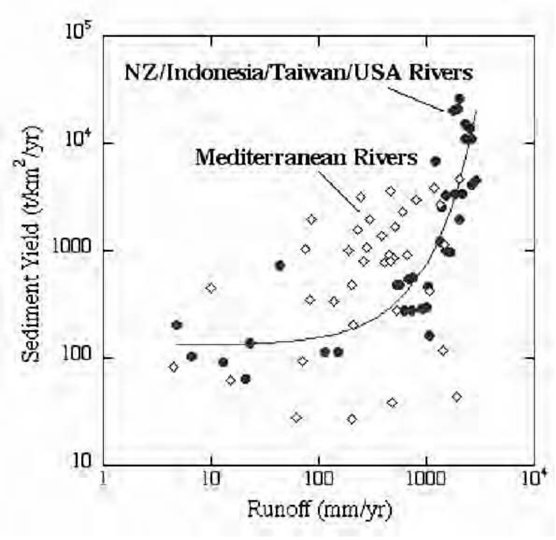

Fig. 2. Sediment yield versus runoff for rivers with 1,000-5,000 km^2 drainage basin areas. Data from J. Milliman and K. Farnsworth.

CHANGING CONDITIONS AND PERSPECTIVES

The above comparison between Mediterranean and other rivers no longer is completely valid, as many rivers and their watersheds have been greatly altered over the past 50-100 years. In southern Europe, for example, considerable amounts of agricultural land have been allowed to evolve back into forest, thereby decreasing greatly land erosion (e.g., Simeoni and Bondesan, 1997); in northern rivers the mining of riverbeds for sand and gravel also has reduced sediment discharge. In contrast, increased landuse combined with decreasing precipitation has led to continued land degradation throughout much of North Africa and the Middle East (e.g., Turner, 1990; Goudie, 2000).

Augmenting the decreased erosion in the north and counter-balancing the increased erosion in the south has been the effect of the increased damming of many Mediterranean rivers, for irrigation (primarily in arid regions) as well as for flood control and hydroelectric power. In part, particularly in northern Africa, the increased need for dam construction has coincided with dramatic decreases in regional precipitation. In southern Morocco and Algeria, for example, precipitation over the past 50 years has declined by as much as 20-30%. Decreasing precipitation together with increased population pressures have accentuated the need to utilize as much fluvial water as possible.

While the impacts of river damming and irrigation have global dimensions, particularly in Africa, western Asia and Australia, perhaps nowhere has the impact been as great as in the Mediterranean (Figures 3 and 4). Rivers discharging the wide swath of Mediterranean coastline, from Spain, through northern Africa, into Turkey and eastern Greece have been so compromised by dam construction and irrigation, that at present little water (and much less sediment, most of it being trapped behind dams) reaches those coastal areas of the Mediterranean. While the impact of this decreased sediment flux can be seen, such as the well-documented erosion of the Nile, Po and Ebro deltas (e.g., Smith and Abdelkader, 1988; Cencini, 1998; Guillén and Palanques, 1997), demographers and policy-makers face an uncertain future. It is not unlikely to predict that by the year 2025 there will be very little freshwater flux to the southern or eastern Mediterranean except during periods of very heavy rains or snow melt. How the coastline will respond to such change probably has no simple, unifying answer, but one might predict that coastal erosion will accelerate; building coastal defenses may help in the short-term, but together with rising sea level, such short-term fixes ultimately may cause more problems than they solve.

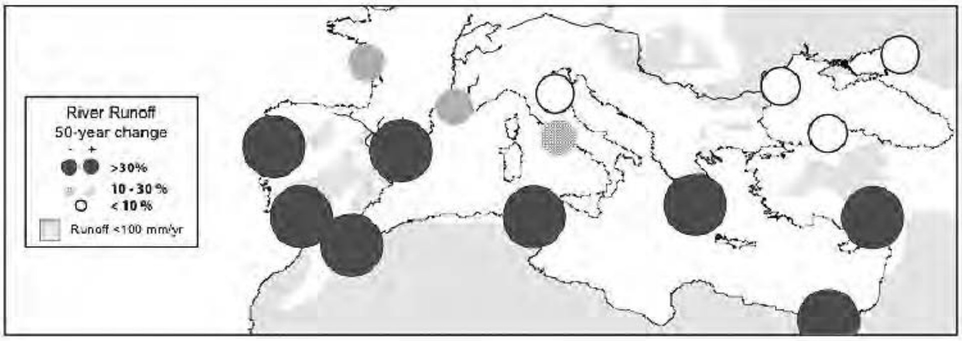

Fig. 3. Discharge trends of selected Mediterranean and neighboring rivers, 1951-2000. Note the relatively minor changes seen in French and Italian rivers compared to those seen in Spanish and North African rivers.

If precipitation continues to decline and rivers remain channelized and dammed, there will be an increased need for artificial fertilizers, which, together with increased urbanization (particularly in the southern portions of the Mediterranean) almost certainly will result in greater pollution, even as discharge from many of these rivers declines. Nixon (2003) reports an interesting phenomenon for the Nile delta coastal fisheries following construction of the Aswan Dam: the abrupt decrease in fish catches noted in the mid-1960s and '70s – the result of drastically reduced

Nile discharge - gradually changed beginning in the 1980s, in response to increased discharge of agricultural and urban pollutants, such that coastal fisheries at present are higher than they were before construction of the dam. But the quality of the caught fish, however, might be open to question.

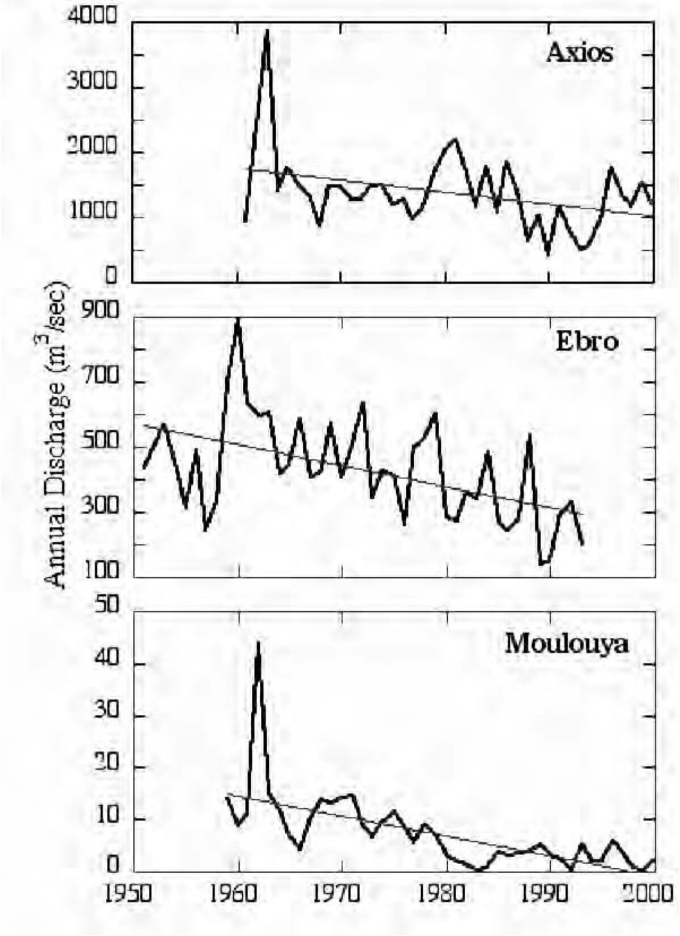

Fig. 4. Annual discharge 1950-2000 for the Axios (Greece), Ebro (Spain) and Moulouya (Morocco) rivers. Note the steep decline in discharge for all three rivers. Data courtesy of A. Karageorgis (Axios) and M. Snoussi (Moulouya).

Could a similar situation occur in the Mediterranean – already an oligotrophic sea? The ensuing 25 years almost certainly will bring greater insights into the consequences of the rather drastic anthropogenic manipulation of river discharge to the coastal sea. Whether the answers will be pleasant or not - or, as in the case of the Nile, we can even predict the consequences - remains to the seen.

Acknowledgements

I thank my colleagues at CIESM for stimulating discussions that helped reshape much of this paper. Katie Farnsworth (US Geological Survey) created the map shown in Figure 3. This work in part has been supported by the US National Science Foundation and the Office of Naval Research.

Specificity and heterogeneity of the Mediterranean Sea and its river catchments under human pressures

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The Mediterranean Sea and its catchment is the archetype of a quasi-enclosed Regional Sea. Human activities and resulting pressures have developed on its entire coastline for centuries. It is also very heterogeneous in terms of climate and of pressures: on its southern shores, river inputs are naturally limited and are even more reduced due to water uses while some northern Mediterranean tributaries from the Rhone to the Idrijca are among Europe's most humid catchments.

Facing such heterogeneity and complexity of river inputs to the Mediterranean, we will first compare the major European Regional Seas together (Mediterranean, Baltic, North Sea, Black Sea) and scaling them to other regional seas. Then we consider the Mediterranean coastline into ten specific coastal catchments, which are reclustered into European, Asian and African catchments. In section 3, we will estimate the share of Mediterranean rivers within the European river fluxes. The anthropisation of rivers is addressed in section 4 with a set of three examples (Idrijca, Axios, Po) showing a wide variability. The final section concerns the Driver Pressure State Impact Response analysis of river-coast systems and its limits.

1. THE MEDITERRANEAN SEA AND ITS CATCHMENT COMPARED TO OTHER REGIONAL SEAS

The regional seas of the world (RS) can be classified into three categories: quasi-enclosed, the semi-enclosed and open. The Mediterranean Sea is the archetype of the first category, the Gulf of Mexico of the second, the North Sea of the third. Regional seas have a limited exchange with ocean which, in turn, corresponds to a marked retention of river fluxes as carbon, nutrients and contaminants. Particulate matter is nearly 100 % retained by RS.

The Mediterranean is among the world's greatest RS in terms of area and volume and is characterized by the biggest potential river catchment (exorheism) with 8.3 Mkm^2 of area compared to 5.4 Mkm^2 for the Gulf of Mexico and 4.0 Mkm^2 for the East China Sea. The average depth (Zrs) of the Mediterranean is 1,496 m, a figure which is close to many other RS of tectonic origin such as the Black Sea (1,057 m) (Figure 1a), but markedly higher than RS of glacial origin as the Baltic (99 m) and the North Sea (93 m). As a consequence, the theoretical river water residence time (sea volume divided by annual river flow) for the Mediterranean is much longer (4,700 y) than for the Baltic (100 y) and the North Sea (160 y). The Black Sea river residence time is 1,320 years (Figure 1b).

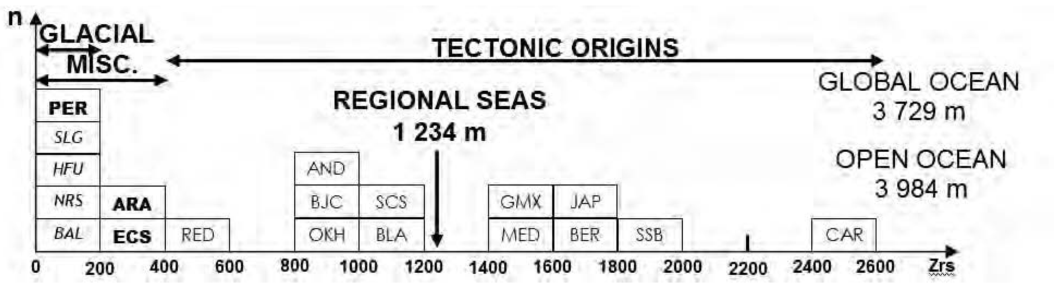


Fig. 1a. Distribution of regional seas mean depths (Zrs in m) (SCS tectonic; *BAL* glacial, **PER** other or miscellaneous) (Meybeck *et al.*, 2006).

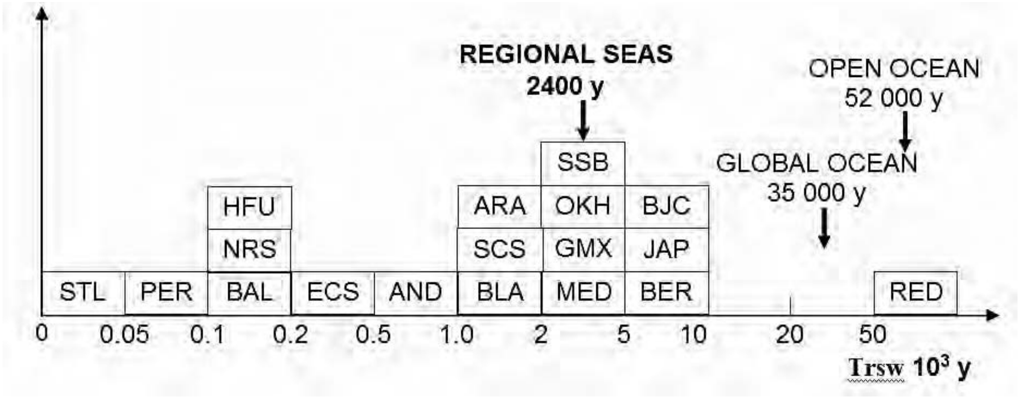


Fig. 1b. Distribution of theoretical river water residence time (Trsw in 1,000 y) in regional seas (Meybeck *et al.*, 2006).

The potential river catchment of the Mediterranean Sea (Figure 2) includes large parts of the North Sahara that were hydrologically active some 6,000 years ago and are now completely dry (runoff q<3 mm/y, arheism). Only the Nile River, fed by the Ethiopian Plateau, had enough water

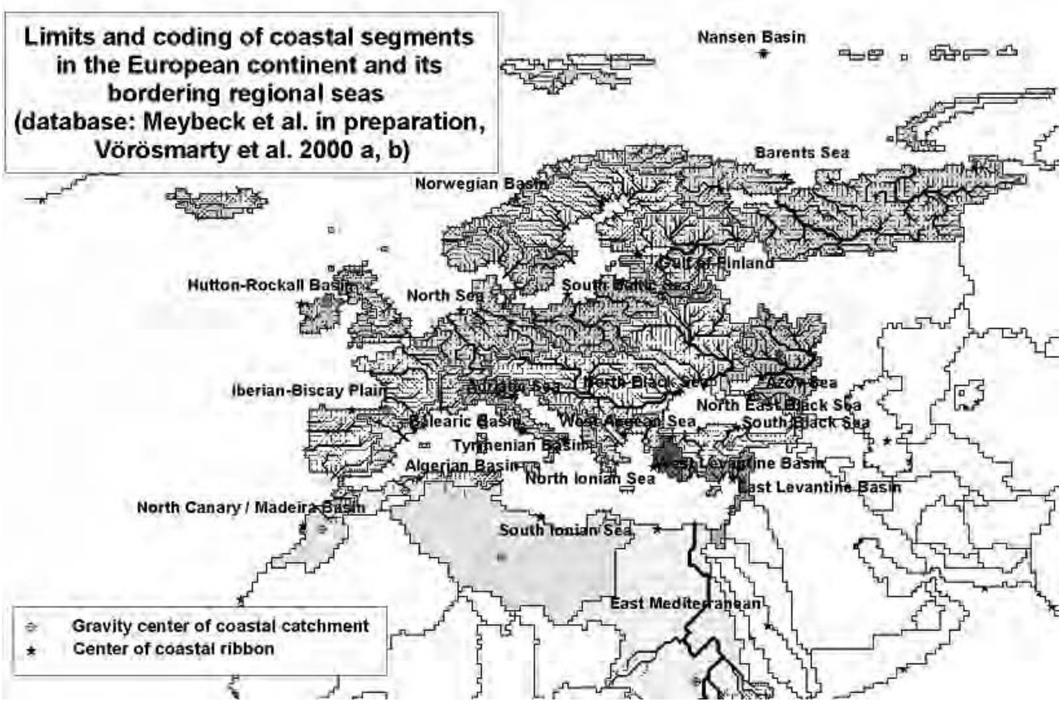


Fig. 2. Limits and coding of coastal segments in the European continent and its bordering regional seas (Meybeck *et al.*, 2006).

–in pre-damming conditions– to cross the Sahara and reach the sea (allogenic river). Its natural runoff is very close to the one conventionally chosen to describe rivers that flow permanently (q> 30 mm/y). As a result the Mediterranean Sea has 61 % of its catchment within the dry arheic climate, 17.2 % within the temperate climate and 13.6 % within the humid tropical climate (with q< 680 mm/y). Such proportion of dry arheic climate is the world's maximum after the Red Sea catchment (93 %) and the Persian Gulf (79 %) (see Meybeck *et al*., 2004).

The Mediterranean catchment is also characterized by a higher proportion of carbonated rocks and a lower proportion of plutonic rocks than other European RS (Dürr *et al*., 2005; Meybeck *et al*., 2006): about 53 % of its catchment is constituted of carbonated rocks (limestones, mixed carbonated and carbonated alluvium) and 17.5 % of plutonic and metamorphic rocks compared to 23 % and 38 % for the same rock types in the Baltic catchment.

Another contrast between the Mediterranean and the Baltic concerns the relief classes: the Mediterranean catchment is characterized by the occurrence of mid-altitude plateaus (28 %) and mid-altitude mountains (22 %), compared to their very low occurrence for the Baltic catchment (0.5 % and 6.1 %), which is dominated by plains (34.8 %) and low-altitude plateaus (51.1 %), therefore very much limiting the mechanical erosion and the river sediment yield.

The human pressures on RS catchments are very variable with population densities ranging from less than 1 p.km^{-2} for the Hudson/Foxe/Ungawa catchment to 229 p.km^{-2} for the East China Sea. The Mediterranean catchment figure is 38 p.km^{-2}, much lower than the world RS average (61.7 p.km^{-2}). However, since more than 2/3 of the 8.3 Mkm^2 is actually arheic and not part of the œcoumen, a corrected population density would give a higher value, 115 p.km^{-2} (316 Mpeople over 2.75 Mkm^2 of non-desertic catchments). With such corrections, the population densities of the north Mediterranean catchment in Europe (121 p.km^{-2}), of the East Mediterranean catchment in Asia (109 p.km^{-2}) and of the South Mediterranean catchment in Africa – hydrologically active area only - would be very close to each others.

2. Coastal segmentation and river inputs to the Mediterranean

River catchments of the coastal zone (COSCATs) have been aggregated at the global level by Meybeck *et al*. (2006), who provided estimates for water inputs, total nitrogen and total suspended solids (in pre-damming conditions mostly from global models developed by Fekete *et al*. (2002), Green *et al*. (2003), Ludwig and Probst (1998). The assemblage and coding of the European and Mediterranean COSCATs are presented in Table 1 and in Figure 2.

Each COSCAT has a set of attributes (Meybeck *et al*., 2006) including riverine fluxes. They can be recombined to set up the river inputs per regional sea (e.g. Baltic, North Sea, Black/Azov, Mediterranean), or left as such. The Mediterranean Sea is decomposed into ten COSCATs which are actually corresponding to its classical subdivisions: West Aegean, North Ionian, Adriatic, Tyrrhenian and Balearic COSCATs for the European coast, the East and the West Levantine COSCATs for the Asian coast and the Algerian, South Ionian and East Mediterranean COSCATs for the African coast (Table 2).

The water inputs to the Mediterranean Sea are presented for each COSCAT in Table 2; they are based on the global model of Fekete *et al*. (2002) and include both river and phreatic groundwater inputs. When the 10 COSCATs are reclustered into the European, Asian and African catchments of the Mediterranean, the figure is much contrasted. The European catchment (0.94 Mkm^2 or 11.3 % of the whole potential catchment) corresponds in natural conditions, i.e. prior damming and irrigation, to an input of 358 km^3.y^{-1} i.e. 45 % (average runoff q= 382 mm.y^{-1}); the Asian catchment corresponds to 3.6 % of the drainage area and to 9 % of the water inputs, the African catchment (7.03 Mkm^2) to 85 % of the drainage area and 46 % of the water inputs. This figure has now very much changed due to the generalized runoff decrease from Spain, Maghreb, South and Central Italy, Greece, Turkey, Middle East and Egypt (Ludwig *et al*., 2005).

Table 1. Coastal catchments to the Mediterranean and other European Seas (Meybeck *et al.,* 2006).

	Nr	Sea basin name	Principal river basins
Atlantic	401	Iberian-Biscay Plains	Loire, Douro, Seine, Tejo, Guadiana, Garonne, Guadalquivir, Dordogne, Tamar
	402	Hutton-Rockall Basin	Thjorsa, Olfusa, Shannon, Severn
North Sea	403	North Sea	Rhine, Elbe, Gota, Glama, Weser, Meuse, Thames, Humber
Baltic Sea	404	South Baltic Sea	Wisla, Odra, Nemanus, Daugava
	405	Botnian Bay	Kemijoki, Tornionjoki, Amgerman, Dalalven
	406	Gulf of Finland	Neva, Narva, Kymijoki, Luga
Arctic	407	Norwegian Basin	Trondheims Fjord, Soge Fjord, Alta R.
	408	Barents Sea	Dvina, Pechora, Mezen, Onega
	409	Nansen Basin	no important rivers
Black Sea	411	Azov Sea	Don, Kuban
	412	North West Black Sea	Danube, Dnepr, Dnestr, Bug, Provadijska
	413	North East Black Sea	no important rivers
	1303	*South Black Sea*	*Kizil Irmak, Sakarya, Yesil, Coroch*
North Med. Sea	414	West Aegean Sea	Evros, Strymon, Axios, Aliakmon, Pinios
	415	North Ionian Sea	Bradano, Salso, Smeto, Acheloos, Alfias
	416	Adriatic Sea	Po, Brenta, Adige, Piave, Tagliamento, Idrija-Isonzo, Neretva, Drina, Semani, Vijose
	417	Tyrrhenian Basin	Arno, Tevere
	418	Balearic Basin	Rhone, Ebro, Segura, Jucar
East Med. Sea	*1301*	*East Levantine Basin*	*Ceyhan, Asi, Seyhan, Aksu*
	1302	*West Levantine Basin*	*Buyuk Menderes, Gediz, Simav*
South Med. Sea	*1*	*Algerian Basin*	*Moulouya, Cheliff, Medjerda*
	2	*South Ionian Sea*	*Irharhar*, Araye**
	3	*East Mediterranean*	*Nile, Qattara*

* presently non flowing rivers (arheic).

Table 2. General morphological features of Mediterranean coastal catchments (data compiled by Meybeck, Dürr, Roussenac and Ludwig).

Non-European rivers in Italics.

Ab: total basin area. **Lc**: total length of coastline (0,5° resolution). **Lm**: maximum length of rivers in the coastal basin **D**: average depth of coastal basin. **Qb**: total volume discharge from coastal catchment. **qb**: average runoff of coastal catchment. **% rheic**: percentage of coastal catchment area with active river network (q> 3 mm/y).

	Nr	Coastal segment	Ab	Lc	Qb	qb	rheic
			Mkm^2	**km**	**km^3.y^{-1}**	**mm.y^{-1}**	**%**
	414	West Aegean Sea	0,21	1891	43,0	201,24	91,30
	415	North Ionian Sea	0,07	1721	28,9	427,57	100,00
	416	Adriatic Sea	0,26	2533	167,7	655,79	100,00
	417	Tyrrhenian Basin	0,06	2046	22,8	392,78	100,00
	418	Balearic Basin	0,34	3543	95,6	278,89	70,30
North Mediterranean Sea			**0,94**	**11734**	**358,0**	**381,79**	**87,16**
	1301	*East Levantine Basin*	*0,21*	*2313*	*52,9*	*257,25*	*79,60*
	1302	*West Levantine Basin*	*0,09*	*743*	*20,0*	*216,57*	*97,40*
East Mediterranean Sea			***0,30***	***3056***	***72,8***	***244,66***	***85,11***
	1	*Algerian Basin*	*0,25*	*2236*	*22,0*	*86,30*	*43,10*
	2	*South Ionian Sea*	*2,26*	*2154*	*1,1*	*0,47*	*1,20*
	3	*East Mediterranean*	*4,52*	*1377*	*348,2*	*76,95*	*39,80*
South Mediterranean Sea			***7,03***	***5767***	***371,3***	***52,78***	***27,55***
Mediterranean Sea			**8,27**	**20557**	**802,1**	**96,99**	**36,38**

3. SHARE OF THE MEDITERRANEAN CATCHMENT IN THE EUROPEAN RIVER FLUXES

The European continent is defined here by its natural watershed boundaries: the Ural and Caucasus Mountains and the Bosphorus Strait. It includes therefore the Barentz-White Sea catchments but the Volga is not considered in this comparison as their river is draining to the Caspian, an internal sea. As shown in Table 3, the Mediterranean catchment represents a variable share of the European rivers budget (Meybeck *et al*., 2004).

Table 3. Relative weights of European Regional Seas basins (Meybeck and Dürr, in prep.).

Bold: proportions much higher than the area weight; *Italics*: proportions much lower than the area weight.

		North Atlantic / North Sea	Baltic	Arctic	N. Black Sea	N. Mediterranean	Europe Total (1)
Basin	M km^2	1.92	1.62	1.63	2.09	0.94	8.2
Area	%	23.4	19.7	19.9	25.5	11.5	100
Water	km^3/y	723	388	559	328	358	2356
Volume	%	**30.7**	16.5	23.7	13.9	15.2	100
Population	Mp	251	78	10.8	163	113	616
	%	**40.7**	12.7	*1.7*	26.4	18.3	100
Suspended	Mt/y	168	20.3	79	107	284	658
Sediment	%	25.5	*3.1*	12.0	16.2	**43.1**	100
Total N	Mt/y	2.74	0.64	0.475	0.90	0.95	5.7
	%	**48.0**	*11.2*	*8.3*	15.8	16.7	100
Population density	p/km^2	131	48	6.6	78	120	75.1
Runoff	mm/y	376	240	343	157	381	287
N yield	t km^{-2} y^{-1}	1.43	0.40	0.29	0.43	1.0	0.70
Total N	mg/L	3.8	1.65	0.85	2.74	2.65	2.42

(1) Caspian drainage excluded

These budgets of water and suspended sediments do not take into account damming and irrigation. The total nitrogen budget refers to the sum of nitrate, ammonia and total organic N and takes into account multiple human pressures such as urban wastes, fertilization, cattle emissions, atmospheric pollution (see Green *et al*., 2003 for details).

The N. Mediterranean catchment of all European river water amounts to 11.5 % of Europe's total drainage to the Sea (8.2 Mkm^2), 15.2 % of all European river water (without irrigation), 18.3 % of Europe's population and 16.7 % of total nitrogen export by European rivers. All these figures are very close to each other. This is not the case for the suspended solids, which correspond to 43.1 % of the European river exportation according to Ludwig and Probst (1998) model (without the influence of damming).

These figures are no longer valid as there is a general decrease of runoff and sediment loads for African, Asian tributaries listed in Table 1 and of many of the European tributaries in Spain, Central and South Italy and in the Balkans (see a review by Ludwig *et al*., 2004). The river water budget of the Mediterranean is therefore much affected. For instance, the actual Nile discharge dropped from 80 to 90 km^3.y^{-1} prior to the construction of the first Asswan Dam to 0.26 km^3.y^{-1} in 1999/2000 (Abdel-Gawah *et al*., 2004).

The present sediment inputs from African tributaries are also probably less than 10 % of what they used to be when considering the generalized damming from Morocco to Egypt. The Nile River sediment load at Cairo dropped from 120 to 2 Mt.y^{-1}. A similar decrease is noted for other N. Mediterranean rivers as the Ebro and Axios (Ludwig *et al*., 2004).

The average natural runoff of the N. Mediterranean river is estimated to 381 mm.y^{-1} according to Fekete *et al*. model (2002). This figure is similar to the one for the North Sea and Atlantic Ocean drainage (376 mm.y^{-1}), higher than for the Baltic (240 mm.y^{-1}) and Black (157 mm.y^{1}) Seas. Actually the East Adriatic coast is characterized by very high runoff, from Slovenia to Albania, that exceeds 1,000 mm.y^{-1}. The Rhone, Po, Brenta and Adige rivers have also very high runoff values due to their humid alpine catchment and the Ebro River is also partially fed by the Pyrenees. The Arctic catchment ranges here from W. Norway to the Ural Mountains and is heterogeneous: the very humid coast of Norway is responsible for this relatively high runoff.

4. ANTHROPISATION OF MEDITERRANEAN RIVERS

4.1. From natural to impacted river systems

Mediterranean river systems are often under multiple climatic and anthropogenic stress and they have more evolved in the last 50 years than most river systems, excepted for the Aral Sea catchment. The resulting river fluxes to the sea are also much affected. These changes have been presented and illustrated in details in Meybeck (2006), also reproduced in the Executive Summary of this C.I.E.S.M. Monograph.

In summary for river systems under multiple human pressures two opposite impacts on fluxes can be combined (Meybeck, 2003; Meybeck and Vorosmarty, 2005):

(i) an acceleration of river fluxes due to erosion and pollution and

(ii) an acceleration of river retention due to damming and water use, such as irrigation; the overall direction of the river systems is very variable and depends on local condition of each system.

In the Mediterranean catchment, it is often difficult to differentiate the natural functioning of river systems from human impacts: agriculture, urbanisation, mining, industries and fluvial transportation are in the Mediterranean catchment among the oldest of the world, from 6 000 BP to the present period. Compared to other regions of the Globe, the issue is the recent acceleration of these multiple and ancient pressures. These pressures and impacts will be illustrated here on a set of case studies for three Mediterranean rivers compared to a few other European rivers.

4.2. The Idrijca, Axios and Po river systems under current conditions

The former EUROCAT programme funded by the European Community compared the water quality issues and river transfers to the sea of nine European catchments: Vistula, Elbe, Rhine, Humber (UK), Seine, Po, Idrijca (Slovenia/Italy), Axios (FYROM/Greece), Provadijska (Bulgaria) and Po (Meybeck *et al*., 2004).

The **Idrijca / Isonzo** river (3,000 km^2) has a record of atmospheric precipitation (3,000 mm/y) and is discharging to the Gulf of Trieste (Figure 3). The Idrijca mercury mine, in operation over the last 500 years, is now stopped since 1990 but the mercury contamination is stored for hundred of years in soils, floodplain sediments and in three reservoirs. The contaminated coastal sediments are under a methylation threat in the Bay of Trieste due to the sewage released by this city. The maximum Hg content is reaching 14 ppm in surficial sediments and peaked in the 1930s in dated cores (Hines *et al*., 2001).

The **Axios** river (25,000 km^2) is originating from the FYROM and discharges into the Thermaikos Gulf in N. Greece (Figure 4). The Greater Thermaikos Gulf (9,500 km^2) and the waste waters from Thessanoliki (2 Mpeople) were not treated until very recently. The Axios River is actually very regulated by upstream and mid-course reservoirs in FYROM that are retaining a great part of the pollution load from this country, particularly from Skopje. In the Axios delta, a great part of the river water is abstracted for irrigation. Mussel parks in the delta, Greece biggest production, are very sensitive to the remaining Axios pollutant load. Multiple water conflicts (upstream/downstream; irrigated agriculture vs. urban and industrial needs; Aliakmon vs. Axios residents) are occurring in Thermaikos Gulf.

The **Po River delta** (380 km^2) is another example of multiple uses and human impacts, although at another scale. It is the outlet of the Po River (74,000 km^2). The river flux figures of the Po are actually determined at the Pontelagoscuro station some 60 km upstream of the coastline. The Po delta is now very much controlled by human activities. This delta was once common to the Adige River now channelized separately from the Po. The Brenta River which used to flow across the Venice Lagoon has been derived few hundred years ago to the Po-Adige delta. Coastal lagoons in the Delta are now used for shellfish industry and are regulated. The main Po River navigation channel is engineered and dredged.

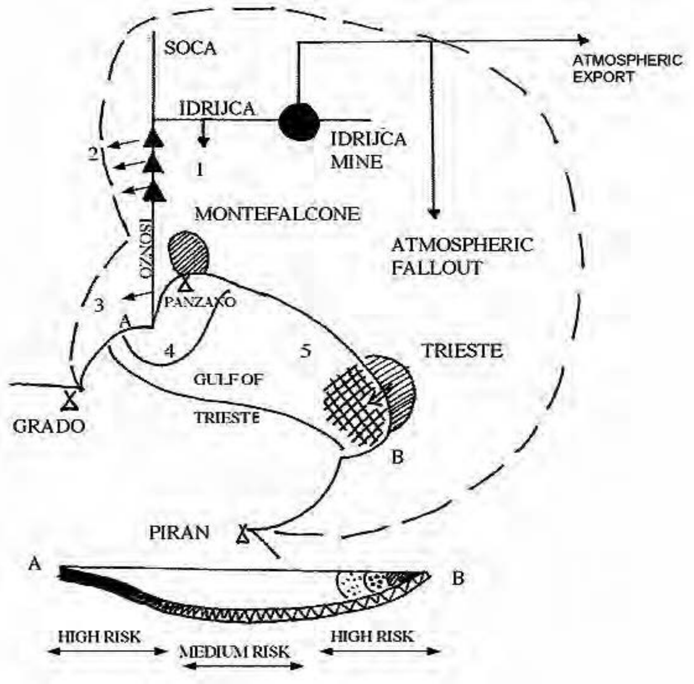


Fig. 3. Schematic transfer of mercury in the Idrija-Gulf of Trieste system.

The Idrija mine has been the #2 world producer of mercury for hundreds of years. The mine has been stopped in 1990. However the generated mercury is still transfered and transformed across the system causing an extreme contamination in the whole system from the mine to the Gulf.

Storage of contaminated particulate matter carried by the river is found at all stages: (1) floodplain soils, (2) small hydropower electric plants reservoirs A = Doblan, B = Ajba, C = Solkan, (3) inland delta soils, (4) outer delta sediment (5) gulf sediments. In each of these reservoirs mercury methylation is likely to occur. As the methylation also depends on the content of organic matter and on the redox potential of sediment there is a high methylation rate in the Eastern part of the Gulf impacted by Trieste city sewage outfall. Due to the highest contamination found in the outer delta the methylation risk is also very high in this area where beach recreation has been developed.

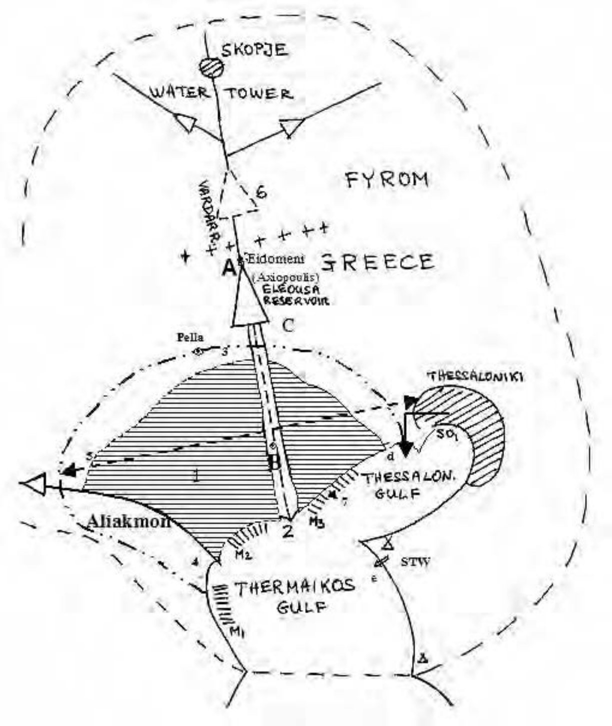


Fig. 4. Schematic water transfers in the Axios/Thermaïkos system (Greece/FYROM).

The upper Axios, or Vardar, is the water tower of the system. Major tributaries (Treka, Belganika, Onerna Reka) are already dammed but not the main river course, particularly downstream of Skopje. After the FYROM-Greece border at Eidomeni/Axiopoulis (water control station A) the river is dammed by the Eleousa reservoir (Pochroma, water quality station, C) near Polykastro. From there water is diverted to Thessaloniki for its water supply and canalized along the river course through the Axios delta plain where it is used for irrigation, mainly rice fields. As a consequence the water discharge of the Axios at the Chalastra station (B) has decreased by at least 40% since the 1970s. Important mussel farms (M_1, M_2, M_3) are located along the Aliakmon-Axios delta. New water transfer from the Aliakmon River to Thessaloniki took place in 2003, and another reservoir on the Vardar. Most of the delta has been drained, the remaining wetlands (5% of the original area) are protected under the Ramsar conventions and other conservation measures.

1: lateral irrigation canals, 2: present Axios mouth, 3: limit of original wetland 500 BC with Pella sea port 4: Aliakmon regulated course, 5: New Thessaloniki supply with Aliakmon waters, 6: envisaged new reservoir in FYROM, 7: unknown groundwater inputs to the Gulf. (d) and (e): main sewage outlets.

Compared to the other European river catchments that have been studied within the Eurocat programme, there is no common characteristics of the Po, Idrijca and Axios that could be related to their Mediterranean nature (Table 4a,b,c): each of these nine European cachments is actually very specific.

The river-sea interface is very much engineered in all case studies: the lower river courses of the Po, Idrijca, Axios are channelized by levees and the estuaries of the Rhine, Elbe, Seine are continuously dredged for navigation. Many of Central and Southern Europe catchments have important reservoirs that intercept more than 50 % of their area (Idrijca, Axios, Vistula). Finally the urban, industrial or mining pollution sources are not fundamentally different between the Baltic, Mediterranean and North sea catchments.

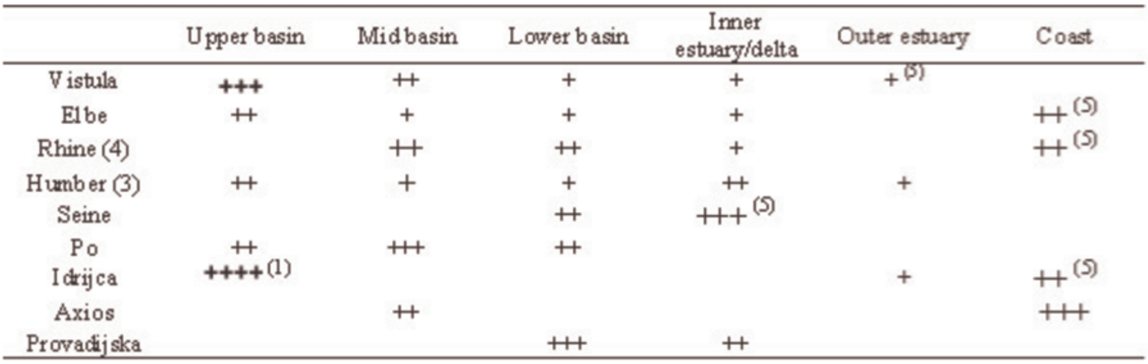
The greatest difference between Mediterranean catchments and other European rivers is probably the rate of river water abstraction for irrigation which is very limited in Central Europe and high to very high in most Mediterranean rivers, with the noted exception of the Rhone and of the Northern and Eastern Adriatic rivers. Irrigation is usually connected by important river flow regulation through damming.

Table 4a. Relative importance of artificialisation of some European river basins and their coastal zone (EUROCAT programme) (Meybeck *et al.*, 2004).

	River basin				Land/ocean interface					
	Runoff reduction (1)	Regulated reaches(2)	Sediment transfer(3)	Wetland drainage	Water transfer	Irrigation in delta	Wetland filling	Dredging	Dikes	Channel change
Vistula	-	+	-	+					+	++
Elbe		+	?					++		
Rhine		+			+	++		++	+++	
Humber		++	-(10)	+			++(6)	++	+++(4)	
Seine		++		++(7)			+	++		
Po		+		+(7)+ (8)			+	+	++	++
Idrija			--				?		+	++
Axios	-- (40%)	+	--- (90%)		++	+++	++(8)		+++	++
Provadijska			+++(9)		+			+++(5)		

+ to +++ relative importance; (1) 1995-2000 versus natural runoff; (2) for navigation (e.g. dykes, locks); (3) retention (-) or increase (+); (4) coastal defences; (5) induces salt intrusion; (6) in intertidal area; (7) in mid-basin; (8) in delta; (9) sediment increase due to industrial impact; (10) weirs dividing freshwater from tidal reaches.

Table 4b. Relative position and weights of industrial/mining pressures and mining pressures (in bold) in Eurocat rivers and their coastal zone.



	Upper basin	Mid basin	Lower basin	Inner estuary/delta	Outer estuary	Coast
Vistula	**+++**	++	+	+	+ (5)	
Elbe	++	+	+	+		++ (5)
Rhine (4)		++	++	+		++ (5)
Humber (3)	++	+	+	++	+	
Seine			++	+++ (5)		
Po	++	+++	++			
Idrijca	**++++** (1)				+	++ (5)
Axios		++				+++
Provadijska			+++	++		

(1) past Idrijca mines; (2) Veles; (3) former coal, lead and zinc mines; (4) coal mines; uranium mines; (5) Gdansk refineries.

Table 4c. Identified pollution sources hot spots in EUROCAT river/coast systems (internal sources in coastal zone not considered) (scaling not attempted).

	Upper basin	Mid basin	Lower basin	Inner estuary/delta	Outer estuary	Adjacent Coast
Vistula	$+^{(1)}$	$+^{(18)}$			$+^{(19)}$	
Elbe ?	$+^{(14)}$	$+^{(13)}$	$+^{(12)}$			
Rhine		$+^{(2)}$	$+^{(3)}$			
Humber ?	$+^{(15)}$		$+^{(16)}$		$+^{(17)}$	
Seine			$+^{(7)}$			
Po	$+^{(4)}$	$+^{(5)}$				
Idrijca	$+^{(6)}$				$+^{(18)}$	
Axios	$+^{(11)}$	$+^{(10)}$				$+^{(8)}$
Provadijska			$+^{(9)}$	$+^{(9)}$		

(1) Silesia mining district; (2) Alsace potash mine; (3) Ruhr; (4) Torino; (5) Milano, Brescia, Bergamo; (6) Idrija mines; (7) Paris Seine-aval sewage treatment plant; (8) Thessaloniki sewage; (9) Industrial complex of Desnya; (10) + Veles + fertilizer plant; (11) Skopje; (12) Rotterdam harbour dredged sediments; (13) Bitterfeld-Wolfen and Magdeburg-Rotensee chemical complex; BUNA & LEUNA coalmines; WISMUT manium mining; (14) Most, Teplice, Usti/Labern coalmines; Spolana Chemical plant; (15) R. Tame sewage water treatment; (16) sugar factory in tidal ouse; (17) TiO_2 plant (unscaled list); (18) Trieste and Koper harbours.

5. D.P.S.I.R. ANALYSIS OF CATCHMENT-COAST SYSTEM AND RIVER INPUTS TO THE SEA

The D.P.S.I.R. approach (Driver-Pressure-State-Impact-Response) is now recommended by the European Water France Directive (WFD) and by the European Environmental Agency. It is here first presented for the catchment-coast system as discussed by Meybeck (2006) and Meybeck *et al*. (2004), as a result of the EU funded Eurocat programme.

5.1. D.P.S.I.R. analysis on river catchment-coast systems

The Driver-Pressure-State-Impact-Response concept along the catchment coast system should be carefully analysed in terms of spatial organisation (Figure 4). The river basin may be directly connected to the coastal zone (# B) or by an extended intermediate estuarine system (#A). In Mediterranean conditions the estuarine systems (i.e. deltas, lagoons) are generally limited for small river catchments but should be taken into consideration for medium and large catchments. In other European regional seas, as the North Sea, the estuarine systems are important even for small catchments, particularly the macrotidal estuaries. The river basin output (F) is generally measured at a control station S5 which can be located far up the estuarine zone. The net estuarine flux (F5) to the coastal zone is determined at the control station (S6). For many estuarine systems, S5 can be used as a net input station but for macrotidal estuaries and some deltas/lagoons types S5 and S6 can be far apart, up to 150km. Thus direct inputs (F10) and human interactions can occur between S5 and S6. In the Mediterranean coast, S5 and S6 are much close to one another. However S5 is sampled from bridges or from small boats while S6 is sampled by ocean-going vessels, thus leaving the estuarine processes between S5 and S6 actually poorly documented (e.g.: Po, Ebro Rhone). Inputs of material to the river basin include diffuse sources from soils (F1), from atmospheric fallout (F4) and point sources (F2), such as urban industrial effluents. The outer coastal zone is also receiving and exchanging material with the deposited sediments (F6), F10B), the atmosphere (F11 and F12) and the open Sea (F8 and F9) and producing biomass (F13) that is exported on land as economic resources (shellfish, fishes).

In order to apply biogeochemical models that concern material transfers and water quality, the spatial boundaries of the river/coast system should be carefully limited. External sources, i.e. those from neighbouring basins and from the open sea, should be identified. In some systems models can only be developed if several rivers are considered together with direct urban inputs (e.g. Gulf of Thermaikos, Figure 4).

The D.P.S.I.R. components are the following:

Drivers are multiple and can be defined on the basin, on the coast and outside the system (e.g.: river catchments population, national shellfish market, global shrimp market, local to international coastal tourists population, etc.).

Pressures are those occurring: (i) on the catchment: from industries, mining, agriculture, urbanization, tourism and (ii) on the direct estuarine catchment downstream of the river control station S5: e.g. a city located on an estuary or at river mouth, a channelized estuary, use of the fertilizers and pesticides in the estuarine zone.

Impacts are here those related to the degradation of the coastal state indicators impairing key coastal uses, such as tourism, shellfish aquaculture, fisheries, or coastal functions such as coastal defence against sea-storms, or coastal conservation. Indicators of coastal waters pollution, of coastal food-webs degradation, of coastal erosion can be used together with indicators of economic impacts.

Responses to catchment - related impacts should take into account the critical loads (nutrients, contaminants) that have to be defined for each river/system. Responses usually combine policy and pollution control measures, as effluent treatment, which necessitate the generation of financial fluxes. Responses can be generated from the very local level to the whole Mediterranean Sea Region (e.g.: Mediterranean Action Plan, Barcelona Convention).

The D.P.S.I.R. steps are therefore combining very different types of interactions and fluxes (Figure 4) as fluxes of information and social interactions, financial fluxes and material fluxes (e.g. nutrients, carbon, contaminants). Each of these elements should ideally be combined in a set of interlinked tools as databases models, scenarios and expert systems.

This complexity is schematically presented in Figure 5, combining three levels: (i) the policy/decision level (ii) the socio-economic level (ii) the biophysical level, and two domains: the river basin (left) and the coast zone (right). River basin drivers regulate the catchment economy (interaction A). However this regulation is not instantaneous and a certain reaction time - materialized by a cycle - is observed. There is generally no linear relation between drivers and pressures (e.g.; industrial wastes effluents can decline while the production is increasing) since pressures also depend on the policy constraints (F) and the stakeholders interactions on the basin (e.g. political will to enforce the policies, timing of policy application etc.). Pressures are generally translated in terms of material inputs (B) to the aquatic system. The multiple filters existing in the aquatic system (e.g. wetlands, lakes, floodplains, reservoirs, deltas, irrigated crops) may in turn modify and slow down the transfer of these materials, particularly if river discharge is controlled. There is therefore another time-lag between the transfer of river material to the coast (C) and its related pressures. The coastal biophysical reactions can also be complex

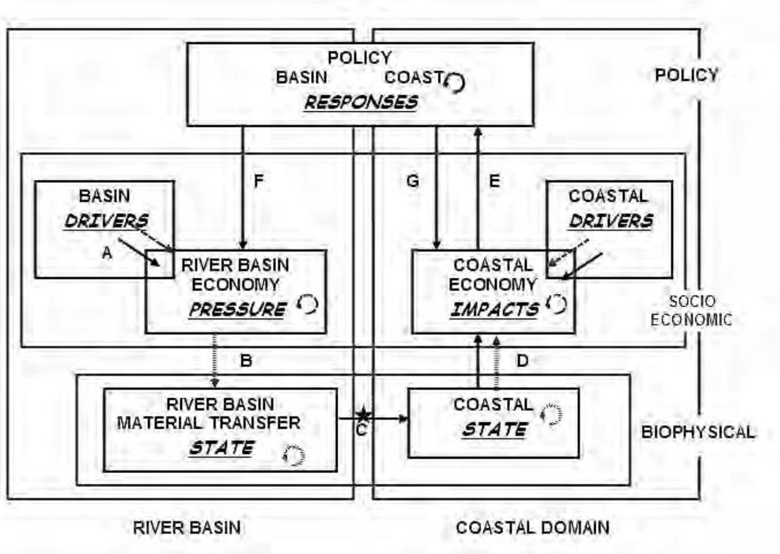


Fig. 5. Schematic DPSIR decomposition of basin/coast interactions into six domains.

Left: river basin domain; right: coastal domain; bottom: biophysical interactions; middle: socio economic interactions; top: decisions processes. C: river to coast transfer. Interactions code: ——➤ = fluxes of information and social interactions; --------➤ = financial fluxes; ··········➤ = fluxes and concentrations of materials. Cycles: economic, social, political, and biophysical reaction time-lags (Meybeck *et al.*, 2004).

and delayed before the coastal state at which coastal uses are impacted (D) is reached. When the ecological value of the coastal zone is reduced, it generates economic and/or social impacts that may be accelerated or reduced by coastal drivers. When coastal stakeholders have identified the riverine inputs as the major cause of coastal impacts they may react in multiple ways (E), particularly on river basin and coastal policies (F) and (G).

This DPSIR chain is actually a continuous endless conveyor belt of information, materials, and money. Most of the concerned actors have a reduced vision on the whole process and/or look at it as a static process. Actually, environmental trajectories, rapidity of interactions between socio-economic agents, and biophysical interactions have to be taken into account. As a result, the temporal and spatial dimensions of DPSIR can be quite complex: each catchment-coast system has its own dynamics, including some very rapid interactions, multiple time-lags, slow and fast changes. These dynamics are controlled by internal factors both in the catchment and on the coast and by few external factors (e.g. some drivers and responses as global markets, tourism, EU and national regulations).

5.2. Limits of the D.P.S.I.R. approach

There are several limits to the application of D.P.S.I.R. approach for catchment to coast impacts.

Solving the spatial scale complexity

Some medium-sized Mediterranean rivers are shared by several countries or provinces and do not have yet a single management entity (e.g. Idrijca, Axios). Another type of limitation concerns the ecological and economic impacts of river inputs to the coastal zone: how to differentiate the individual impacts of several rivers or cities discharging to the same coastal entity (e.g. Po, Adige, Brenta for the Po Delta; Aliakmon, Axios and Thessaloniki wastewaters for the Thermaikos Gulf), unless very accurate budgets are made.

Bridging the monitoring gap

It is much linked to the spatial heterogeneity. Biophysical and economic models on which scenarios of responses can be tested actually need a great set of information on land use, pollution sources, economic drivers and environmental uses, ecological impacts at key stations from headwaters to the coast and from atmospheric inputs to water use, sewage treatment, pesticide use, metal emissions etc.

Reference levels: where to go?

The reference level, which is now required within the WFD should be carefully determined on selected subpristine stations, from earliest environmental studies or from sedimentary archives. For the Mediterranean environment, such reference may be very delicate since river systems have been used and misused since Roman times: pristine pre-historic levels will never be found again and the reference will probably be an achievable target agreed by all stakeholders rather than an hypothetical pre-anthropic reference, particularly for reference aquatic habitat.

Accounting for the Mediterranean river flux regime

The typical Mediterranean river regime is characterized by its skewed distribution of river flows and their related fluxes of dissolved matter and by its even more skewed distribution of sediment supply. Alpine tributaries of the Mediterranean from the Rhone to the Idrijca rivers are much less variable. In North African rivers (Nile excepted), the natural variability of rivers and waddies are among the world’s greatest as for the Oued Zeroud (see a review by Ludwig *et al*., 2005). In the few documented rivers, the duration curve of sediment transport shows that half of the sediment can, be transported in less than 5 % of time, sometimes 2 %, in natural conditions (Meybeck *et al*., 2003). The present “water quality monitoring” with 12 to 24 samples/year analysed for Total Suspended Solids, widely used in Europe and around the Mediterranean, is totally inadequate for sediment supply determination: the errors can exceed one order of magnitude between discharge-weighted loads and medians or arithmetic-averages loads. TSS variations in Mediterranean rivers range from less than 10 mg/L to 10 g/L or more and sediments loads from 1 to 10^6 units at the same station. (see Ludwig, Milliman, this volume).

Detecting early contamination and establish common indicator

The best responses are those that occur before the environmental issue is too serious. For that reason *alarm bell indicators* of state changes should be established at an earlier stage: they will act as watchtowers looking far ahead (i.e. beyond the classical 5 years election period). Similar indicators can be established on drivers, pressures or economic impacts.

All indicators should result from an agreement between concerned stake holders and should be shared between stakeholders and river/coast managers.

Including long-term perspective in D.P.S.I.R. application

Trends of river water quality and river fluxes have multiple shapes and temporal scales; most of them are particularly slow, with multi-decadal time scales, particularly for the sediment quality. In many riverine studies, it is shown from sediment archives that the maximum contamination has occurred before any monitoring activity as for the metal contamination in most European rivers (Meuse, Rhine, Seine, Idrijca). These pollution peaks occurred from 1950 to 1970 and have reached world records: they were two orders of magnitude above the natural background and even more for Cd and Hg. They are linked to mines and/or to industries at a time where the environmental concern was totally absent, where the waste treatment facilities were limited and where the contamination state was very difficult to analyse (analytical darkness). This environmental decontamination phase therefore started because of technological changes or of economic collapse, thus reducing the contaminant emissions, and was not linked to any societal response following an economic or ecological impact of the contamination.

Considering pollution heritages and reaction time of aquatic systems

Some impacts on driver systems can be quite slow, from decades to centuries. The present day river inputs and their related issues are sometimes linked to pressures resulting from ancient human activities that no longer exist. This is typically the case for the contamination resulting from past mining that sometimes dates from Roman times or even before (orphan pollutions). The coarse sediment transfer through river systems from headwaters to the coast, that shapes the river bed morphology, is also very slow: the responses to any land cover change (e.g.: deforestation, aforestation) or damming will take decades to hundred of years, depending on basin size. Large aquifers and some lakes (Alpine lakes of the Po catchment, Ohrid Lake) are also characterized by very long water residence time (10 y or more) and slow reactivity to human pressures changes. For such systems, the reduction of human pressures will not have many effects until several decades.

Enlarging actors and stakeholders vision

The D.P.S.I.R. analysis shows different types of stakeholders both on the catchment side and on the coastal side. Most of them (policy maker, economist, river basin manager, coastal manager, social scientist, river user, coastal user, etc.) have a very partial and biased view of the system complexity (Figures 4 and 5). They over-emphasize their own subsystem, which they consider as central, and sometimes view it as barely influenced by external factors while controlling many other sub-systems. This is particularly evident when the catchment-coast relationships are analysed in models. Generally these actors and stakeholders are lacking a holistic perspective of their system, of their nested scales, temporal variability, and of their natural and anthropogenic complexities. Communication between stakeholders can be difficult: different agents do not share the same vocabulary and they use different types of units (e.g. monetary units, material fluxes, contaminant concentrations, fish catches or tourist fluxes). Sharing tools as river-coast GIS and constructing common indicators may be a way to better integrate these different visions.

Riverine freshwater fluxes in the Mediterranean and Black Seas

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ABSTRACT

The drainage basin of the Mediterranean Sea accounts for some 4,135 10^3 km^2 (including the R. Nile), which is larger than that of the Black Sea (2,350 10^3 km^2, including the Azov Sea). Estimates of the annual water load for the Mediterranean rivers are 570 km^3 and, for the Black Sea, 414 km^3. Accordingly, the corresponding values of water yield 0.14 m^3/km^2/yr (Med) and 0.18 m^3/km^2/yr (Black) show that Black Sea rivers have a larger water capacity. Another difference is that in the case of the Black Sea, the large river systems (>50,000 km^2) drain 87% of its catchments, these providing the 60% of the freshwater input. In the Mediterranean Sea, rivers with catchments >50,000 km^2 (excluding the Nile) represent only 18% of its catchment; in turn, they provide 27% of the freshwater inputs. In contrast, medium and small rivers (<5,000 km^2) in the case of the Mediterranean have a greater significance in comparison to those of the Black Sea, as they provide >40% of the freshwater inputs; the Black Sea rivers contribute <20%.

INTRODUCTION

The Mediterranean and Black Seas are two basins interconnected by the Sea of Marmara, through which they exchange water masses (Figure 1). Some 1200 km^3 of Black Sea water enters the Aegean Sea, whilst some 900 km^3 of Aegean water flows into the Black Sea, through the Dardanelles Strait and the Sea of Marmara. The surface area of the Mediterranean Sea (2,500 10^3 km^2) is about six times larger than that of the Black Sea (463 10^3 km^2) (Table 1). Accordingly, the length of the coastline is about 11 times longer, as the Mediterranean has a more complex and active recent geological evolution. On Figure 1 the drainage basins of the Mediterranean and Black Seas are presented: more than 165 rivers discharge in the Mediterranean and more than 94 into the Black Sea (including the Azov Sea).

The purpose of this presentation is to provide comparative information regarding the freshwater fluxes into the Mediterranean and Black Seas. More specifically, we focus upon: (i) the physiographic characteristics of the drainage basins; (ii) the freshwater contribution of the small and medium-sized river systems; (iii) the relation of freshwater inputs to the basin hydrology; and, (iv) the effect of dam construction.

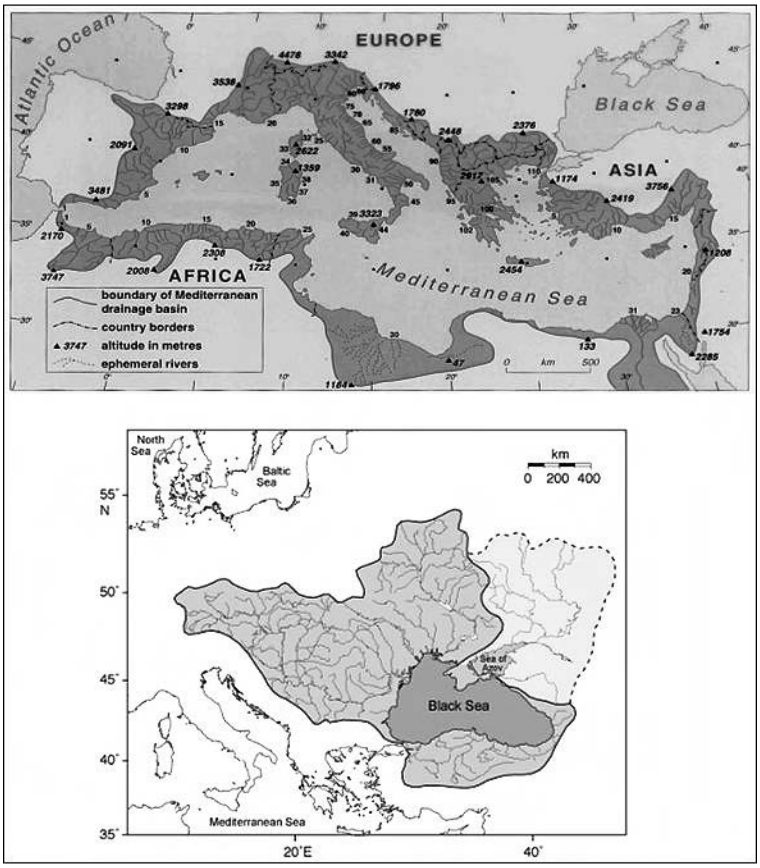


Fig. 1. Schematic representation of the drainage basins of the Mediterranean (upper) and Black Sea (lower).

Table 1. Physical geographical characteristics of the Mediterranean and Black Seas basins and catchments.

	Mediterranean Sea	Black Sea
Water surface (km^2)	2,500,000	425,000 (+38,000)*
Water volume (km^3)	1,335,000	560,000 (+320)*
Drainage basin area (km^2)	4,135,000	1,864,000 (+490,000)*
Length of coastline (km)	46,000	4,125 (+450)*
Number of rivers	165+	94+

(*) : values in parentheses refer to the Sea of Azov.

DATA AND METHODS

In order to calculate the overall water load of the Mediterranean rivers, its catchments have been divided into (five) physiographic regions (Region I-V), on the basis of their geographical locations and climatological conditions (Figure 2). Subsequently, the water yields (m^3/km^2) for each of the five regions was estimated. This estimation is based upon the calculation of the weighted-average of the corresponding water yields, from field-measurements of the water fluxes of 69 rivers discharging along the Mediterranean coastline. Subsequently, the mean (weighted) value for each region was calculated, using the known water yields and the weighted area of the watersheds, corresponding to the measured water fluxes (see Table inserted within Figure 2).

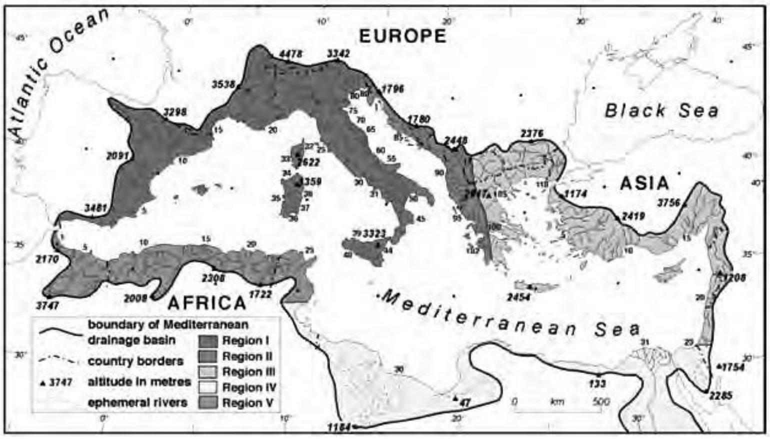
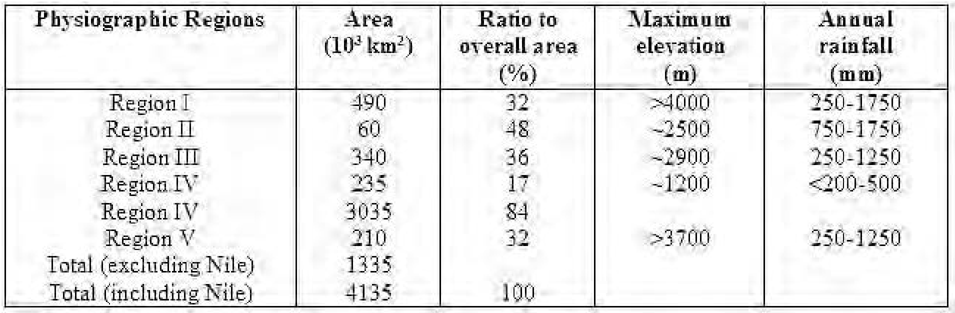


Fig. 2. Physiographic characteristics of the (five) regions of the total Mediterranean catchment area (originally from Poulos and Collins, 2002).



Physiographic Regions	Area (10^3 km^2)	Ratio to overall area (%)	Maximum elevation (m)	Annual rainfall (mm)
Region I	490	32	>4000	250-1750
Region II	60	48	~2500	750-1750
Region III	340	36	~2900	250-1250
Region IV	235	17	~1200	<200-500
Region IV	3035	84		
Region V	210	32	>3700	250-1250
Total (excluding Nile)	1335			
Total (including Nile)	4135	100		

Similarly, the drainage basin of the Black Sea was divided into four physiographic regions (Figure 3). The water discharge of this region was calculated on the basis of existing data (Jaoshvilli, 2002) that cover all rivers with a catchment >200 km^2 (see Table inserted within Figure 3).

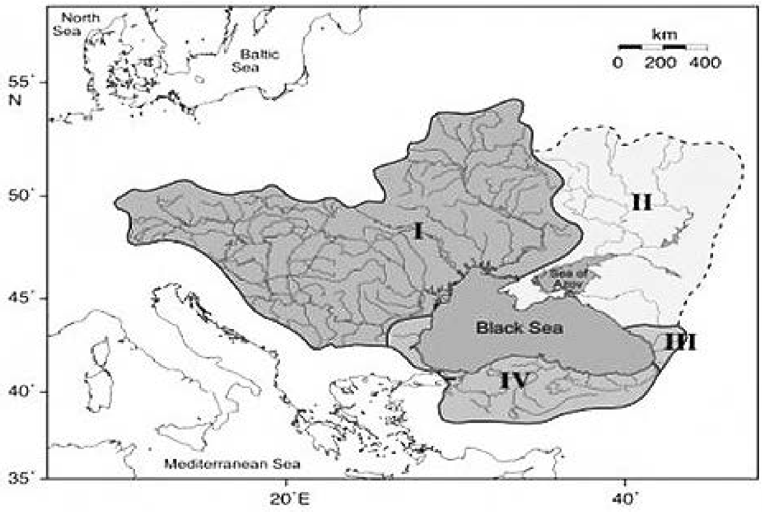
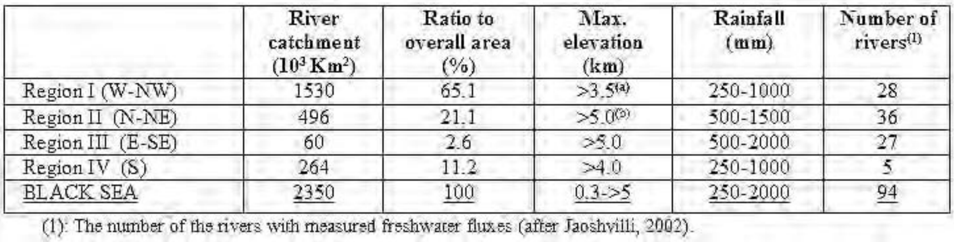


Fig. 3. Physiographic characteristics of the (four) regions of the Black Sea (including the Azov Sea within Region II) catchment.



	River catchment (10^3 Km^2)	Ratio to overall area (%)	Max. elevation (km)	Rainfall (mm)	Number of rivers(1)
Region I (W-NW)	1530	65.1	>3.5(a)	250-1000	28
Region II (N-NE)	496	21.1	>5.0(b)	500-1500	36
Region III (E-SE)	60	2.6	>5.0	500-2000	27
Region IV (S)	264	11.2	>4.0	250-1000	5
BLACK SEA	2350	100	0.3->5	250-2000	94

(1): The number of the rivers with measured freshwater fluxes (after Jaoshvilli, 2002).

RESULTS AND DISCUSSION

Mediterranean Sea

In the case of the Mediterranean catchment, physiographic region I supplies, annually, the largest amount of freshwater (254 km^3), whilst the lowest fluxes are associated with region IV (12 km^3). The overall (potential) annual freshwater load is estimated to be about 570 km^3 (Table 2); this is 18% higher than that provided by UNEP (2003).

Table 2. Water load of the (five) physiographic regions of the Mediterranean catchment and the effect of dams (after Poulos and Collins, 2002).

	Water load (Q) (km^3)	Q/Q_t (%)	Water load retained (temporarily) behind dam (km^3)	Percentage of retained water (%)
Region I	254	44.6	137.0	54
Region II	63	11.1	31.0	49
Region III	150	26.3	94.5	63
Region IV	12	2.1	3.6	30
Region V	91	15.6	7.3	8
Total (Q_t)	570	100.0	273	48

However, within the second half of the 19th century the construction of almost 3000 dams has reduced, the (natural) drainage basin area of the Mediterranean by 78% (Poulos and Collins, 2002). Furthermore, an analogous reduction has been caused in the overall water supply within each physiographic region, in response to dam construction. Thus, the overall estimation of the freshwater load, controlled by hydro-electric and irrigation dams, accounts to some 297 $km^3yr^{-1;}$ which corresponds to 52% of the total water volume: only 273 km^3yr^{-1} flows freely to the coastal ocean.

It is emphasised that the freshwater contribution of the small and medium-sized river systems (drainage basins <5,000 km^2) is larger than has been assumed in earlier studies, representing >40% of the total influx (Table 3); these drain 42.4% of the Mediterranean catchment, excluding the Nile drainage basin, but around 13% when the Nile catchment is included in the calculations. For comparison, although the R. Nile has an extremely large catchment (70% of the total Mediterranean catchment), before dumping it contributed only 16% of the total annual freshwater input.

Table 3. Area and freshwater fluxes of rivers with different sized catchments of the Mediterranean Sea (data abstracted from UNESCO, 1974; UNEP, 2003).

Size of catchment ($10^3 km^2$)	<5	5-50	50–500	Sub-total (excl. Nile)	>500 (Nile)	Total
Total area (A) (10^3 km^2)	530	380	340	1,250	2,870	4,120.0
A (%) (excl Nile)	42.4	30.4	27.2	100.0		
A (%) (incl.Nile)	12.8	9.2	8.3	30.3	69.7	100.0
Number of Rivers	150+	25	5	>180	1	
Water discharge (Q) (km^3/yr)	250.5	101.2	128.3	480	90	570.0
Q (%) (excl Nile)	52.2	21.1	26.7	100.0		
Q(%) (incl. Nile)	43.9	17.8	22.5	84.2	15.8	100.0

Black Sea

The rivers outflow into the Black Sea discharge annually >400 km^3, with Region I (the northwestern) providing 2/3 of the total, as it hosts the mouth of the largest rivers (Danube, Dniester, Dnieper). Furthermore, the Black Sea rivers have a larger water capacity (0.18 10^3 km^3/km^2) than those of the Mediterranean (0.14 10^3 km^3/km^2) drainage basin. Such a difference is related to the fact that the Black Sea rivers drain a larger hinterland area with mean levels of precipitation >750 mm/yr. In comparison the Mediterranean catchment is characterised by a mean precipitation of <350 mm/yr. The latter figure remains smaller (at some 650 mm/yr) than that of the Black Sea, even when the R. Nile is excluded.

The contribution of small and medium rivers (catchment size <5,000 km^2), to the Mediterranean Sea is significant; they drain only 10% of the total catchment area, but provide 18% of the total freshwater flux (Table 5).

Finally, on the basis of measured reduced values after damming, Table 4 shows that, although a much higher amount of freshwater is retained temporarily behind the dams, the coast is deprived of less than 10%.

Table 4. Black Sea: freshwater fluxes before (Q) and after damming (Q_D) (data from Jaoshvilli, 2002; Dimitrov *et al.*, 2003).

Black Sea	Q (km^3/yr)	Q/Q_T (%)	Q_D (km^3/yr)	Q_D/Q (%)
Region I	275.2	66.5	249.3	9.6
Region II	47.7	11.5	44.7	6.3
Region III	49.7	12.0	49.7	-
Region IV	42.0	10.2	38.0	9.5
Total (Q_T)	414.6	100.0	381.7	8.0

Table 5. Area and water discharge of different sized river catchments of the Black Sea drainage basin (data abstracted from Jaoshvilli, 2002).

Catchment area A			Rivers	Water discharge (Q)	
Size (km^2)	A (10^3 km^2)	(%)	Number	km^3/yr	(%)
<5,000	234,600	10.0	>80	75	18.0
5,000-50,000	86,700	3.7	5	24	5.7
50,000–500,000	712,700	30.3	5	63	15.1
>500,000	1,320,000	56.1	2	253	61.2
sub-total (>5,000)	2,119,400	90.0	12	339	82.0
TOTAL:	2,354,000	100.0		413.6	100.0

CONCLUDING REMARKS

The rivers discharging into the Black Sea drain a larger land area (2,350 10^3 km^2) than those that flow into the Mediterranean (4,135 10^3 km^2), when the R. Nile (some 2,870 10^3 km^2) is excluded from the total Mediterranean catchment area. A tentative estimate of the annual water load for the Mediterranean rivers is 570 km^3; for the Black Sea, it is 414 km^3. According to these figures, the corresponding water yield values (0.14 m^3/km^2/yr and 0.18 m^3/km^2/yr) show that the Black Sea rivers have a larger water capacity.

Furthermore, in the case of the Black Sea, the large river systems (>50,000 km^2) drain 87% of its catchment area, providing 60% of the freshwater input. In contrast, the Mediterranean rivers with catchments >50,000 km^2 (excluding the Nile) represent only 18% of the remaining catchment area and 27% of the freshwater inputs; the latter figure reveals the importance of the medium and small river systems in the case of the Mediterranean Sea, as they contribute >40% of the water flux.

In the case of the Mediterranean catchment, regulation of river flows through dam construction for hydroelectric power and irrigation purposes has reached the point where 50% of it is currently dammed presently. Measurements undertaken on Black Sea rivers show a net loss of freshwater reaching the coast by some 10%.

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Fluvial sediment fluxes, in the Mediterranean and Black Seas, in relation to coastal evolution: a comparison

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ABSTRACT

The Mediterranean and Black Seas receive annually some 1,000 and 300 million tones of riverine sediment, respectively; these correspond to sediment yields of 240 (10^3 t /km^2) and 160 (10^3 t /km^2). Thus, the Mediterranean catchment has a higher sediment capacity, which expresses primarily from the ratio between the suspended sediment load and the dissolved load (SSL/DL is 2.6:1 for the Mediterranean and 1.5:1 for the Black Sea). Furthermore, the small and medium-sized rivers (<5,000 km^2) contribute large amounts of sediment, as they drain >10% of both of the overall catchments; this is due to their increased yields. Human interference, in both basins, is associated mostly to river dams; these have reduced substantially the riverine sediment supply to the coast (>40%), implying often enhanced coastline retreat.

INTRODUCTION

The present-day geomorphological configuration of the coastal environment of the Mediterranean and Black Sea Basins is related to riverine sediment fluxes; the latter has been identified as one of the key parameters in understanding the ‘Earth System’ (Walling and Webb, 1998). Globally, around 40% of river discharges are intercepted today by large impoundments (Vorosmarty *et al*., 1997). Within the next few decades, more than 50% of the total global flow to the ocean may be dammed or diverted, influencing: (i) the export of carbon to the atmosphere and ocean, by fluvial systems; and (ii) continental shelves operating under a much less efficient ‘biological pump’, with a smaller delivery of nutrients. Fish production will decrease, accordingly.

The Mediterranean coastline is approximately 11 times longer (46 10^3 km) than that of the Black Sea (4.1 10^3 km) (Figure 1); this is due to more complex morphometry and active recent geological evolution of the Mediterranean Basin. Nonetheless, despite the difference in the length of the coastline, the catchment area of the Mediterranean Basin (4,135 10^3 km^2) is only 1.8 times larger that that of the Basin of the Black Sea (2,354 10^3 km^2. Further, if the R. Nile (some 2,800 10^3 km^2) is excluded from the total Mediterranean catchment area, then the Black Sea drains a larger land area. Another interesting observation is that, in the case of the Black Sea, six rivers with catchments >50,000 km^2 represent 87% of its total drainage basin; in the Mediterranean, if the R. Nile is excluded, the remaining five rivers with catchments >50,000 km^2 represent only 18% of the remaining catchment area.

This contribution provides a comparison between the fluvial sediment fluxes into both basins, in relation to the evolution of the coastal zone; incorporates the major anthropogenic influence (over the last century) affecting the water and sediment fluxes, i.e. the construction of river dams. Within this context, the consequences of sediment retention by the dams on the deltaic coasts are also examined.

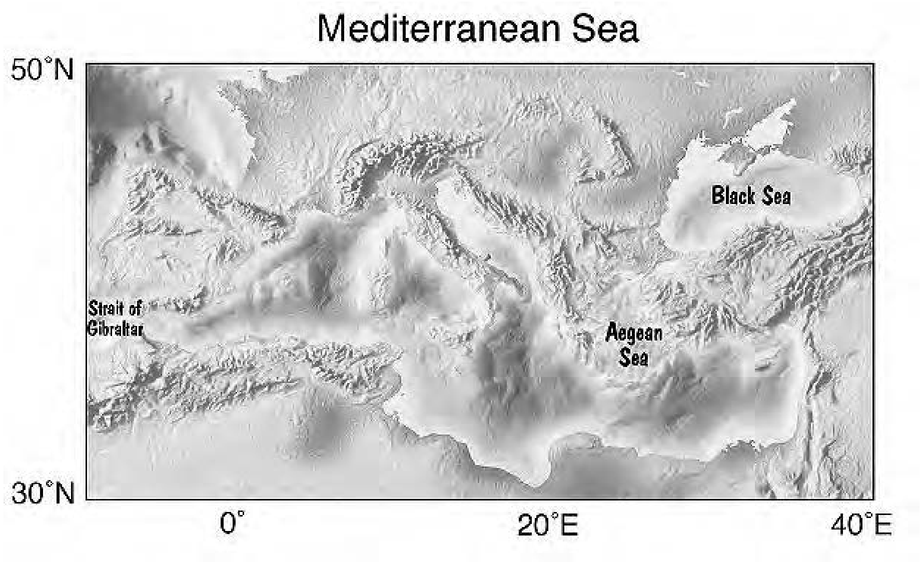


Fig. 1. Physiographic characteristics of the Mediterranean Sea, including the Black Sea.

MATERIALS AND METHODS

The estimation of the total sediment load transported by the river networks, draining the catchment of the Mediterranean and Black basins, includes material that is transported in suspension (SSL: suspended sediment load), in solution (DL: dissolved load) and along the river bed (BL: bed load). Most of the available data refer to the suspended load, as only limited field measurements exist for the dissolved and bed load components (even on a global basis).

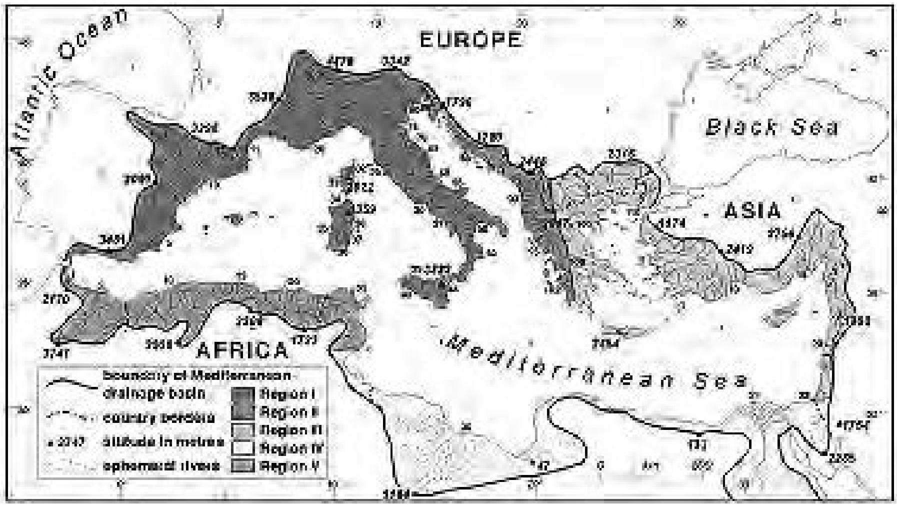
The estimation of SSL of the Mediterranean catchment is based upon published data relating to field measurements from 69 rivers discharging along its coastline. Subsequently, the overall SSL of each of the (five) physiographic regions, into which the Mediterranean drainage basin has been divided (for the identification and physiographic characteristics of the (five) regions, see Poulos and Collins, this volume). Thus, the estimation of the annual suspended sediment yields of each region is based upon the calculation of the weighed average of the corresponding yields; these have been obtained for an appropriate number of rivers, which represent >2/3 of the total area for each of the (5) regions (with the exception of Region III, where the available data incorporate only around 21% of the watershed). These values were scaled then, in relation to the area of each of the regions, assuming the run-off weathering processes to be similar throughout each region. An analogous approach to the procedure described above has been followed for the calculation of the sediment load associated with the Black Sea catchment; this, in turn, has been divided into (4) physiographic regions (for details see Poulos and Collins, this volume). Here, the difference in the SSL calculation arises from the fact that data (abstracted from Jaoshvilli, 2002) are available from almost all the rivers with catchment areas >200 km^2.

The estimation of DL for the (five) physiographic regions (I–V) of the Mediterranean drainage basin is a gross estimate, based upon the ratio SSL:DL; these have been deduced from field measurements obtained from selected river basins (Poulos and Collins, 2002); these are: Region I - 1.8/1.0; Region II - 9.8/1.0; Region III - 3/2.3; and, Regions IV & V -4&5: 4/1. In the case of the (four) physiographic regions of the Black Sea drainage basin, dissolved load (DL) estimation is based for Region I upon field data for the Ukraine rivers and the R. Danube, (SSL/DL= 1.1); and for the Regions II, III and IV (mountainous catchments) the ratio SSL/DL=2.5 used is based on field measurements from mountainous rivers of the Southern Balkans (UNESCO, 1974).

Finally, for the calculation of the BL, in general, there is a world-wide dearth of comprehensive field measurements relating to bed load transport, by rivers and with only a few exceptions; this applies also to the Mediterranean and Black sea Basins. Thus, between 1950 and 1970 the R. Ebro presented a ratio SSL:BL=4:1 (Guillén *et al*., 1992; Maldonado, 1985), the R. Arno (Italy) a percentage of 1-15% (Tazioli and Billi, 1987), whilst a similar value of the BL component (i.e. 15-20%) of the total sediment load was found for Albanian rivers by Pano (1992). On the basis of these observations, it seems appropriate to assume that BL represents overall, 10-15% of the total sediment load. For the present estimations, the 10% reported by UNESCO (1974) has been used.

RESULTS AND DISCUSSION

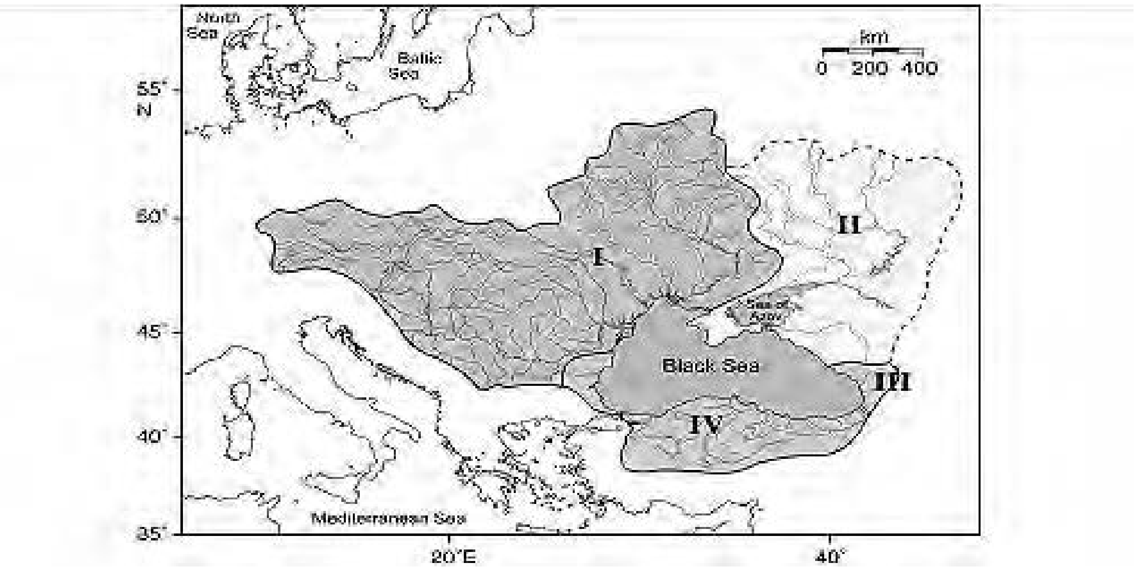
The catchment area of the Mediterranean Basin is related to a potential suspended sediment flux that accounts for some 650x10^6 tones, 195-260x10^6 (i.e. 30±5% of the SSL) carried in solution and another 100-160x10^6 tones transferred as bed load (i.e. 10-15%, relative to the total sediment load) (see Table inserted in Figure 2). Hence, the overall 'total' load may be estimated to be in excess of 10^9 tones. This overall sediment budget means that the Mediterranean hinterland area (some 4.1x10^6 km^2, in area), has a sediment yield of around 250 t/km^2. However, a mean value of 250 t/km^2 for the Mediterranean is modified to 400 t/km^2, when the catchment area of the R. Nile is excluded, which is characterised by low sediment fluxes and yields (of approx. 50 t/km^2).



	SSL (10^6 t/yr)	DL (10^6 t/yr)	BL (10^6 t/yr)	TL (10^6 t/yr)
Region I	257.2	142.9	25.7	425.8
Region II	84.0	8.6	16.8	109.4
Region III	107.0	46.5	10.7	164.2
Region IV	88.2	22.1	8.8	119.1
Region V	121.4	30.3	18.2	169.9
Total	657.8	250.4	80.2	988.4

Fig. 2. Suspended sediment (SSL), dissolved load (DL), bed load (BL) and total sediment load (TL) for the (five) physiographic regions of the Mediterranean catchment (after Poulos and Collins, 2002).

The drainage basin of the Black Sea is characterised by an overall potential sediment flux of 311 10^6 tones per year, of this, 172 10^6 tones is transferred in suspension, 118 10^6 tones in solution and 18 10^6 tones as bed load (see Table inserted in Figure 3). When these values are compared to those of the Mediterranean catchment, DL is more significant in the case of the Black Sea, whilst its overall sediment load is lower. This latter observation is more evident if sediment loads are compared on the basis of normalisation in relation to the size of the two catchments, i.e. sediment yields. Thus, the Black Sea annual sediment yield is 90 t/km^2; for the Mediterranean, it is 160 t/km^2. The difference between the Seas can be attributed to the transporting capability of the rivers controlled, in turn, governed by their catchment lithology and geomorphology (topographic slopes). The mountainous rivers are characterised by larger sediment yields.



	SSL (10^6 t/yr)	DL (10^6 t/yr)	BL (10^6 t/yr)	TL (10^6 t/yr)
Region I	96.5	87.5	9.6	193.6
Region II	18.0	16.5	1.8	36.3
Region III	20.8	5.2	2.1	28.1
Region IV	37.9	9.5	3.8	51.2
Total	172.2	118.7	18.3	311.2

Fig. 3. Suspended sediment (SSL), dissolved load (DL), bed load (BL) and total sediment load (TL) for the five physiographic regions of the Black Sea catchment (data from Jaoshvilli, 2002 and Dimitrov *et al.*, 2003).

It should be noted that small and medium-sized rivers (catchment areas <5,000 km^2) play a primarily role in the transportation of the riverine sediment fluxes, in both of the Seas; this is not only as they drain a significant percentage of their total catchment areas, but they are characterised by the highest sediment yields (Table 1). Furthermore, this contribution is more pronounced in the case of the Mediterranean Sea, as they drain 22% of its catchment (for the Black Sea, they represent only 10%) and have sediment yields >1,800 t/km^2/yr; in the case of Black Sea, they have values <500 t/km^2/yr.

Table 1. Total area (A) and suspended sediment (SS) yield of rivers with various catchment sizes.

	Mediterranean Sea			Black Sea		
Catchment Size (10^3 km^2)	Area (A) (10^3 km^2)	A/ T$_A$ (%)	SS yield (t/km^2)	Area (A) (10^3 km^2)	A/ T$_A$ (%)	SS yield (t/km^2)
<5	530	12.8	1820	234,600	10.0	467
5–50	380	9.2	570	86,700	3.7	307
50-500	340	8.2	250	712,700	30.3	125
>500	2,870	69.7	42	1,320,000	56.1	35
Total (T$_A$)	4,130	100.0		2,354,000	100.0	

HUMAN IMPACT

The major anthropogenic influence affecting sediment fluxes is the construction of river dams, over the last century. Retention of the sediments behind the dams has been related to the dammed area i.e. the area upstream of the location of the dam nearest to the sea. On the basis of this calculation (Table 2) more than 50% of the drainage basin of the Mediterranean is blocked by dams, which means that an analogous percentage of the sediment load is retained within the reservoirs. In the case of the Black Sea rivers, from data available in sediment transport before and after damming (Table 3), riverine sediment fluxes have been reduced by some 40%.

Table 2. Mediterranean Sea: a gross estimate of fluvial sediment fluxes, after damming (TL_D).

	TL (10^6 t/yr)	TL_D (a) (10^6 t/yr)	TL_D/TL (%)
Region I	425.8	289.1	32.0
Region II	109.4	57.5	52.6
Region III	164.2	118.9	72.4
Region V	119.1	49.7	41.7
Region IV	169.9	38.6	22.7
Total	988.4	553.8	56.0

(a): The estimation of sediment load reduction is based upon the percentage of the catchment controlled by dams for each region (after Poulos and Collins, 2002).

Table 3. Black Sea: a gross estimate of fluvial sediment fluxes after damming (data from Jaoshvilli, 2002; Dimitrov *et al.*, 2003).

	TL (10^6 t/yr)	TL_D (10^6 t/yr)	Reduction (TL_D/TL) (%)
Region I	193.6	165.8	14.4
Region II	36.3	18.2	50.1
Region III	28.1	20.0	28.8
Region IV	51.2	17.4	66.0
TOTAL	277.4	205.3	39.8

Note: the calculation of the total load after damming is based on measurements regarding the SSL, on the assumption that only 10% of the DL and the total bed load (BL) are retained behind the dams.

In both of the regions, a reduction in sediment supply is considered to be the primary factor responsible for the loss of coastal (mainly deltaic) land. Examples of deltaic coastline retreat, as the consequence of riverine sediment reduction due to dams is presented in Table 4, for some of the largest river deltas of the Mediterranean and Black Seas. Coastline retreat can be seen to vary from a few, up to some tens of, metres, annually.

CONCLUSIONS

The rivers draining the Mediterranean and Black Sea catchments transport, towards their associated coastlines, some 1000 10^6 and 300 10^6 tones of sediment on an annual basis; these correspond to annual sediment yields of 240 (10^3 t /km^2) and 160 (10^3 t /km^2), respectively. Hence, the Mediterranean rivers reveal a higher sediment load capacity, which expresses primarily from the ratio between SSL and DL, of 2.6:1; for the Black Sea it is 1.5:1.

The small and medium-sized rivers (<5,000 km^2) contribute large amounts of sediment load, due to their increased yields; their role is more significant in the case of the Mediterranean, as they present much higher yields (>1,500 t/km^2). In the case of the Mediterranean, such rivers drain an

Table 4. Rates of coastal retreat and related reduced sediment supply of Mediterranean rivers, following dam construction.

River/Delta	Coastal retreat (m/yr)	Reduced sediment supply (10^6 t/yr)	References
Ebro (Spain)	10-60 (1957-1973)	from 15-21, to 0.2	Jimenez *et al.* (1997); Palanques and Drake (1990)
Rhone (France)	4.5 (1954-1971)	40 in 18th century, to 12 in 1956-57 and only 4-5 in 1970	Bird (1988); Ookmens (1970)
Po (Italy)	10 (1954-1978)	from 8.4 (1945), to 6.4 (1972)	Simeoni and Bondesan (1997)
Nile (Egypt) (Rosetta Promotory)	120-240 (1965-1991)	from 125 (1900-1960), to >2 (1965-1991)	Fanos (1995) ; Degens *et al.* (1991)
Danube (Rom./Ukr.)	up to 20 1900 -1988	from 65 (1900), to 38 (1988)	McManus (2002)

area of about 22% of its overall catchment (if the R. Nile is excluded) when, in the case of the Black Sea, they represent 10% of this overall catchment.

The main human impact in both of the basins relates to the presence of the dams which have reduced the sediment supply by some 40% to 50%. Such a sediment deficit has caused enhanced coastline retreat affecting primarily the deltaic coasts. Some of the largest river deltas present retreat rates, up to tens of metres, on an annual basis.

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The authors are grateful to Mrs Kate Davis, for the artistic presentation of the figures included.

Riverine fluxes into the Black and Marmara Seas

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ABSTRACT

The Black and Marmara Seas, two land-locked seas, constitute the eastern extension of the Mediterranean Basin. The Black Sea is a large depositional basin for the rivers discharging from extensive plains of southeastern Europe, the Caucasian Mountains and from northern Anatolia. Despite their smaller drainage areas and water flows compared to those of other rivers (Danube, Dnepr, Dnester), the Anatolian rivers produce a high sediment flux to the Black Sea because of the high relief of the Pontic mountains and the absence of any flood-plain. Anatolian rivers discharge 24 million t/y sediment and 40 km^3/y water into the Black Sea, based on 20-year data. Sediment fluxes of the Anatolian rivers display variations along south-west and south-east Black Sea, due to differences in relief and the amount of precipitation in the two regions. Fresh-water fluxes of the rivers in the eastern region are higher than in the western region. Most of the sediment is carried by rivers of the central and eastern sections of the Black Sea coast of Anatolia. The riverine fluxes into the Marmara Sea are less than 1 million ton/y suspended sediment and 5 km^3/y fresh water and derived mainly from the southern coasts.

ENVIRONMENTAL SETTING

The Black Sea is the largest anoxic basin in the world; it is connected to the Mediterranean Sea via the Marmara Sea and its narrow straits, the Straits of Istanbul and Çanakkale (Figure 1).

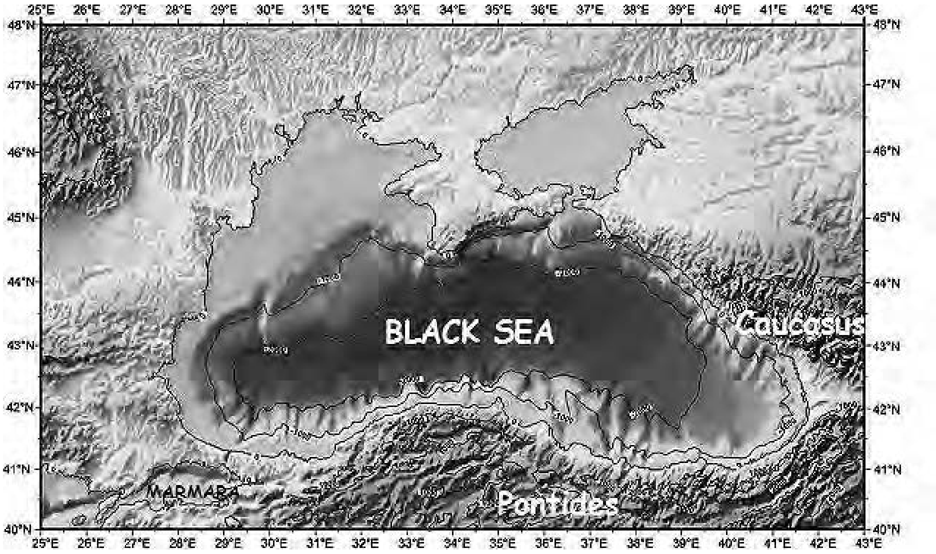

Fig. 1. Physiographic features of the Black and Marmara Seas.

Although the connection between these basins is restricted, their oceanography is closely related to each other. The fluvial sediments drained into the northern and northwestern part of the Black Sea are mostly trapped in the Danube Delta and Sea of Azov; however significant amount of suspended sediment and dissolved pollution loads from the Danube are transported towards the Istanbul Strait into the Marmara Sea by alongshore currents (Sur *et al*., 1994; Tuğrul and Polat, 1995).

The Black Sea has an approximate surface area of 425,000 km^2 which is one-fifth that of the Mediterranean Sea, and a volume of 537,000 km^3. It has a drainage area of about 2 million km^2 (1,864,000 km^2) which is almost five times greater than its surface area. Extensive plain in the west and north, and high-steep mountains in the south (Balkans and Pontides) and east (Caucasus) surround the Black Sea. 85 % of the drainage area belongs to flat relief, and only 15 % is part of the high mountains (Müller and Stoffers, 1974) where numerous small un-dammed rivers discharge into the Black Sea. The shelf area in the northwest is very wide due to accumulation of considerable amount of sediments carried by the rivers Danube, Dnester, Bug, and Dnepr (Figure 1).

The Marmara Sea is a small body of water with a surface area of 11,500 km^2 and a volume of 3,378 km^3. It is connected to the Mediterranean via Çanakkale Strait (62 km long and 1.2 -7 km wide) and to the Black Sea via Istanbul Strait (31 km long and 0.5-3.5 km wide). Less saline Black Sea waters (18-22 ppt) enter into the Marmara Sea, forming the upper layer, whereas the saltier and heavier waters of Mediterranean Sea (37.5-38.5 ppt) constitute the lower layer (Figure 2) (Ünlüata *et al*., 1990). Consequently, a permanent pycnocline between these two layers occurs at about 25 m water depth. The residence time of Black Sea originated upper layer is 4-5 months, whereas it is 6-7 years for the lower layer (Beşiktepe *et al*., 1994). Approximately 650 km^3/y of Black Sea water enters the Marmara Sea from the Istanbul Strait, but about 7 % of it is entrained into the lower layer. About 920 km^3/y of Mediterranean water enters from the Çanakkale Strait and 550 km^3/y of it enters into the Marmara Sea due to entrainment of 45 % into the upper layer in the Çanakkale Strait. 45 % of the amount reaching the Marmara is lost to the upper layer by basin-wide entrainment and 25 % of it entrains into the upper layer at the Istanbul Strait (Beşiktepe *et al*., 1994). As a result, only 300 km^3/y Mediterranean water inflows into the Black Sea. During this exchange, the Mediterranean water enters the Black Sea less salty (22 ppt) than when it started its passage at the Aegean end of the Çanakkale Strait (38 ppt) (Ünlüata *et al*., 1990). The Istanbul Strait annually carries 1.25 million ton/y of suspended solids from the Black Sea, whereas 0.9 million ton/y of suspended solids enters from the Çanakkale Strait (Baştürk *et al*., 1986).

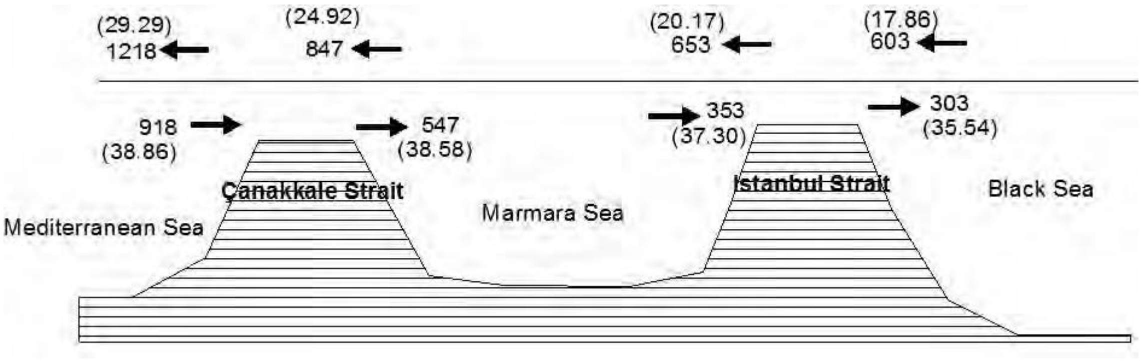

Fig. 2. Present-day water exchange between the Mediterranean and Black Seas across the Marmara Sea and TSS. Numbers in parenthesis indicate the salinity values (from Beşiktepe *et al*., 1994).

RIVERINE FLUXES INTO THE BLACK SEA: DISCHARGES FROM ANATOLIAN RIVERS

Total riverine water and sediment fluxes (after dam constructions) are summarized in Table 1. The Danube has the largest contribution with almost 50 % of the total water and sediment fluxes, among the other rivers draining into the Black Sea. A substantial amount of the sediment carried by the northern and northwestern rivers flowing over the relatively flat Eastern Europe into the Black Sea is retained by the Danube Delta and the Sea of Azov. The annual contribution of small rivers (Georgian, Russian, Bulgarian and Anatolian), discharging from the mountainous areas are 54 km^3 water and 3 million ton sediment load (Table 1).

Table 1. Rivers discharging into the Black Sea: drainage area, water discharges and sediment loads (from Shimkus and Trimonis, 1974; Müller and Stoffers, 1974; Tolmazin, 1985; Ross, 1977; Algan *et al.*, 1999; Joashvili, 2003).

River	Drainage Area (km^2)	Water (km^3/yr)/ (% in total)	Sediment (10^{6}t/yr)/(% in total)
Danube	816,000	200	51.2
Dnester	75,200	9.1	1.73
South Bug	34,000	2.2	0.2
Dnepr	574,610	43.5	0.8
Don	422,000	28.0	7.75
Kuban	63,500	12.8	8.40
Bulgarian Rivers	8,678	1.2	0.8
Russian Rivers	5,079	6.3	1.6
Georgian Rivers	28,235	37	10.1
Anatolian Rivers	251,035	40	24
TOTAL		**380**	**107**
Only Small Rivers	10,749.6	54	3

Anatolian coasts of the Black Sea are mainly of erosional type with 20-30 m high cliffs, but depositional coasts with a relatively low topography (Kızılırmak and Yeşilırmak Deltas) are also locally present. Along the 1,625 km long (Darkot, 1975) Anatolian coastline, extending from Bulgarian to Georgian borders, five major rivers and various small rivers discharge their water and sediment load into the Black Sea. The majority of Anatolian Rivers are generally linear drainage patterns and short in length, compared to other rivers flowing into the Black Sea. Sakarya, Filyos, Kızılırmak, Yeşilırmak, and Çoruh are the major rivers, whilst Karasu, Devrekani, Harşit, İyidere, and Melet are the small rivers mainly located in the east part (Figure 3). The Kızılırmak is the longest river and has the largest drainage area (Table 2).

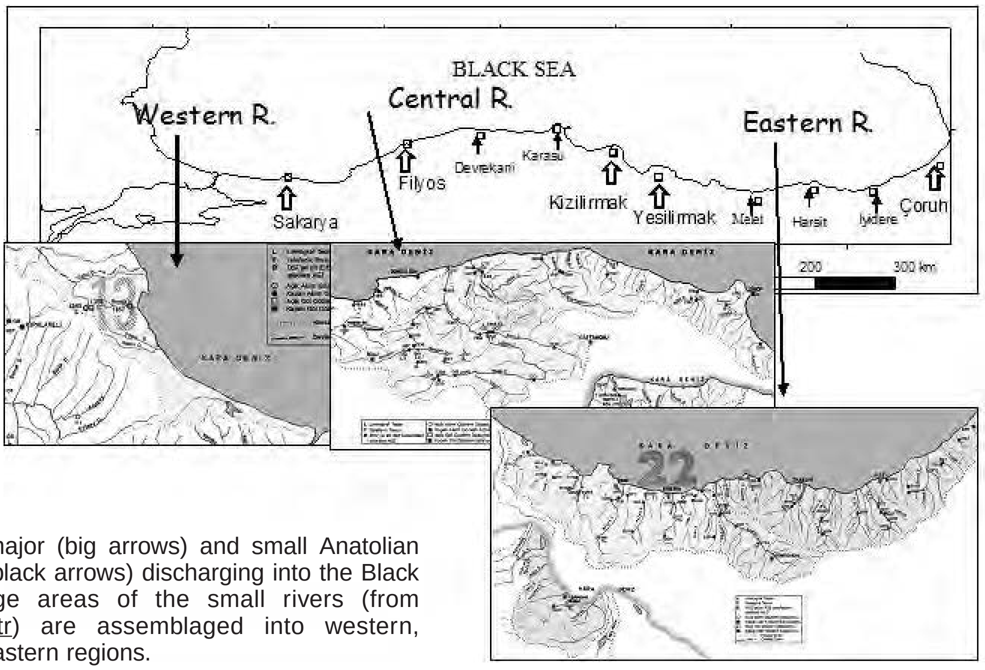

Fig. 3. The major (big arrows) and small Anatolian rivers (small black arrows) discharging into the Black Sea. Drainage areas of the small rivers (from www.eie.gov.tr) are assemblaged into western, central and eastern regions.

Average annual freshwater flux (20-year average between 1970 and 1990) of the Anatolian rivers is 40 km^3/y (Algan *et al*., 1999), contributing 10 % of the total water discharges into the Black Sea. The fresh-water discharge by rivers of the eastern and central regions is higher than by rivers of the western region because of the higher precipitation in the former regions. However, the high freshwater flux by the Sakarya River (14 %) is due to the large drainage area of this river (Table 2).

Table 2. Anatolian riverine fluxes into Black Sea: length, drainage area, water and sediment fluxes (Algan *et al*., 1999). [1] Statistical Year Book of Turkey, 1985; [2] Atalay, 1994; zbırak, 1972; EIE, 1993; [3]Algan *et al*., 1999; [4] calculated according to the same sediment load reduction rate of the Yeşilırmak; [5] Hay, 1994 and Aksu *et al*., 2002.

Rivers	Length (km)[1]	Drainage A. (km^2)[2]	Water (km^3/yr)[3]	Sediment (10^6 t/y)[3]	Sediment (Pre-dam) (10^6 t/y)[3]
Sakarya	824	56,504	5.6	3.8 (1972-90)	4.6
Filyos	228	13,156	2.9	3.7	3.7
Small Western R.[5]		7,700	2.8	1.5	1.4
Small Central R.[5]		14,600	4.5	2.7	2.7
Kızılırmak	1355	78,646	5.9	0.4[*]	16.7
Yeşilırmak	519	36,129	5.3	0.33 (1979-84)	12.5
Small Eastern R[5.]		22,200	6.8	4.0	4.0
Çoruh	466	19,984	6.3	7.5	7.5
Total		**248,919**	**39.7**	**23.9**	**53.7**

The suspended sediment load discharged into the Black Sea by Anatolian rivers is 24 million t/y (20-year average), contributing 22 % of the total load and derived mostly by the major rivers from the central and eastern regions (Algan *et al*., 1999). The highest sediment load is carried by the Çoruh River (7.5 million t/y; Figure 4). Kızılırmak and Yeşilırmak rivers appear to contribute only 2 % and 1 % of the total sediment load, respectively. However, prior to the completion of dam constructions in 1988 and 1981, Kızılırmak and Yeşilırmak rivers provided the Black Sea with more than half the sediments from Anatolia, amounting to 31 % and 24 % of the total at that time, respectively. The annual average sediment load of the Sakarya seems to have decreased since 1972 with the completion of Gökçekaya dam which is located close to the upper-course of Sakarya River.

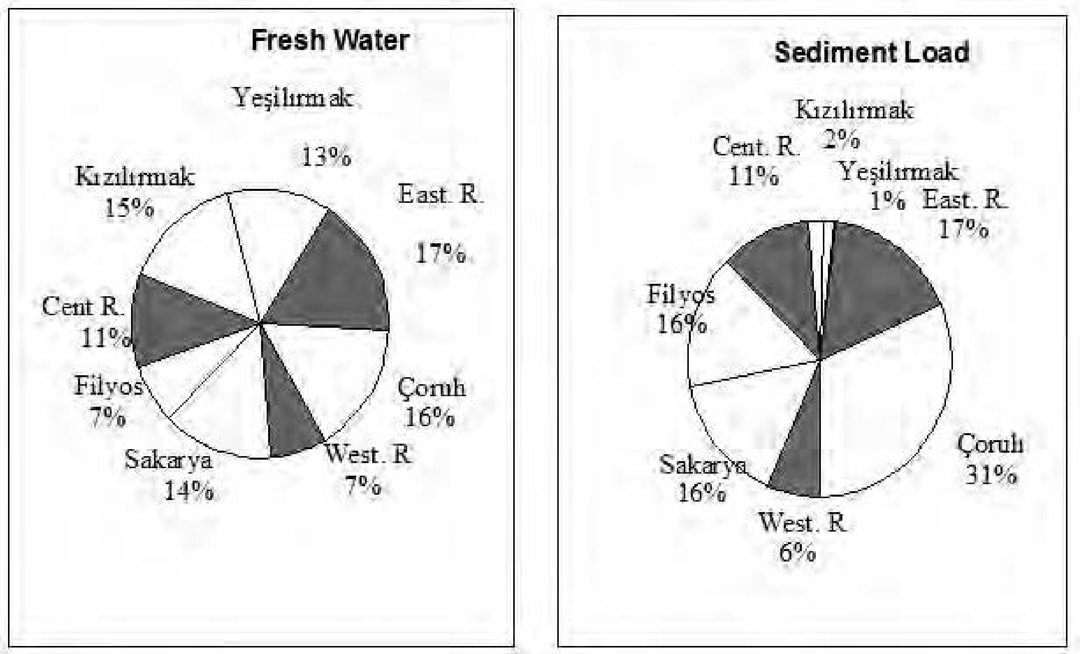

Fig. 4. Proportions of water and sediment discharges of the Anatolian Rivers. Contributions of small western, central and eastern rivers are shown in gray shades.

Maximum freshwater and suspended sediment fluxes of the major rivers (Çoruh, Yeşilırmak and Kızılırmak) generally occur in the spring, although this pattern shows small variations during the last 20 years (Figure 5). The sediment loads, with maximum discharges occurring in different months in the Sakarya and Filyos, start to increase in December and decrease in April, reaching their minima during summer. In the small rivers of the eastern region (Harşit, İyidere and Melet) the maximum discharges occurs between March and July, and the lowest in late summer (Figure6). All the rivers in the eastern and central region of the Anatolian Black Sea coast have similar characteristics, whereas the western rivers (the Sakarya and Filyos) seem to be influenced by climatic and topographical conditions different from those in the drainage areas of other rivers. The Sakarya River is longer and has a larger drainage area compared to those of the Yeşilırmak and Çoruh. The Eastern Black Sea region has a high relief with a maximum elevation of 3,932 m at Mt. Kaçkar, while the elevations and relief are much lower in the western region. The rivers of the northern slopes of the eastern mountains have much steeper gradients and narrower and deeper valleys than those of the southern slopes. Northern slopes of the eastern mountains receive higher precipitation than southern slopes. The eastern rivers receive the highest precipitation (rainfall and snowfall) between late autumn to late winter. An important portion accumulates in the mountains as snow and glaciers and melts during the spring, increasing river flow. The small rivers of the eastern region show peak sediment yields in spring and decrease in late summer. All the rivers in the eastern and central region of the Anatolian Black Sea coast have similar characteristics, whereas the Sakarya and Filyos rivers in the west seem to be influenced by climatic and topographical conditions different from those in the drainage areas of other rivers.

Two principal factors have strong impact on the sediment fluxes of Anatolian rivers discharging into the Black Sea: relief and precipitation. Despite their smaller drainage areas and water flows compared to those of other rivers (Danube, Dnepr, Dnester), the Anatolian rivers produce a high sediment flux to the Black Sea because of the high relief of the Pontic mountains and the absence of any flood-plain. The effect of relief can also be noticed among the Anatolian rivers. Most of the sediment comes from the eastern rivers (excluding the dam effects) with load being in the order: Kızılırmak>Yeşilırmak>Çoruh> Sakarya.

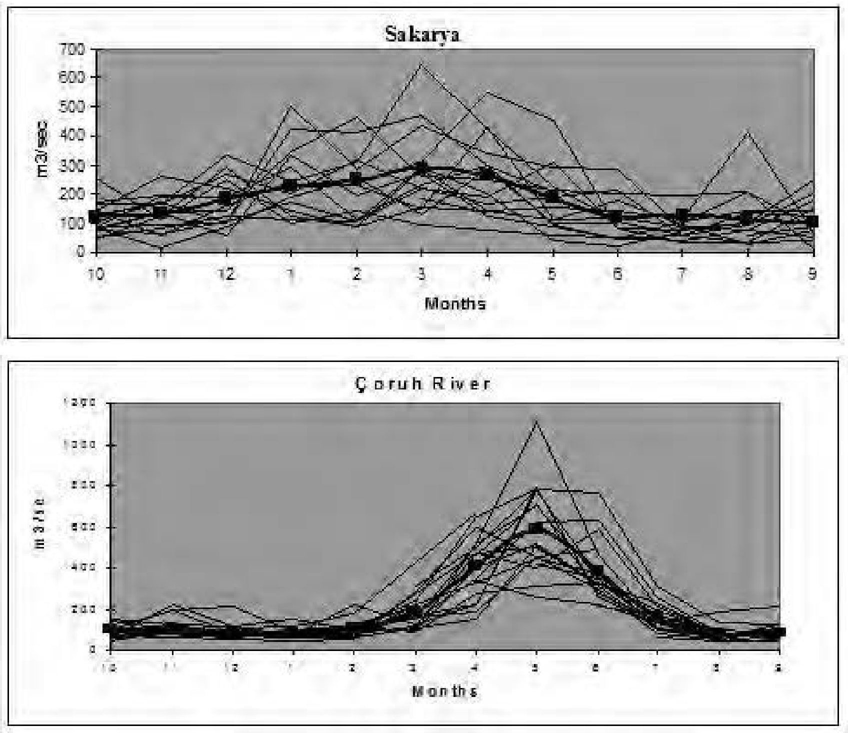

Fig. 5 a. Seasonal variations of water discharges from two major rivers (20-year data). Line with black squares denotes the 20-year average.

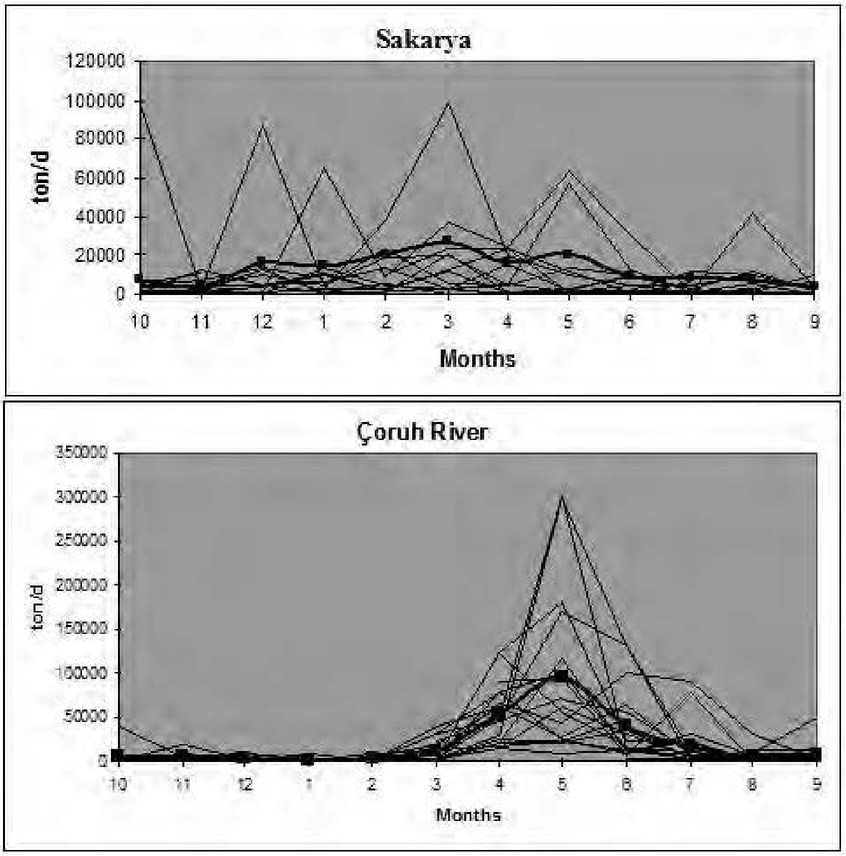

Fig. 5 b. Seasonal variations of sediment loads from two major rivers (20-year data). Line with black squares denotes the 20-year average.

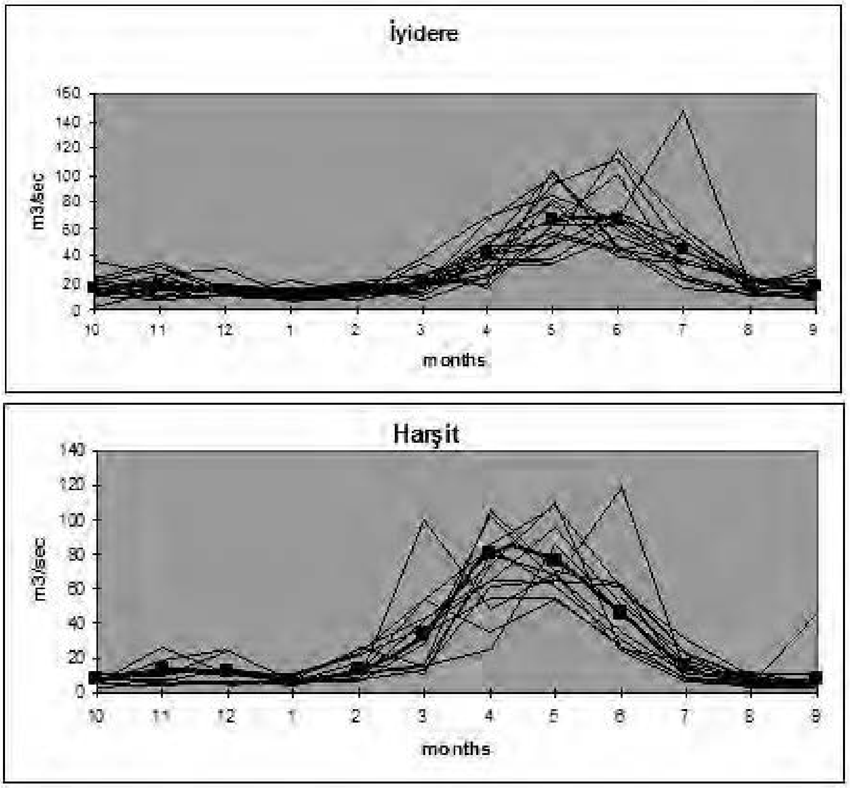

Fig. 6 a. Seasonal variations of water discharges from small eastern rivers (20-year data). Line with black squares denotes the 20-year average.

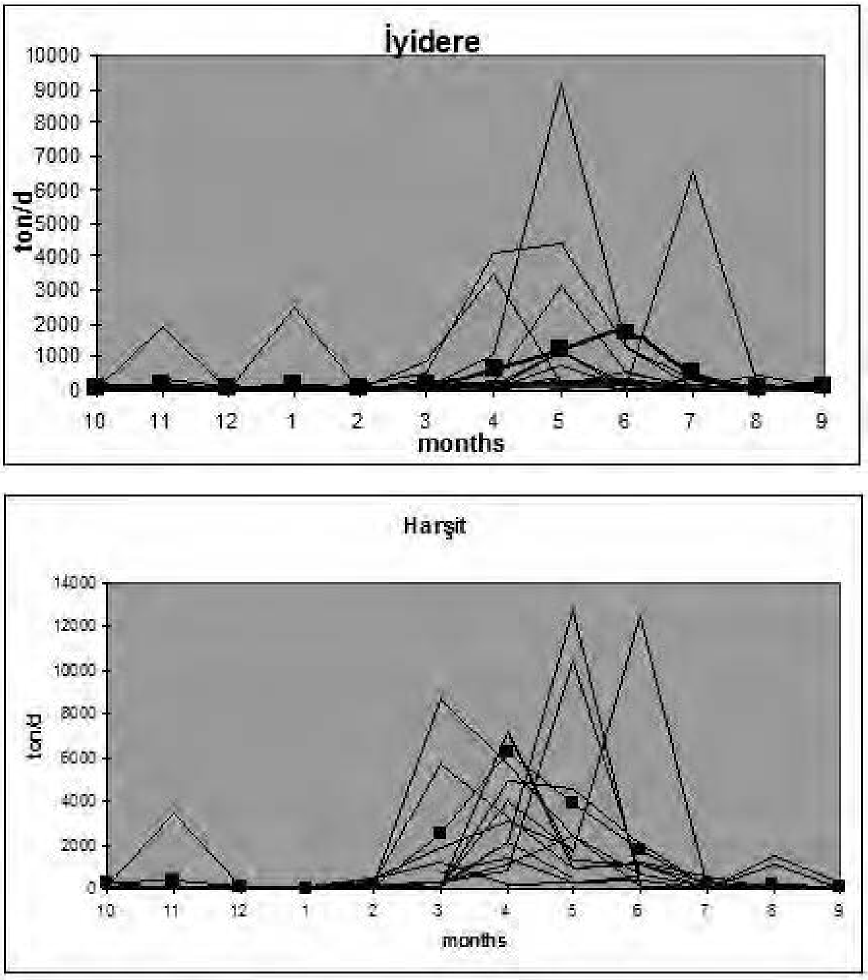

Fig. 6 b. Seasonal variations of sediment loads from small eastern rivers (20-year data). Line with black squares denotes the 20-year average.

RIVERINE FLUXES INTO THE MARMARA SEA

The Marmara Sea receives the major riverine influx from southern hinterland where relatively higher elevations are found, whereas the riverine input into the northern shelf which has a low topography, is negligible.

Table 3. Rivers discharging into Marmara Sea: drainage area, water discharges and sediment yields. [1] Statistical Year Book of Turkey, 1985; [2] Atalay, 1994; zbırak, 1972; [3] EIE, 1993.

Rivers	Length (km)[1]	Drainage A. (km^2)[2]	Water (km^3/yr)[3]	Sediment (10^6 t/y)[3]
Biga	108	2,096	0.6	0.1
Gönen	134	1,194	0.4	0.13
Kocasu/Susurluk	321	23,765	3.9	0.7
Total			**4.9**	**0.93**

There are mainly three rivers discharging into the Marmara Sea (Table 3) from the southern region. The riverine input from the northern region, where only linear small creeks are present is negligible. Kocasu/Susurluk River has the largest freshwater and suspended sediment fluxes. The total sediment load transported into the Marmara Sea is less than 1 million t/y (average between 1973-1990, EIE, 1993). The suspended sediment load of Kocasu River has reduced since 1982 after the completion of dam constructions. Maximum fresh water and suspended sediment fluxes of these rivers start in late winter and continue to spring.

Aménagements hydrauliques des bassins exoréiques de la Tunisie.
Impact sur le flux sédimentaire et la stabilité du littoral

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La mobilisation des eaux de surface en Tunisie fut depuis l'Antiquité une pratique courante en raison de l'irrégularité des précipitations. Les vestiges hydrauliques d'époques historiques différentes montrent l'importance de cette pratique au niveau de tout le territoire. Au cours du siècle dernier, l'effort de mobilisation des eaux de surface est devenu une nécessité pour répondre à une demande en eau de plus en plus importante. L'évaluation la plus récente des ressources en eau fait état de 4,503 millions de m^3 (Mm^3), dont 2,700 Mm^3 sont des eaux de surface. Afin de répondre à une demande de plus en plus croissante, des stratégies et des plans directeurs de mobilisation et d'utilisation ont été tracés par les services d'hydrauliques de Tunisie. Ainsi 23 grands barrages, 203 barrages collinaires et environ 720 lacs collinaires ont été construits. D'autres ouvrages sont programmés pour mobiliser au maximum 2,260 Mm^3/an (Ministère de l'Agriculture, 1995). Les principaux ouvrages de mobilisation des eaux de surface (grands barrages, barrages collinaires et lacs collinaires) ont été construits en particulier sur les cours d'eau du bassin hydrologique de la Mejerda.

Les bassins hydrologiques du Nord de la Tunisie se caractérisent par des reliefs jeunes dominés d'une part par des terrains marneux, des formations meubles, des sols vulnérables à l'érosion et d'autre part par un couvert végétal forestier limité aux parties les plus arrosées. A ces conditions naturelles s'ajoute le caractère torrentiel des précipitations qui s'abattent à la fin de la saison sèche et qui seraient responsables de l'érosion et de la charge solide importante des eaux de crues. Des concentrations solides supérieures à 100 g/l sont enregistrées lors des crues des Oueds Mejerda, Zeroud et Merguellil (Rodier *et al*., 1981 ; Bouzaiane et Lafforgue, 1986) situés respectivement au Nord et au Centre du pays. De ce fait, les retenues créées par les différents ouvrages hydrauliques sont toutes confrontées à plus au moins long terme à l'alluvionnement. Cette charge solide confère aux eaux des crues une densité plus élevée que celle des eaux stockées créant ainsi un courant de turbidité qui se propage au fond du réservoir quand les conditions morphologiques du fond de la retenue n'entravent pas son écoulement. Les particules solides transportées par les eaux de crues se sédimentent progressivement avec la réduction de la vitesse du courant de turbidité. Ce dernier transporte les particules fines jusqu'à l'organe de dévasement et de vidange du barrage. Une partie des apports solides fins peut être soutirée grâce à ces ouvrages. Les lâchers efficaces permettent de réduire le taux de l'alluvionnement et d'augmenter la durée de vie des barrages. De ce fait, les parties aval des cours d'eau se retrouvent privées d'une charge solide grossière importante et sont alimentées par des sédiments relativement fins. Ainsi, le flux sédimentaire en aval des ouvrages hydrauliques est-il déficitaire par rapport aux conditions hydrologiques naturelles.

1. BASSINS HYDROLOGIQUES ET AMÉNAGEMENTS HYDRAULIQUES

Le territoire tunisien est subdivisé en bassins hydrologiques (Figure 1) : Nefza-Ichkeul, Mejerda, Melian et Cap-Bon, Centre, Sahel Sousse et Sfax, Centre-Sud et Sud. A l'exception des bassins du Centre et du Centre Sud endoréiques, les autres bassins hydrologiques de la Tunisie sont exoréiques.

Fig. 1. Bassins hydrologiques exoréiques de la Tunisie.

1.1. Le bassin de Nefza-Ichkeul

Il couvre l'extrême nord de la Tunisie sur une superficie de 4,865 km^2. Son apport liquide moyen annuel est estimé à 860 Mm^3. L'abondance des eaux de surface dans ce bassin versant et leurs qualités chimiques font de cette région un véritable château d'eau du territoire tunisien.

Le bassin de l'Ichkeul en communication avec le Lac de Bizerte par l'intermédiaire de l'Oued Tinja assurait, dans les conditions naturelles, un apport liquide moyen annuel de 345 Mm^3 et 750,000 tonnes de sédiment au Lac de Bizerte. La mobilisation des eaux de surface par les barrages Joumine (1983), Ghezala (1984) et Sejnane (1994) d'une capacité de stockage totale d'environ 250 Mm^3 a entraîné un déficit des apports liquides estimés à 189 Mm^3 ainsi qu'un déficit du flux solide (non estimé) vers le lac de Bizerte.

La mobilisation des eaux superficielles du bassin de Nefza, plus récente, est assurée par les barrages Sidi El Barrak (1999) et Zouitina (1999), d'une capacité totale de 350 Mm^3. Six grands barrages sont programmés dans le bassin de Nefza : Kébir, Zerga, Moula, Ziatine, Guemgoum et El Harka (Figure 2). Avec la mise en eau de ces ouvrages, les eaux du bassin de Nefza seraient en grande partie mobilisées. De plus, soixante lacs collinaires emmagasinent les eaux de ruissellement des sous bassins versants amont; ils totalisent une capacité de stockage d'environ 3,5 Mm^3.

1.2. Le bassin de la Mejerda

Il s'étend sur une superficie totale de 23,700 km^2 sur les territoires tunisien et algérien; la partie tunisienne couvre une superficie de 16,100 km^2 (Figure 1). L'embouchure de la Mejerda se situe dans le Golfe de Tunis ; en 1939, un émissaire artificiel a été creusé au Sud de l'embouchure naturelle. L'apport liquide moyen annuel, avant les travaux d'aménagement hydrauliques (1954),

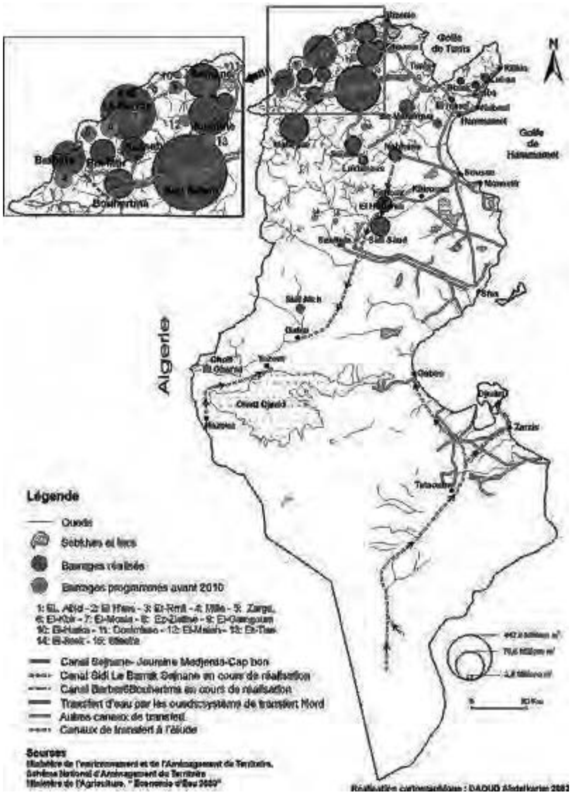

Fig. 2. Aménagements hydrauliques et réseau de transfert des eaux de Tunisie.

a été estimé à 1,000 Mm^3 avec un apport solide de 17 millions de tonnes (MT) (Pimienta, 1959) soit un taux de dégradation du bassin versant de 717 t/km^2/an. Lors des crues exceptionnelles, les apports liquides et solides peuvent atteindre des proportions plus importantes. Par exemple, en mars 1973, l'apport liquide total durant six jours a été estimé à 943 Mm^3, et les apports solides ont été évalués à 29,2 MT (Claude *et al.*, 1973). Les quatre crues de 11 janvier au 24 février 2003 ont généré l'écoulement de 1,223 Mm^3 d'eau (Ben Hassine et Rejeb, 2003) dont 1,100 Mm^3 ont été évacués du barrage Sidi Salem (Abdelhadi, 2003) et restitués à la Mejerda et par conséquent à la mer. Les apports solides relatifs à ce dernier événement hydrologique n'ont pas été quantifiés.

Les principaux affluents des deux rives de la Mejerda ont été barrés par des grands barrages (Nebeur, 1954 ; Kasseb, 1968 ; Bou Heurtma, 1976 et Siliana, 1987). D'autres barrages sont projetés, soit pour augmenter la capacité de stockage (Béjà, Tessa, Khalled, Sarrat, Chafrou), soit pour remplacer les barrages envasés (Nebeur, Sidi Salem) (Figure 3).

Le cours de la Mejerda a été barré en 1954 par un barrage de dérivation (Laroussia) puis en 1981, par un barrage de stockage (Sidi Salem). La superficie contrôlée par le barrage Sidi Salem est de 7,950 km^2. Ce dernier est le plus grand barrage de la Tunisie au point de vue capacité de stockage (550 Mm^3 portée à 615 Mm^3 après la surélévation du déversoir de 1,5 m puis à 842 Mm^3 après une deuxième surélévation du seuil à la cote 115.5 m). Les eaux stockées sont restituées au cours de la Mejerda, elles s'écoulent dans le lit de l'oued jusqu'au barrage Laroussia où elles sont déviées vers le canal Mejerda Cap Bon et le canal de la basse vallée (Figure 4). Lors des apports exceptionnels et les lâchers du barrage Sidi Salem, les eaux de la Mejerda s'écoulent vers l'embouchure en mer Méditerranée.

En plus des grands barrages, des barrages collinaires et des lacs collinaires construits dans le bassin de la Mejerda mobilisent les eaux de surface et protègent les retenues des grands barrages contre l'alluvionnement.

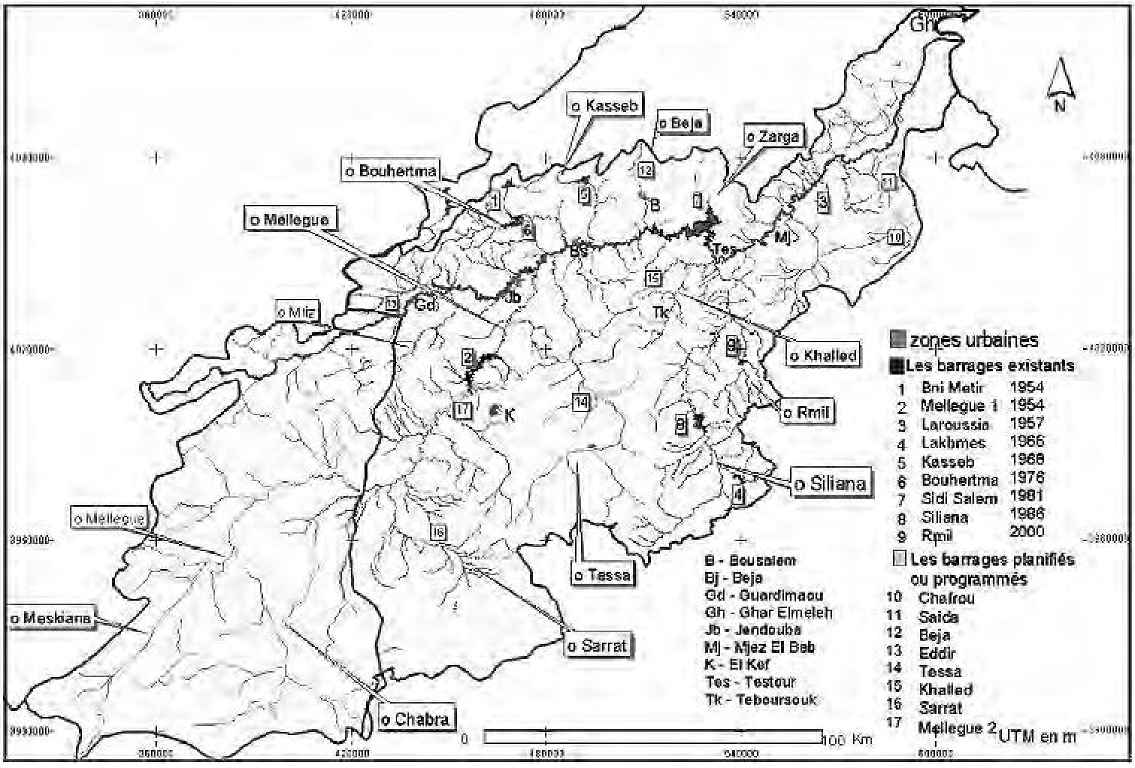

Fig. 3. Aménagements hydrauliques du bassin de la Mejerda.

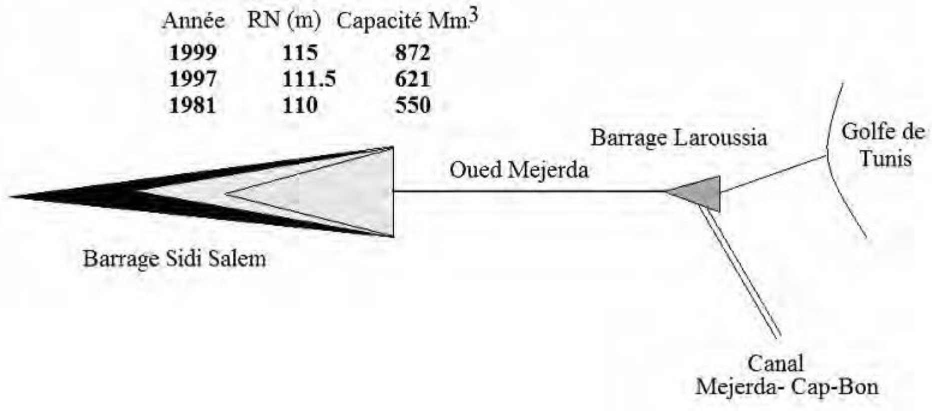

Fig. 4. Aménagement hydraulique de l'Oued Mejerda.

1.3. Les bassins côtiers de Tunis, de Meliane et du Cap Bon

La superficie totale de ces bassins est de 7,410 km^2 et l'apport hydrique moyen annuel est de 250 Mm^3. Les principaux cours d'eau des bassins côtiers de Tunis sont aménagés par des barrages et des lacs collinaires.

Le bassin amont de l'Oued Meliane (l'Oued El Kébir) a été barré depuis 1925 à Sidi Boubaker. La capacité initiale du barrage était de 22 Mm^3. Plus en aval, l'Oued Meliane a été barré en 1971 par le barrage Bir M'Cherga. Sa capacité d'exploitation est de 53 Mm^3, elle peut être augmentée à 103 Mm^3. Dans la partie aval du bassin versant, l'affluent de la rive droite de l'Oued Meliane a été barré en 2002 par le barrage El Hma d'une capacité de 12 Mm^3.

Au Cap Bon, les principaux cours d'eau sont barrés par les barrages Bezirk 1959, Masri 1968, Chiba 1963, Lebna 1986, El Abid 2002. La capacité totale de ces barrages est d'environ 50 Mm^3. Dans ce bassin plusieurs lacs collinaires sont construits.

Le total des ressources mobilisées des bassins hydrologiques du Nord est d'environ 1,450 Mm^3 sur un volume total de 1,910 Mm^3, soit 75 % du total mobilisable par le plan directeur des eaux du nord.

1.4. Le bassin du Centre

Le bassin du Centre est endoréique ; son exutoire est Sabkhet El Kalbia. Il couvre une superficie de 14,500 km^2 assurant un apport liquide moyen annuel de 190 Mm^3. Les principaux cours d'eau sont les Oueds Nebhana, Merguellil et Zeroud. Les crues importantes de ces oueds remplissaient la Sebkha et une partie des apports se déversaient en Méditerranée comme ce fut le cas en septembre 1969 avec un apport liquide total de 2,750 Mm^3. Trois grands barrages ont été construits sur ces cours d'eau : Nebhana (1965) Sidi Sâad (1982) et El Haoureb (1989) avec une capacité de stockage respective de 86,5, 209 et 95,3 Mm^3. Plusieurs barrages collinaires et lacs collinaires ont été construits dans le bassin du centre de la Tunisie. Les bassins de Nebhana et Merguellil ont fait l'objet de travaux de la Conservation des Eaux et des Sols (CES) pour réduire l'alluvionnement des retenues des barrages. L'ensemble de ces aménagements a entraîné l'assèchement prolongé de Sabkhet El Kalbia.

1.5. Le bassin du Sahel, Sousse et Sfax

Il s'étend sur 13,270 km^2 et son apport liquide moyen annuel n'est que de 60 Mm^3. Le premier grand barrage a été mis en eau en 1999 sur l'Oued Rmel d'une capacité de stockage de 22 Mm^3. Les bassins côtiers du Sahel, Sousse et Sfax drainent des bassins hydrologiques de superficie limitée et ayant des apports liquides faibles. Quelques petits ouvrages ont été construits dans ces bassins côtiers du Sahel de Tunisie.

1.6. Le bassin Centre Sud

C'est un bassin endoréique d'une superficie totale de 19,730 km^2 dont la partie tunisienne couvre 17,530 km^2 ; son apport moyen annuel est de 120 Mm^3. Les ouvrages hydrauliques construits ont pour but la recharge des nappes souterraines.

1.7. Le bassin sud

La superficie totale du bassin sud est de 32,315 km^2 et son apport moyen annuel est estimé à 120 Mm^3. Il se subdivise en deux sous-bassins côtiers (Djeffara 8,540 km^2) dont une partie est en communication directe avec le littoral et un bassin endoréique. Les bassins du sud sont aménagés par des ouvrages hydrauliques traditionnels (Tabia et Jessour) implantés le long des ravins permettant la rétention des eaux et le piégeage des produits d'érosion. De plus, les bassins côtiers ont fait l'objet de nombreux travaux de la CES réduisant les écoulements et le transport solide vers la zone littorale.

Tableau 1. Bassins hydrologiques et grands barrages de Tunisie.

Bassins	Sous bassin	Superficie (km²)	Apport liquide moyen annuel (10^6 m^3)	Grands Barrages	Superficie Contrôlée (km²)	Capacité initiale (10^6 m^3)
Nefza–Ichkeul	Nefza	2,100	500	Sidi el Barrak		250
				Zouitina		100
	Ichkeul-Bizerte	2,765	360	Joumie	418	130
				Ghezala	48	12
				Sejnane	366	138
Mejerda	Mellègue	10,600	190	Nebeur	10,300	220
	Tessa	2,500	100			
	Bou Heurtma	390	135	Bou Heurtma	390	117
	Kasseb	450	59	Kasseb	101	82
	Khalled	440	35			
	Siliana	2,200	80	Siliana	1,040	70
	Moyenne	16,130	660	Sidi Salem	7,650	550-621-824
	Mejerda	22,100	960			
Nord-est	Côtier Tunis	540				
	Meliane	2,280	50	Kébir	250	22
				Bir Mchergua	1,263	53
				El Hma	123	12
	Cap Bon	1,520	160	Bezirk	84	6.4
				Chiba	64	7.6
				Masri	53	6.7
				Lebna	199	25
				El Aid	54	18
				El Hajar	61	10
	Sahel Nord	2,070	20	Rmel	675	22

2. ALLUVIONNEMENT DES RETENUES DES BARRAGES ET DÉFICIT DU FLUX SÉDIMENTAIRE

Les retenues des barrages et les travaux de la CES piègent les alluvions et les produits d'érosion. Ils entravent le flux naturel des sédiments le long des cours d'eau et réduisent les apports détritiques aux embouchures des cours d'eau. La quantité des sédiments piégés dans les retenues des barrages varie en fonction des apports hydriques, de l'érosion du bassin hydrologique, du couvert végétal, de l'action anthropique, etc.

La quantification des sédiments piégés dans les retenues est effectuée par la direction d'exploitation des barrages. Le suivi de l'alluvionnement de quelques retenues des lacs collinaires est accompli dans le cadre d'une convention entre la direction de la CES et l'Institut de Recherche pour le Développement (IRD). Les sédiments piégés dans les retenues des barrages collinaires sont mesurés dans deux retenues sur 203 ouvrages réalisés.

Pour quelques retenues de grands barrages, il existe des données qui permettent d'évaluer l'évolution de l'alluvionnement au cours du temps. Par contre les données relatives à l'impact hydrologique des ouvrages CES sont rares voire inexistantes dans certaines régions.

Les impacts négatifs de l'alluvionnement des retenues des barrages sont multiples : diminution de la capacité de stockage, altération de la qualité des eaux, réduction du flux liquide et solide en aval, etc. Ces impacts diffèrent d'un bassin hydrologique à un autre.

2.1. Bassin de Nefza

Les aménagements hydrauliques du bassin de Nefza, récemment mis en eau, n'ont pas fait l'objet de mesures d'alluvionnement. Toutefois la connaissance de la dynamique des sables dunaires de la côte nord du pays (Oueslati, 2004) nous laisse supposer que les retenues de ces barrages seraient ensablées à un rythme accéléré. En effet, les sables dunaires du littoral sont transportés par le vent et dépassent les lignes de crêtes. Ils sont repris par les eaux de ruissellement et ils se retrouvent à l'embouchure des Oueds Ziatine et Gamgoum dans la région de Cap Serrat et Sid El

Barrak (Figure 5 a, b). L'équilibre des plages dépend d'une part de l'apport des oueds et d'autre part de l'activité de la dérive littorale, ainsi tout aménagement est susceptible de déséquilibrer le budget sédimentaire (Bourgou, 2002). La perturbation du flux des sables dunaires provoquera à long terme un déséquilibre sédimentaire important du fait que ces ouvrages sont construits près de l'embouchure des oueds. Les impacts seraient fonction du bilan entre la quantité de matériel frais qui entre dans les retenues et celle qui les quitte par soutirage.

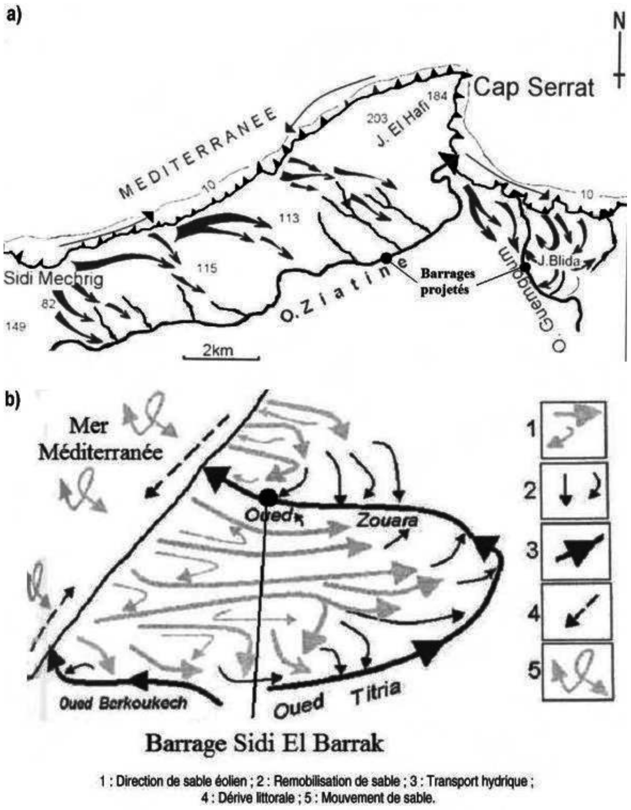

Fig. 5. Cycle du sable dunaire du littoral **a)** de Cap Serrat, nord de la Tunisie (Oueslati, 2004) ; **b)** de l'Oued Zouarar, nord de la Tunisie (Oueslati, 2004).

D'après Louati et Milutin (2000), la perte moyenne annuelle de la capacité du barrage Sidi El Barrak est estimée à environ 2 Mm^3.

Les ouvrages hydrauliques du bassin de Nefza auraient un impact négatif sur le flux sédimentaire des cours d'eau et par conséquent sur la stabilité du littoral, en particulier au niveau des embouchures des oueds. Un grand nombre de ces ouvrages se situe à quelques centaines de mètres de l'embouchure en mer.

2.2. Bassin de la Mejerda

La Mejerda, principal cours d'eau de la Tunisie, traverse le territoire d'Ouest en Est, pour déboucher dans le golfe de Tunis. A l'époque romaine, la tendance a été, au moins dans un premier temps, à une progradation de la côte, favorisée par l'apport moyen annuel de 17 MT de sédiments poussés par les courants côtiers, à partir de l'embouchure de l'Oued Mejerda. Les vestiges du port d'Utique situés à 13 kilomètres de la côte actuelle témoignent de cette progradation.

Le cours aval de la Mejerda a été canalisé vers un nouvel émissaire en mer Méditerranée en 1939 afin de réduire l'alluvionnement de la lagune de Ghar el Melah. La Mejerda et ses principaux affluents ont été barrés par six grands barrages depuis les années 1950. Deux grandes retenues ont fait l'objet de suivis de leur alluvionnement : Nebeur et Sidi Salem (Tableau 2).

Tableau 2. Caractéristiques et alluvionnement des barrages de Tunisie.

Barrage	Année de mise en eau	Ql (Mm^3)	Capacité (Mm^3)	Années des campagnes	Evolution de l'alluvionnement (Mm^3)	Alluvionnement moy. (Mm^3/an)
Beni Mtir	1954	44	61,6	1986	4	0,12
Nebeur	1954	174	270	1975, 1980, 1991, 2000	54,5 ; 90 ; 142 ; 179	2,59 ; 3,46 ; 3,8 ; 3,9
Kasseb	1968	50	82	1986	2,8	0,15
B. Heurtma	1976	73	117,5	1993	2	0,13
Lakhmess	1966	12	8,2	1975, 1991, 2000	2 ; 1,2 ; 1	0,22 ; 0,048 ; 0,029
Siliana	1987	58	70	1994, 2002	4,1	0,63
Sidi Salem	1981	448 335	550 840**	1987, 1989, 1991, 1998, 2002	30,6 ; 47 ; 52 ; 87,5 ; 139	5,1 ; 5,87 ; 5,2 ; 5,15 ; 6,6
Masri	1968	2	6,9	1975, 1991	0,88	0,037
Lebna	1986	10	30,1	1994, 2002	0,54	0,068
Bezirk	1959	4	6,4	1975, 1977, 1993		0,017
Chiba	1963	7	8	1975, 1981, 1995		0,109
Nebhana	1965	30	86	1975, 1985, 2000, 2002	12,9 ; 20 ; 24	1,29 ; 1 ; 0,68
Sidi Saad	1981	94	209	1988, 1993, 2000	6,9 ; 28,9 ; 55,2	0,98 ; 2,41 ; 2,9
El Houareb	1989	43	95,3	1994, 1998	13,3	1,48
Joumine	1983	136	130	2000	10,8	0,675
Sejnane	1994	99	137,5	2002	2,7	0,332
Ghezala	1984	14	11,7	1993	0,2	0,022
B.M'cherga	1971	44	53	1987, 1994, 2002	21,6 ; 11,4	0,37
El Kébir	1925	12,5	22	1931 ; 1945 ; 1950 ; 1954 ; 1967 ; 1968 ; 1979 1981 ; 1995	1,5 : 2,8 ; 4,8 ; 6,5 ; 10,3 ; 11,7 ; 12,8 : 13,8 ; 17,65	0,25 ; 0,14 ; 0,192 ; 0,224 ; 0,245 ; 0,272 ; 0,237 ; 0,246 ; 0,252

La retenue du barrage Nebeur d'une capacité initiale de 220 Mm^3 a piégé 179 Mm^3 de sédiments entre 1954 et 2000 soit une moyenne annuelle de 3,25 Mm^3. D'après Abid (1980), environ 25% des apports solides ont été soutirés lors des manoeuvres de dévasement. Les sédiments soutirés sont essentiellement formés de particules fines argilo-silteuses.

La mise en eau du barrage Sidi Salem sur le cours de la Mejerda en 1981 a nettement réduit la fréquence des crues dans la partie aval (Zouaoui, 2004).

Les sédiments piégés dans la retenue du barrage Sidi Salem (Figure 6) ont été évalués en 2002 à 139 Mm^3 soit une sédimentation moyenne annuelle de 6,6 Mm^3. Les volumes moyens annuels des sédiments soutirés sont de 2 Mm^3.

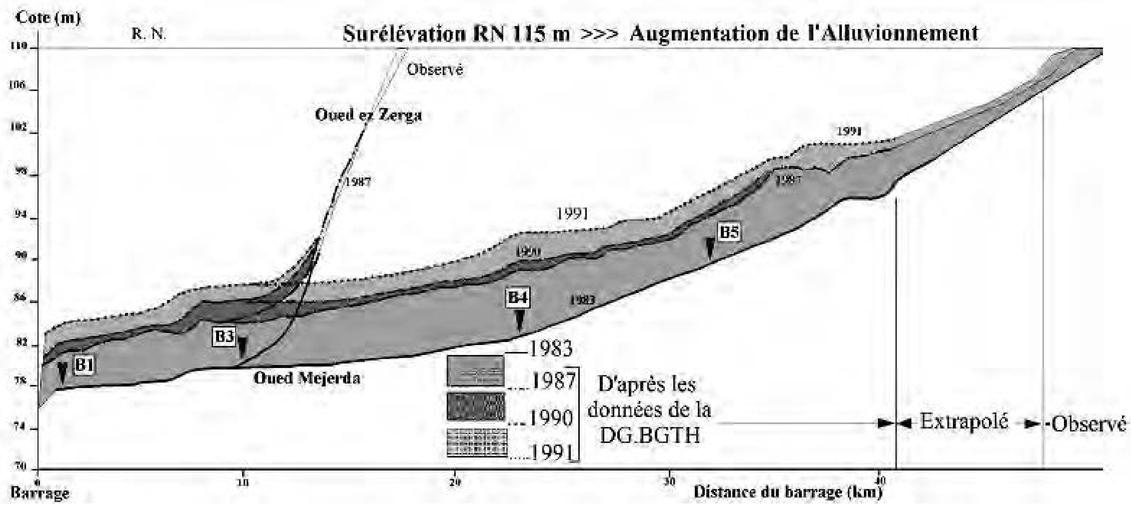

Fig. 6. Evolution de l'alluvionnement de la retenue du barrage Sidi Salem (Ben Mammou, 1998).

Les produits soutirés du barrage Sidi Salem, ont engraissé le lit de l'Oued Mejerda, réduit les sections du cours d'eau et le débit maximum de l'oued. Les changements morphologiques en aval du barrage Sidi Salem seraient en partie à l'origine de nombreux débordement et inondations enregistrées ces dernières années. En effet la débitance de la Mejerda qui était de 1,000 m^3/s avant la construction du barrage n'est plus que de 200 m^3/s (Abdelhadi, 2003).

Ces dernières années, la ville de Mejez el Bab, située en aval du barrage, est inondée dès que le débit du cours d'eau dépasse 260 m^3/s.

Les sédiments soutirés parviennent à long terme au barrage Laroussia et s'écoulent vers le canal Mejerda Cap Bon. De ce fait, la « cuvette » du barrage et le canal se colmatent annuellement. Des travaux de curage sont effectués afin d'assurer l'écoulement vers le canal et dans le canal. Les produits dragués de la retenue sont stockés sur les berges de l'oued et le long du canal.

Le déficit du flux sédimentaire à l'embouchure de l'Oued Mejerda s'est traduit au cours du temps par un amincissement de la flèche littorale. Cette dernière s'est retrouvée fragilisée et par conséquent plus vulnérable à l'érosion marine. L'évolution morphologique de l'embouchure et de la flèche littorale témoigne de l'impact de la réduction du flux sédimentaire de l'Oued Mejerda (Figure 7 a, b).

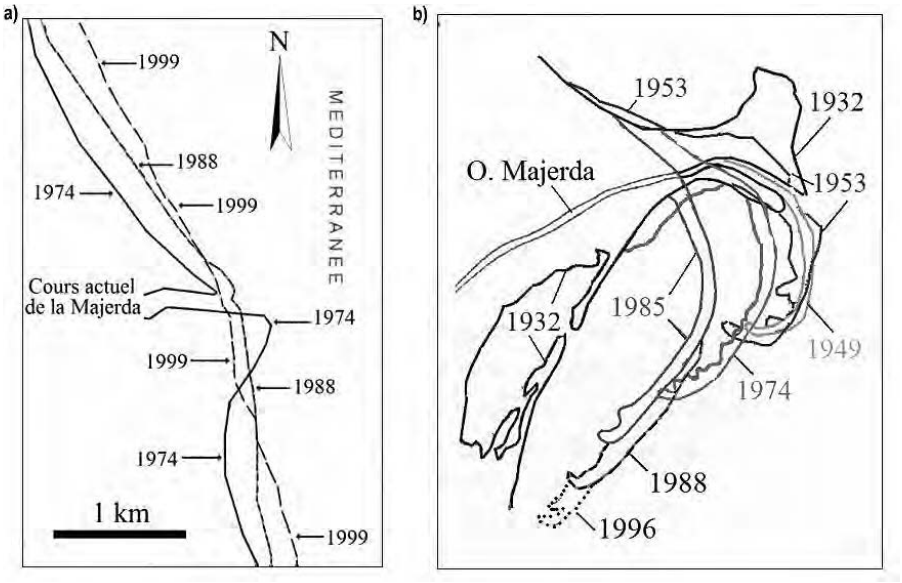

Fig. 7. **a)** Evolution de la position du rivage autour de la nouvelle embouchure de la Mejerda (Ayachi, 2004) ; **b)** Un demi siècle d'évolution de la flèche littorale de la Mejerda (Oueslati, 2004).

Ainsi ces deux ouvrages (Sidi Salem et Laroussia) piègent la totalité des apports solides de la partie amont et moyenne de la Mejerda.

Les flux liquide et solide à l'embouchure de l'oued ne sont assurés que par les apports du bassin aval non encore aménagé ou par les apports lors des crues exceptionnelles telles que celles de 2002, 2003 et 2004. Toutefois, Oueslati (2004) signale que autour de la nouvelle embouchure de l'Oued Mejerda la plage montre le maximum de son extension. La tendance générale du rivage est dans le sens de la progradation et d'une redistribution du matériel détritique de l'embouchure (Oueslati, 2004). Par contre l'érosion est très active au niveau de la flèche littorale de l'ancienne embouchure en raison de la création du nouvel émissaire de la Mejerda et des aménagements du littoral au nord de l'embouchure (Port de Ghar el Melh).

2.3. Bassin de l'Oued Miliane

Le cours de l'Oued Miliane et son affluent (Oued el Hma) ont été barrés par trois grands barrages (El Kébir, Bir M'Chergua et El Hama). Le premier grand barrage de stockage de Tunisie, construit en 1925 avec une capacité initiale de 22 Mm^3 est comblé à plus de 95% de sédiments soit une sédimentation moyenne annuelle de 0,252 Mm^3 (Ben Mammou, 1998). La retenue du barrage Bir Mcherga a piégé 11,4 Mm^3 de sédiment pour une capacité initiale de 53 Mm^3.

Le déficit de l'apport sableux continental à l'embouchure de l'Oued Miliane serait une des causes de la déstabilisation du système littoral du petit Golfe de Tunis (Soussi, 1998). Toutefois, Oueslati (2004) signale un engraissement de la plage dans les environnements immédiats de l'embouchure de l'Oued Miliane et un déficit sédimentaire par ailleurs. Ceci est lié aux apports du bassin aval dominé par un matériel sableux d'une part et par les aménagements du littoral sud du Golfe d'autre part.

2.4. Bassin de Cap Bon

Les retenues des grands barrages du Cap Bon ont piégés au total 3,59 Mm^3 de sédiments (Abid, 2003).

Les deux lacs collinaires du Cap Bon (Es Séghir et Kamech) contrôlant des bassins versants de 431 ha et 245 ha ont piégé respectivement 2,020 m^3 et 24,440 m^3 de sédiment pour une période d'exploitation de 5 et 7 ans, soit une moyenne de 404 et 3,491 m^3/an (Albergel *et al.*, 2001). Malgré la quantité des sédiments piégés dans les retenues des barrages, le déficit sédimentaire n'est pas perceptible sur le littoral du Cap Bon car le démantèlement des falaises est important le long du littoral.

2.5. Autres bassins

L'aménagement hydraulique des bassins côtiers du Sahel, Sousse, Sfax et Gabès est en nombre très réduit voire inexistant en raison de la rareté de l'eau. Le littoral sableux de toute la zone montre de ce fait des signes d'évolution naturelle, engraissement et formation de flèche littorale au niveau des embouchures des oueds tels l'Oued el Ferd et Chaffar (Oueslati, 2004). L'état du littoral à l'embouchure de l'Oued Chaffar traduit une évolution naturelle de cette partie de la côte tunisienne (Figure 8).

Fig. 8. Littoral à l'embouchure de l'Oued Chaffar, Sahel de Sfax.

3. Travaux de la CES et flux liquide et solide

Afin de protéger les retenues des barrages, des travaux de conservation des eaux et du sol ont été effectués au niveau de plusieurs bassins hydrologiques. L'impact hydrologique et sédimentologique de ces aménagements n'a pas été évalué qu'à l'échelle des petits bassins hydrologiques. D'après Nasri *et al.* (2004), l'aménagement anti-érosif en banquettes de 43% de la surface du bassin versant de l'Oued Gouazine (18,1 km^2) a limité de 50 à 80 %, les apports liquides dans la retenue du lac collinaire et par conséquent le taux d'alluvionnement de la cuvette.

La taux d'alluvionnement annuel de la retenue du barrage Nebhana affiche une régression au cours du temps (1,29 Mm^3 en 1975 et 0,68 Mm^3 en 2000). Cette diminution est étroitement liée aux actions de lutte contre l'érosion menées par le service de la CES au niveau des zones les plus exposées à l'érosion dans le bassin versant et aux nombreux lacs collinaires construits dans les parties amont du bassin versant.

Dans le bassin côtier du Sud de la Tunisie, l'impact hydrologique des travaux de la CES à l'échelle du bassin versant de Zeuss Koutine, aménagé à 80%, s'est traduit par une réduction nette des volumes liquides ruisselés (Tableau 3) pour des épisodes pluvieux ayant généré des précipitations différentes (Yahyaoui *et al*., 2002).

Tableau 3. Volume d'eau ruisselé lors des épisodes pluvieux sur le bassin de Zeuss Koutine (Yahyaoui *et al*., 2002).

Episodes pluvieux	Précipitations (mm)	Volume ruisselé (10^6 m^3)
Septembre – octobre 1995	46 à 48	29,4
Septembre 1997	60 à 80	15,7
Octobre 1998	75 à 90	10,6

4. CONCLUSION

Le littoral tunisien, long de 1,148 km, est constitué pour près de moitié de plages de sable. L'érosion côtière touche souvent des dizaines de kilomètres du littoral surtout dans le Golfe de Tunis. Ces derniers temps, la situation est devenue véritablement alarmante en de nombreux endroits des côtes tunisiennes. Des preuves d'une tendance au démaigrissement des plages ont été identifiées même dans les terrains évoluant à l'abri des aménagements, mais les plus manifestes appartiennent aux côtes les plus anciennement et les plus fortement anthropisées (Oueslati, 2004).

L'explication de l'érosion des plages par une pénurie sédimentaire revient dans nombre d'études. Plusieurs explications sur l'origine de cette érosion ont été avancées : variation climatique, actions anthropiques le long du littoral et aménagements hydrauliques dans les bassins versants des principaux cours d'eau exoréiques.

L'évolution régressive des plages tunisiennes a été facilitée par les aménagements portuaires qui altèrent la dynamique côtière et perturbent le transit des matériaux (Oueslati, 2004). L'érosion côtière pourrait être également liée en partie aux aménagements hydrauliques (barrage de stockage), à d'autres formes d'infrastructures hydrauliques (ouvrages d'épandages, canaux de transfert et canaux de drainage) et aux travaux de Conservation des Eaux et des Sols (CES). Tous ces ouvrages entravent le flux naturel d'alluvions des cours d'eau et piègent les produits d'érosion des versants que les cours d'eau charriaient jusqu'à la mer. Les bassins avals non aménagés continuent de fournir une partie des apports solides pouvant maintenir l'équilibre du littoral dans les environs immédiats de l'embouchure.

Il est certain que les aménagements hydrauliques des cours d'eau exoréiques sont à l'origine d'un déficit du flux sédimentaire et ils seraient responsables en partie de la dégradation du littoral. A titre d'exemple le littoral du Golfe de Tunis a été dépourvu depuis 1954 d'un flux solide total d'environ 364 Mm^3, correspondant aux volumes de sédiments piégés dans les retenues des grands barrages des bassins de la Mejerda (333 Mm^3), de Melian (30 Mm^3) et du Cap Bon (1,3 Mm^3). Ce déficit est en réalité plus important si on tient compte de l'ensemble des ouvrages de stockage (grands barrages, barrages et lac collinaires) relativement abondant dans ces bassins. Ce déficit peut être évalué si on tient compte du volume des apports solides moyen annuel avant les aménagements hydrauliques (14,16 Mm^3). De 1954 à 2002, le déficit du flux sédimentaire dans le Golfe de Tunis représente environ 54% des apports. Toutefois cette évaluation est très approximative : en effet, on sait que les crues exceptionnelles peuvent compenser le déficit sédimentaire de plusieurs années (apports solides de 1969).

L'impact des ouvrages hydrauliques du bassin du Golfe de Tunis sur le littoral s'est traduit par une réduction certaine du matériel sableux en faveur d'un matériel plus fin silto-argileux. Ce déficit de sable au niveau des embouchures des Oueds Mejerda et Meliane serait en partie à l'origine de la dégradation des plages et de l'érosion active des plages (Figure 9).

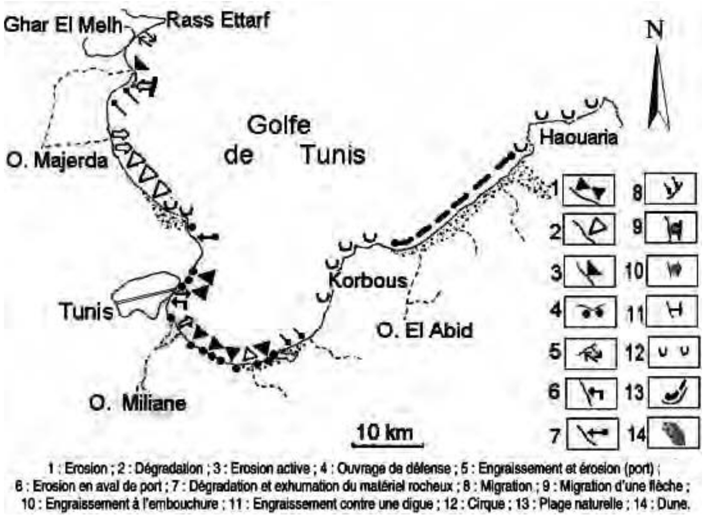

Fig. 9. Etat des plages dans le Golfe de Tunis (Oueslati, 2004).

Par ailleurs le matériel silto-argileux est restitué lors des manoeuvres de dévasement des retenues des barrages. Dans les conditions hydrodynamiques naturelles, les sédiments fins se sédimentaient au niveau des pro delta alors qu'actuellement ce matériel a tendance à floculer au contact des eaux marines et à se sédimenter rapidement. Ceci s'est traduit par une évolution du faciès des dépôts autour de l'embouchure de la Mejerda. Oueslati (2004) signale que le rivage dans les environs de l'embouchure est formé de microfalaise taillée dans un matériel vaseux noirâtre correspondant aux apports de l'Oued Mejerda.

Pour les bassins de l'extrême nord, les aménagements hydrauliques réalisés (Sidi El Barrak) ou projetés (Ziatine, Gamgoum et El Harka) se situent près des embouchures des oueds. Ils seraient à l'origine d'un déficit sédimentaire de 100%. L'impact de ces aménagements sur le littoral serait plus accentué, aussi le suivi s'impose-t-il dans cette partie de la Tunisie.

Problématique de l'érosion hydrique et son impact sur l'environnement en Algérie septentrionale

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RÉSUMÉ

L'érosion hydrique pose de graves problèmes en Algérie du Nord, là où plus de 70 % de la population est concentrée. De par sa nature géologique, l'Algérie du Nord est traversée d'une chaîne tellienne d'Ouest en Est, séparant le littoral des plaines intérieures. Plusieurs bassins versants sont tributaires de la Méditerranée soit sur 1,200 km de côtes. Chaque année, plus d'un million de m^3 de sédiments sont déposés en mer. Cet apport de sédiments en mer contribue largement à la stabilisation du système côtier. Cependant, il présente une gravité majeure dans la gestion conservatoire des ressources en eau et en sol en Algérie du Nord. La question est posée : faut-il préserver le littoral en laissant les sédiments arriver en mer pour la stabilisation du littoral (développement du tourisme) ou lutter contre l'érosion des sols et l'envasement des barrages ?

L'intérêt économique est un enjeu important à définir, une gestion intégrée des systèmes côtiers s'impose.

Land erosion by water and its impact on the environment of northern Algeria

Abstract

Land erosion by water poses serious problems in Northern Algeria, where more than 70 % of the population is concentrated. In terms of its geological setting, Northern Algeria is crossed by a tellienne chain from West to East, separating the littoral from the interior plains. Several basins are tributaries of the Mediterranean, discharging into 1,200 km of coastline. Each year, more than a million m^3 of sediment are deposited within sea, contributing largely to the coastal system stabilisation. However, this presents a serious problem to the conservation/management of the groundwater and water resources of northern Algeria. The question concerns the necessity to preserve the coastline (development of tourism), or to combat erosion and the silting up of dams (water mobilisation).

In the context of high economic interest, integrated management of the coastal systems appears as a priority.

INTRODUCTION

En Algérie septentrionale, les conséquences de l'érosion hydrique sont désastreuses et spectaculaires, offrant un paysage nu, sillonné par un ravinement intense, particulièrement dans les régions montagneuses à réseau d'écoulement dense, menaçant les infrastructures hydrauliques, routières et portuaires par une déposition et une sédimentation précoce.

L'érosion est liée à des facteurs naturels et anthropiques difficilement maîtrisables, évolutifs aussi bien dans l'espace que dans le temps. Elle affecte les infrastructures hydro- agricoles et côtières de telle sorte qu'il est parfois quasi-impossible d'y remédier.

Par ailleurs, si ce phénomène pose de graves problèmes dans la gestion conservatoire en eau et en sol en zone semi aride pour les hydrologues, il reste cependant très bénéfique pour les gestionnaires du littoral qui ne demandent qu'à laisser arriver les sédiments en mer pour la stabilisation du système côtier. Un choix s'impose et ne peut être accepté que dans le cadre d'une gestion intégrée des bassins versants tributaires de la Méditerranée.

PROBLÉMATIQUE DE L'ÉROSION

Le transport solide occupe une place importante et très vaste dans le domaine de l'hydrologie et de la régularisation des débits. Plusieurs définitions sont données au phénomène de l'érosion ; la plus simple est celle de Gréco (1960) qui définit l'érosion comme étant un phénomène spatial et temporel consistant en un arrachage, un transport et un dépôt des particules du sol, sous l'effet d'agents externes : pluie, vent, grêle, température, homme, etc.

La forme hydrique de l'érosion est la plus importante en Algérie septentrionale. Elle menace tous les jours les terres agricoles, les infrastructures hydrauliques par l'arrachage, l'affouillement, le transport et le dépôt des sédiments qui se colmatent pour créer des exhaussements de lits d'oueds, des sapements de berges, des inondations, des envasements d'infrastructures hydrauliques (barrages, canaux, stations de pompage, etc.) et portuaires, sans oublier les dépôts sur les plages le long du littoral.

Plusieurs facteurs entrent en jeu et amplifient le problème. Les averses orageuses de fortes intensités ($I > 100$ mm/h) sont fréquentes en automne (Arabi *et al*., 1989) au moment où la couverture végétale est absente. Les pluies torrentielles [($I > 24$mm/h), Demmak, 1982], irrégulières, aussi bien dans l'espace que dans le temps, engendrent en des temps de concentration très courts, des crues fortes, rapides et chargées dont les conséquences ont des répercussions directes, tant à l'amont par des pertes de sol et des ravinements, qu'à l'aval par des détarages de stations hydrométriques, des inondations et des dépôts de sédiments (routes, autoroutes, barrages, côte, etc.).

Avec une érosion spécifique moyenne annuelle variant entre 2,000 et 4,000t/km^2, l'Algérie se classe parmi les pays les plus érodibles du monde (Demmak, 1982), entraînant une durée d'exploitation des barrages de seulement 30 ans.

Pour la chaîne côtière du Dahra, l'érosion spécifique annuelle est estimée à plus de 4,000t/km^2.

L'érosion hydrique pose de graves problèmes socio-économiques poussant la population à l'exode rural, suite à la réduction de la surface agricole utile. Selon Heusch (1977), l'érosion spécifique est estimée annuellement à 800t/km^2 pour l'Afrique du nord.

A l'arrachage des particules fines, se greffe le transport des sédiments favorisés par des reliefs accidentés, pentus, défrichés et un surpâturage intensif. Cette dernière hypothèse est confirmée par Avias (1997) qui explique que si 800 moutons traversent un pré un jour de pluie, il ne reste plus d'herbe, ni même de racines d'herbes après leur passage, et si la pente est suffisante, il se déclenche lors des grandes pluies une érosion par ruissellement et par ravineaux et ravins dont certains peuvent dépasser 1 m de profondeur.

Chaque année, on estime à plus 1 Millions de m^3 la quantité de sédiments déposés en mer pour les seuls bassins tributaires de la Méditerranée (Demmak, 1982).

L'ampleur de l'érosion et ses stades d'évolution, confère à la nature des paysages très différents les uns des autres, passant graduellement de la griffe au ravinement (Photo 1).

Photo 1. Agriculture d'autosubsistance et accélération de l'érosion. Paysage déchiré par l'érosion (Bassin de la Mina).

Plusieurs travaux de par le monde ont été menés dans le souci de pouvoir quantifier ce phénomène. Cependant, vu les difficultés rencontrées, chaque étude ne concerne en général qu'une forme d'érosion.

La forme la plus grave de l'érosion en Algérie est l'érosion par ravinement du réseau d'écoulement, qui peut représenter à elle seule plus de 50% de l'apport solide annuel.

Les lâchers d'eau des barrages peuvent basculer facilement la balance en apport de sédiment. C'est le cas du barrage de Bakhadda, où nous avons observé pour la seule année 1994/95 au droit de la station de Oued El-Abtal (drainant le bassin versant de l'Oued Mina), un apport de sédiment (suite aux lâchers) représentant cinq fois l'apport moyen interannuel (Touaibia, 2000).

C'est aussi le cas du barrage de dérivation de Mouzaïa (Blida) qui fait transiter les lâchers du barrage Bouroumi vers la capitale, où 50,000 m^3 de vase doivent être enlevés tous les six mois pour le maintenir en exploitation (Touaibia *et al.*, 2005) soit le 5/6 de la capacité de l'ouvrage (Photo 2).

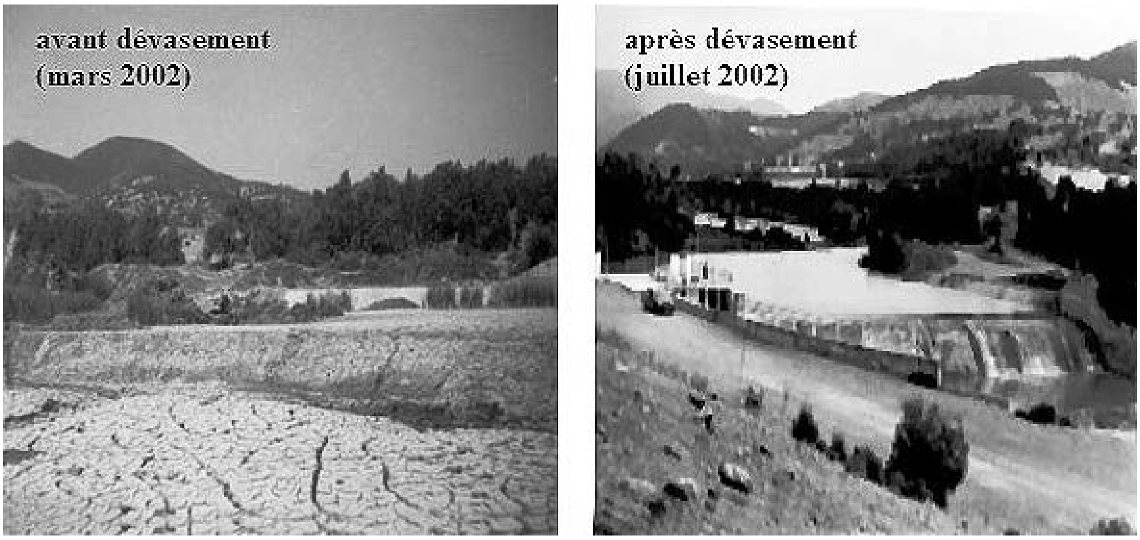

Photo 2. Barrage de dérivation de Mouzaïa (15 km de la côte à vol d'oiseau).

En dehors des bassins versants dominés par des barrages, la quantification de l'érosion n'a pas été faite par manque d'informations relatives aux données de débit solide au niveau des embouchures des oueds. Quelques photos prises le 2 mars 2006, montrent la gravité du phénomène (Photos 3 et 4).

Photo 3. Embouchure de Oued Damous (mars 2006).

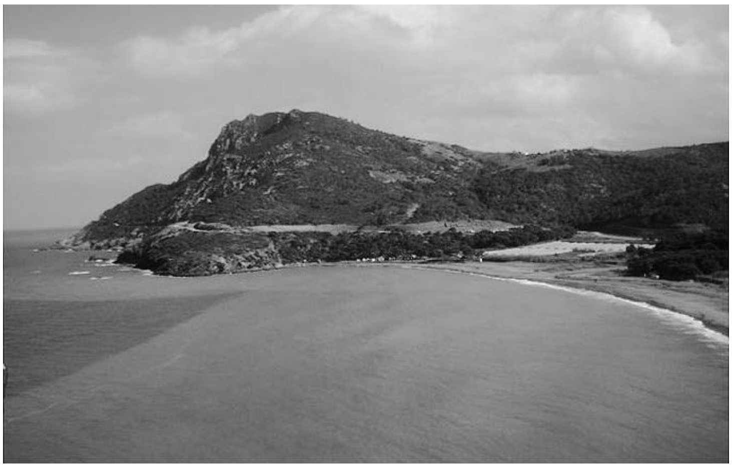

Photo 4. Plage de Boucheral (mars 2006).

Seulement, si nous jalonnons la côte algérienne centrale (Dahra) en fin d'hiver, une bande plus ou moins large à la confluence des oueds montre une eau très chargée de sédiments qui peut s'étendre à des kilomètres de part et d'autre de la confluence touchant de plein fouet les plages (Photo 5).

Photo 5. Plage de Oued Messelmoun (mars 2006).

Le recul des plages et des rivages s'accentue de plus en plus, lié non seulement à une modification de la morphologie des falaises suite à la houle (Photo 6) mais aussi à une urbanisation anarchique avec une concentration de la population, une agriculture maraîchère intensive en bordure de la mer (Photo 7) et une surexploitation des sables de plages et des roches des falaises pour la construction.

Photo 6. Erosion des falaises (Tipaza 2006).

Photo 7. Agriculture maraîchère intensive (mars 2006).

En période estivale, les sables des plages sont mélangés à des argiles et des limons déposés après la houle. Ce phénomène, difficilement maîtrisable, continue à dégrader les terres à l'amont et à déposer les sédiments à l'aval, accentué par le facteur anthropique.

En période hivernale, le transport solide est très visible dans les cours d'eau (Photo 8).

Photo 8. Oued Chiffa, affluent de l'Oued Mazaphran qui se jette dans la mer (30 km de la côte), janvier 2006.

Le bassin côtier central (Dahra) est limité par plus de 350 km de côtes avec un réseau d'écoulement dépassant les 800 km, drainant une surface topographique d'environ 9,000 km².

Cinq barrages s'y trouvent (Figure 1) ; une quantification de l'érosion a été faite sur deux d'entre eux (Bouroumi et Keddara) dont la capacité dépasse 100Mm^3. A partir des données observées en 2002, comparativement à la bathymétrie l'érosion spécifique moyenne annuelle est estimée respectivement à 69.33 et 32.15 t/ha^{-1} (Touaibia *et al*., 2003), dépassant largement le seuil tolérable de 10 t/ha^{-1}.

Fig. 1. Situation du bassin côtier central.

En plus des dépôts de sédiments sur les rivages, se greffe la pollution côtière, liée notamment au rejet des eaux d'égout) (Photos 9 et 10) se répercutant sur la flore et la faune marines.

Photo 9. Crique (pollution).

Photo 10. Embouchure de Oued Allala (transport solide et eaux résiduaires).

Conclusion

L’impact de l’érosion des sols sur les infrastructures hydrauliques et des dépôts des sédiments en mer sur la côte algérienne est spectaculaire. Si, à court terme, il ne se fait pas sentir puisque le tourisme n’est pas développé, avec le progrès socio-économique notre rivage sera vite en danger si des mesures draconiennes ne sont pas prises. Une gestion intégrée de tous les bassins versants tributaires de la Méditerranée est à envisager.

Impact des barrages sur la dynamique des côtes et sur l'évolution des littoraux au Maroc nord oriental (Maroc)

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1. INTRODUCTION

Le littoral méditerranéen du Maroc oriental entre Ras Kebdana et Saidia, est caractérisé par son étendue, par l'importance de sa plage sableuse et par son caractère balnéaire. Ce littoral subit des contraintes et des transformations qui pourraient se répercuter sur l'état présent et futur de ses plages. Ces répercussions sont dues à l'évolution du delta de l'Oued Moulouya d'un côté et à la dérive littorale de l'autre. Depuis la construction des barrages sur la Moulouya à l'amont, les apports sont de plus en plus piégés, entraînant une nette modification du delta ainsi que de la ligne des côtes de part et d'autre de l'embouchure de l'Oued Moulouya.

Sur le littoral, l'évolution morphologique est liée, en premier lieu, à la dynamique météo-marine (dérive littorale) et à la dynamique fluviale de l'Oued Moulouya en tant qu'artère principale drainant un bassin versant de 53,000 km^2 de superficie dont l'apport en éléments fins fût toujours considérable (avant la mise en place des barrages Mechra Hamadi et plus à l'amont celui de Mohamed V et plus récemment celui de Hassan II sur l'Oued Za), et ensuite aux conditions litho-morphologiques qui ont contribué et qui contribuent toujours à influencer la morphogenèse du littoral dans cette zone.

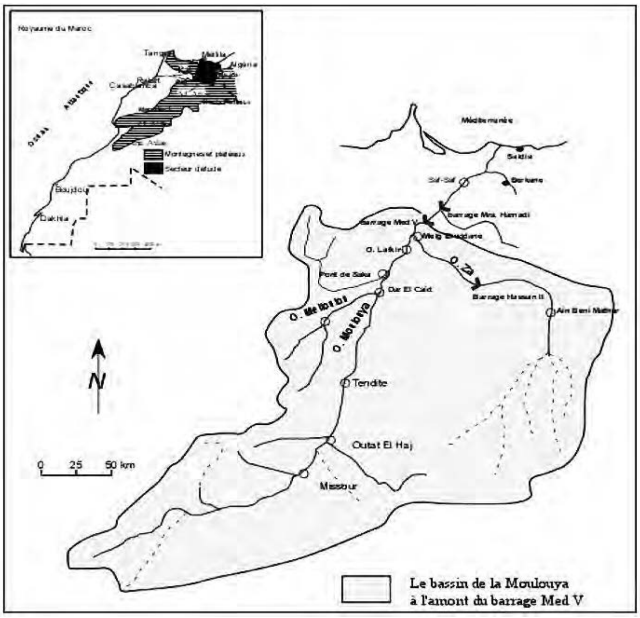

Fig. 1. Le bassin de la Moulouya à l'amont des barrages.

Au Maroc oriental, le milieu naturel est caractérisé par une sécheresse prolongée et des précipitations très réduites mais souvent très brutales en forme d'averses. La faiblesse du couvert végétal et la brutalité des précipitations influencent la dégradation des sols et accélèrent l'érosion et par conséquent accentuent le charriage des alluvions par les talwegs, les oueds et les principaux affluents vers l'Oued Moulouya. Il en résulte le développement de deltas qui se créent à l'amont du lac de barrage et de nouvelles plaines alluviales apparaissent. Mais, néanmoins, la persistance de ce rythme influence avec le temps la capacité d'emmagasinement du barrage.

2. CADRE HYDROLOGIQUE ET DYNAMIQUE DU BASSIN DE LA MOULOUYA

2.1. Dynamique hydrologique de la Moulouya et de ses affluents

Située à 5 km à l'amont du barrage Mohamed V, la station hydrologique de Melg El Widane enregistre le total du débit que reçoit la Moulouya de son bassin amont dont la superficie est de 49,000 km^2. L'apport moyen annuel au barrage est de 768 millions de m^3 d'eau.

Fig. 2. Vue du barrage Mohamed V sur la Moulouya (Image © digital Globe 2005).

Vu la nature du substrat, la densité du couvert végétal et l'intensité des précipitations à l'amont, le barrage Mohamed V reçoit une quantité annuelle d'eau très chargée en éléments en suspension (Tableau 1). Les mesures faites dans les stations hydrologiques de Dar El Caïd à la confluence de l'Oued Melloulou et la Moulouya, sur l'Oued Za, à Taourirt et sur l'Oued M'Soun au pont de Saka-Guercif, ont révélé que la concentration des limons en suspension dans la Moulouya varient de 0,1 à 1,2 kg/m^3 pour les débits de base et de crues et de 50 à 100 kg/m^3 pour les crues exceptionnelles (comme celles de 1963). Ceci entraîne une dégradation moyenne annuelle de 156 t/km^2/an.

Tableau 1. Relevés de débits et des moyennes de transport solide sur la Moulouya entre 1965 et 1985 (Source A. Lahlou, 1994, Rabat).

Stations et oueds	Volume d'eau écoulé M/A	Transports solides M/A
Dar El Caïd (Moulouya + Oued Melloulou)	850 10^6 m^3	7,5 10^6 m^3
Oued Za + Oued M'Soun	250 10^6 m^3	0,3 10^6 m^3
Barrage Mohamed V	1.100 10^6 m^3	7,8 10^6 m^3

Avant la construction des barrages toute cette charge aboutissait à l'aval. Au cours de l'Holocène elle a permis la construction des terrasses limoneuses qu'on observe encore sur la Moulouya. En fait les 726 millions de mètres cubes de réserve du barrage Mohammed V risquent d'être comblés en 2030, soit 63 ans après sa mise en service. A ce jour, il a déjà perdu pratiquement la moitié de son potentiel.

Les débits enregistrés à la station hydrologique de Melg El Widane attestent du caractère parfois torrentiel de l'écoulement de la Moulouya avant son accès au barrage. Des débits moyens journaliers varient selon les saisons et selon les précipitations plus ou moins brutales que subissent quelques parties du bassin moyen et supérieur (voir Figure 3).

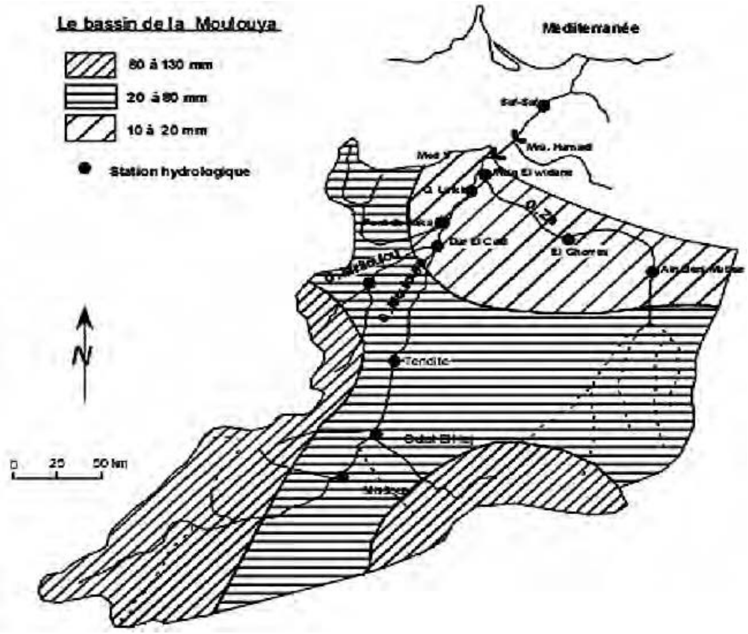

Fig. 3. Total des précipitations pour la période du 12 au 15 novembre 1993, (d'après Messouadi et Chikri 1994, modifié).

D'autres débits, soit journaliers soit instantanés peuvent se produire tel le mois de novembre 1993 (Tableau 2 et Figure 3), suite à des perturbations violentes qui ont intéressé le bassin à l'amont proche, en moyenne Moulouya. Ainsi, le débit maximum journalier a atteint 3,731 m^3/sec le 16 novembre avec un débit exceptionnel instantané enregistré à 6,429 m^3/sec.

Généralement l'Oued Za, constitue la principale artère de drainage des apports issus de l'est, le Melloulou et la Moulouya pour les apports issus du Moyen Atlas et enfin l'Oued Msoun pour les apports issus de l'ouest et du nord ouest. La station de Melga El Widane représente le point de confluence de tous les apports du bassin de la Moulouya avant l'accès au barrage.

Tableau 2. Quelques exemples de débits enregistrés à la station de Melga El Widane juste à l'amont le barrage Mohamed V (Sources : DGH, Rabat 2001).

Années	Mois	Jour	QJ	QI Max	Heure QI Max
1975	4	18	49,9	55,6	0
1975	4	19	208	1400	23h30
1975	4	20	2490	3300	16h00
1975	4	21	1880	2340	0
1975	4	22	963	1580	0
1975	4	23	395	591	0
1993	11	14	209	517	23h30
1993	11	15	496	644	9h00
1993	11	16	3731	6429	6h00
1993	11	17	1146	2750	0
1993	11	18	249	456	1h00
1993	11	19	170	1853	3h00

2.2. Variations hydroclimatiques

En tant que bassin méditerranéen, la Moulouya est soumise à des variations interannuelles. Les données hydrologiques disponibles (1961-1995) (d’après Snoussi et Imassi, 2003) ont été employées pour calculer le coefficient hydroclimatique (EC) :

EC %= [*Qma* – *Qmi*]/ *Qma*

là où *Qma* est le moyen des écoulements annuels et le *Qmi* est le total des écoulements interannuel moyens.

La variation à long terme de ce coefficient (Figure 4) montre une certaine évolution à la baisse à partir de 1962, liée aux conditions climatiques pendant cette période (Belkheiri *et al*., 1987 ; Direction de la Météorologie Nationale, 1993). Entre 1990 et 1994 l’impact de la sécheresse est cependant moins grave dans le bassin d’Oued Moulouya par rapport à d’autres bassins du pays.

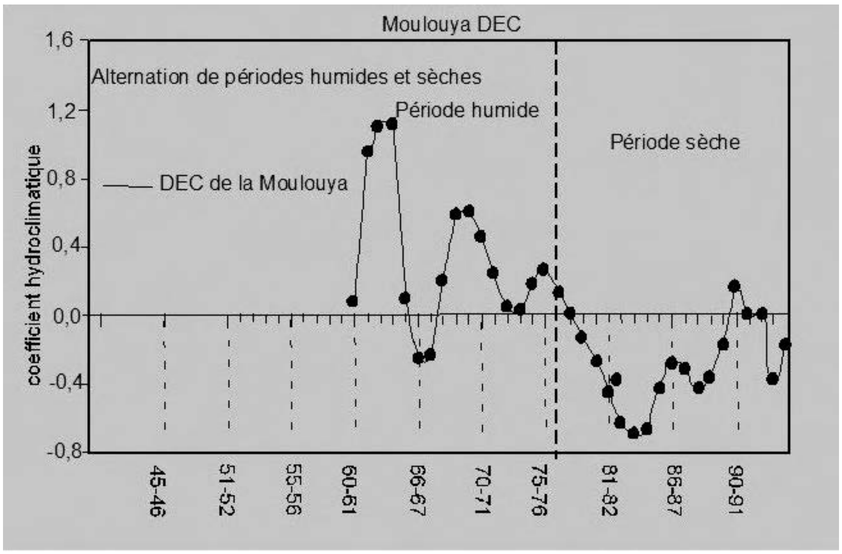

Fig. 4. Coefficient hydroclimatique de la Moulouya.

Si dans le bassin inférieur de la Moulouya, les conditions climatiques sont plus favorables, les précipitations ne favorisent que d’une façon saisonnière un écoulement pour une durée limitée des oueds affluents de la Moulouya. L’Oued Cherrâa est le seul affluent qui alimente la Moulouya dans cette partie inférieure pour la période d’hiver et du printemps. A l’amont du Cherrâa, l’Oued Zegzel reste le seul fournisseur. En périodes de crues, lors des averses locales, intervient également l’Oued Ouaklane. Des crues spectaculaires peuvent être enregistrées dans le Cherrâa ; elles sont rares, ne durent qu’une seule journée et sont en liaison directe avec des averses brutales.

En haute Moulouya les Oueds Melloulou et Za sont les principaux affluents. En été, le cours de la Moulouya peut être à sec et son alimentation se fait à l’approche du barrage Mohamed V par l’Oued Za.

3. Impact de la construction du barrage sur le flux d’eau et de sédiment

La construction du barrage Mohamed V a réduit d’environ 47% la décharge de l’eau au fleuve de Moulouya. La réduction du flux de l’eau est due davantage à la construction des barrages qu’à la sécheresse (Snoussi *et al*., 2003).

4. Impact des barrages sur les lignes du rivage à l’aval

Pour évaluer l’évolution du littoral, nous avons exploité essentiellement les photographies aériennes, et des images satellitaires en plus des relevés sur le terrain durant le mois de février au cours des années 1998, 2000, 2001, 2002, 2003, 2004 et 2005.

Nous avons disposé de trois échelles différentes pour les photographies aériennes, 1/20.000, 1/40.000 et 1/50.000 pour la zone littorale. Généralement, toutes ces missions aériennes ont une bonne résolution sauf celle de 1958 au 1/50.000 dans laquelle la résolution est moyenne, puisqu'il s'agit d'une reproduction de photographies. Les observations de terrain et la photo-interprétation ont été effectuées en concordance et en alternance.

L'analyse de l'évolution du littoral montre des changements survenus entre 1958 et 1995 et les modifications les plus sensibles sont relevées au niveau de l'embouchure de la Moulouya.

En 1958, le cours inférieur de la Moulouya se situait plus à l'est. Cette position était due à l'importance de la dynamique de la dérive littorale qui poussait les apports de l'oued dans cette direction. L'importance des apports en suspension (alluvions fines) favorisait la croissance du delta à l'intérieur de la mer.

Au printemps 1963, de très importantes précipitations sont tombées sur le Maroc oriental ce qui a déclenché d'importantes crues de tous les affluents qui se sont concentrés dans la Moulouya et ont provoqué son débordement et des modifications de son cours avec recoupement des méandres à cause de la forme d'écoulement et une percée rectiligne du littoral et la création d'un nouveau delta.

La construction des barrages de Mechrâa Hamadi en 1958 et de Mohamed V en 1967 a provoqué le piégeage des apports alluviaux à l'amont et limité l'alimentation du delta. Les apports de la plus grande partie du bassin (49,000 km^2) sont retenus par le barrage Mohamed V.

4.1. L'évolution morphologique du littoral

L'évolution morphologique du littoral entre 1942 et 1991 est exprimée en m^2 dans la Figure 5. La somme des surfaces subissant l'érosion et l'accrétion est calculée pour chaque période et également par secteur.

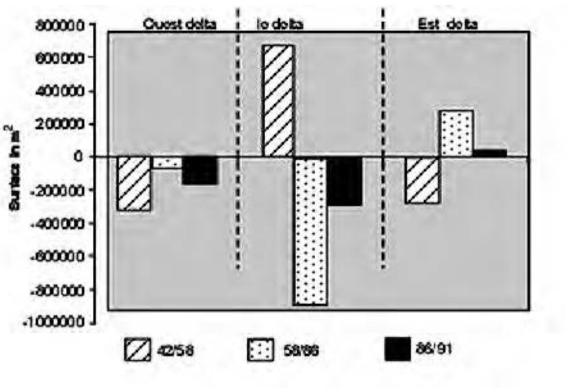

Fig. 5. Évolution morphologique du littoral entre 1942 et 2001 (en m²), d'après Snoussi et Imasi (2003).

– Depuis le commencement du vingtième siècle, la déforestation et la surexploitation des espaces forestiers liées à l'activité humaine ont intensivement augmenté les flux de dépôt de la Moulouya. L'apport était considérable tel qu'observé dans les vastes terrasses limoneuses construites dans la partie basse du bassin. Le delta a progradé, avec la formation d'une série de barres d'embouchure, selon le courant dominant de longshore. L'engraissement fut toujours sur la rive d'Ouest vers l'Est. Ces lignes de rivage successives sont visibles sur les anciennes photos et à partir d'images satellitaires.

– La période entre 1958 et 1986 montre une phase importante d'érosion. En effet le fleuve de Moulouya a éprouvé plusieurs changements de son cours inférieur depuis 1958. L'extension inférieure était sinueuse et serpentante, et l'embouchure était beaucoup plus large qu'aujourd'hui. En 1963, le Maroc a fait face à des inondations énormes et les flux de l'eau et de dépôt du Moulouya étaient si importants que le cours inférieur fut décalé à l'ouest, direction de raccourci (Snoussi et Imassi, 2003) (Figure 6).

– Après la construction du barrage Mohamed V en 1967, l'embouchure et le littoral ont réagi avec des ajustements remarquables. En effet, vu l'énergie hydraulique fluviale faible, les influences marines ont été renforcées, menant au rétrécissement du secteur de l'embouchure. La côte est s'est accrue tandis que la côte occidentale retraitait, n'étant pas alimentée par les dépôts fluviaux.

– Entre 1986 et 1991, le système montre une légère érosion à l'embouchure et à la côte occidentale, alors que la côte est montre une situation relativement stable et évolue probablement vers un profil d'équilibre (Figure 6).

– La période allant de 1991 à 2004, est caractérisée par la construction du port de plaisance à l'est de l'embouchure ce qui va avoir un impact considérable sur la partie située à l'Est qui s'alimentait via la dérive active venant du NO en direction du SE.

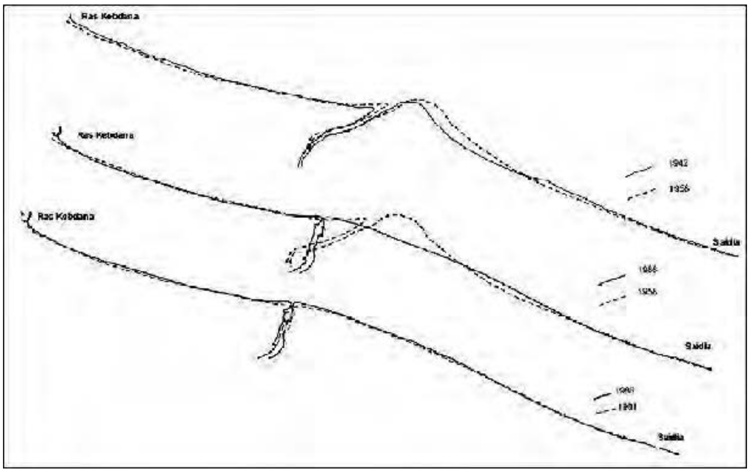

Fig. 6. Séquences d'évolution du littoral entre 1942 et 1991, d'après Snoussi et Imassi (2003).

4.2. Le littoral du Maroc oriental : dynamique et dérive littorale

La Figure 7 permet de constater un changement du delta construit depuis 1958. Le littoral dans sa partie la plus avancée en mer était situé :

- à 650 m de l'axe de la route secondaire en 1958 ;
- à 380 m en 1980 ;
- à 370 m en 1988 ;
- à 320 m en 1995 ;
- à 270 m en février 2001 et à 255 m en février 2003.

La régression du littoral dans cette partie côtière est estimée à 10m/an.

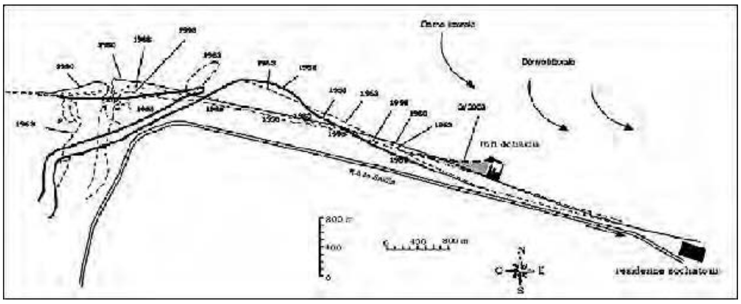

Fig. 7. séquence d'évolution du littoral depuis 1958 à 2004 après la construction du port de Saidia.

A 3,500 m vers l'est près du port de Saidia c'est l'inverse qui s'est produit :

- en 1963 la plage était à 150 m de la route secondaire ;
- en 1980 elle était à 270 m ;
- en 1995 , elle était à 250m ;
- en février 2001 elle a progressé pour atteindre 330 m et 350 m en février 2003. Ceci est lié à l'impact de la jetée ouest du port.

Pour ce dernier relevé, l'impact du port est présent et tout l'apport provenant de l'ouest est bloqué par la jetée.

En réalité, à partir de 1980, le Maroc a connu une longue période de sécheresse qui s'est répercutée sur la réserve d'eau et l'écoulement des oueds pérennes tel la Moulouya et ses principaux affluents. Le faible apport de la Moulouya après la construction des barrages à l'amont d'une part et la dynamique de dérive littorale d'autre part sont à l'origine du développement des plages successives induites par une régression vers l'embouchure depuis 1958.

5. CONCLUSION

L'évolution actuelle du littoral dans cette partie du Maroc oriental est caractérisée par un déficit sédimentaire dû tout d'abord aux barrages à l'amont qui piègent la totalité des flux sédimentaires et d'autre part à la construction du port qui constitue un obstacle face aux courants de dérive qui auparavant étaient responsables de l'engraissement de la partie est du littoral en direction de la frontière avec l'Algérie (Figure 8).

Fig. 8. Aster data image d'octobre 2004 du littoral entre Ras Kebdana et Saidia.

Les aménagements touristiques prévus pour le futur proche dans la région devraient tenir compte de l'érosion des plages, d'autant plus que ce secteur est classé site d'intérêt biologique et écologique.

Coupled monitoring of the delivery and fate of riverborne key elements in the delta of a small Mediterranean river: the case of the Têt River (SW France)

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ABSTRACT

Improving our knowledge about the land-to-sea transfer of carbon by rivers and its subsequent fate within the oceans is one of the priorities for a better understanding of the global carbon cycle. Previous monitoring programs on major world rivers considerably increased the reliability of our global estimates on the riverine carbon fluxes. Relatively little is known, however, about what happens to this carbon once it has been delivered to the sea. This requires coupled studies that closely follow the river carbon from its sources in the drainage basin to its sinks in the coastal waters and sediments. The Têt River is a small coastal river where such a coupled study has been installed. We report results of our monitoring of the fluxes and properties of the riverine particulate organic matter in comparison with the organic matter that is buried in the sediments off the river mouth. Also particulate trace metals were analysed, which are generally enriched in the river particulates because of pollution. Trace metals also show high degrees of association with the organic matter phase both in the terrestrial and marine sediments, giving them hence a useful role in the tracking of terrestrial organic carbon in the marine environment. Our results indicate that, because of the highly dynamic conditions off the river mouth, in particular during short flash-floods when almost all of the river sediments are supplied, only little of the river carbon is buried in the delta sediments. Here, the fine-grained sediments are continuously resuspended and subjected to further offshore transport, together with the associated organic carbon and trace metals.

1. DESCRIPTION OF THE TÊT RIVER

The Têt River is a typical small Mediterranean river that drains the eastern part of the French Pyrenees to the Mediterranean Sea. Its basin area is about 1,400 km^2 and the river length is about 120 km. The uppermost basin parts reach up to elevations of > 2,500 m and are regularly snow-covered during winter. From there, the river descends on a rather steep gradient down to sea level, passing rapidly through various climate and vegetation zones before entering the sea in the SW part of the Gulf of Lions (Figure 1). The lithology of the basin is dominated by old plutonic and metamorphic rocks (granite, gneiss, mica schist and schist), which are weathering resistant and only slowly mineralize. In the middle part of the basin, however, limestone is again present, having a clear impact on the water chemistry. Further downstream, the river enters in its alluvial plain which consists in thick fillings of the erosion products of the upstream rocks that accumulated during Pliocene and Quaternary periods.

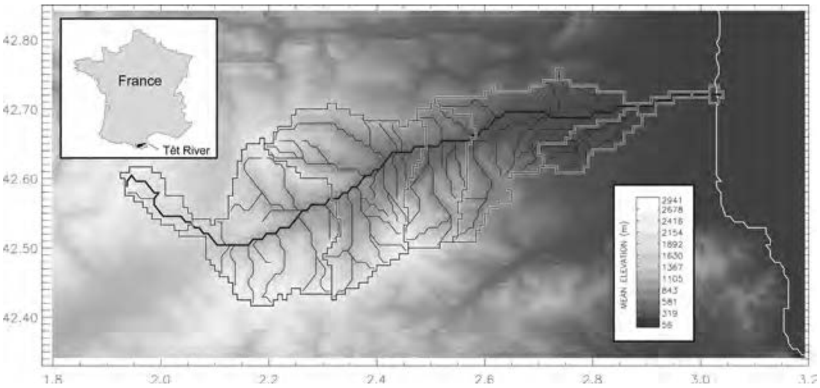

Fig. 1. Morphology of the Têt basin. The sub-basins correspond to the sampling stations which have been regularly monitored in 2000 – 2002.

The uppermost basin parts are only weakly influenced by human activities. They are situated in elevated regions with relatively steep morphologies and population density is extremely low. Natural vegetation types represent more than 90% of the land cover and agricultural activity is mainly limited to extensive practices like animal farming. Then, at lower elevation levels, land use practices change. Intensive cultures like fruit trees and vineyards become a dominant pattern in the basin, while the population density still remains at low levels. Most of the population is concentrated close to the river mouth, where the city of Perpignan is situated: more than 70% of the total basin population is added here and the waste-water inputs from this town profoundly alter the water quality in the river.

Water flow is complex because of anthropogenic water extraction at many places along the major river course. Irrigation channels were developed since the 9th century and can be found almost everywhere along the basin. For this reason, the natural water discharge at the river mouth is probably reduced by about 35% (Ludwig *et al*., 2004) and the average discharge values that are recorded at the gauging stations do not always allow a conservative budgeting of the surface water flow. In the 1970s, a reservoir was constructed in the middle of the basin for flood control. This reservoir has an important impact on the transport of particulate materials and of dissolved nutrients. It is normally maintained at very low levels during late autumn and early winter, when the risk of flash-floods is maximal, and allowed to be filled during spring and summer in order to sustain irrigation in the basin.

2. Monitoring approach

2.1. River monitoring

The Têt River is studied in the framework of the French long-term observation and monitoring programme ORME (Observatoire Régional Méditerranéen sur l’Environnement). This programme, which is part of the “Zone Atelier” network created by the CNRS, focuses on the impact of the riverine inputs on the biogeochemical and sedimentary functioning of the Gulf of Lions. Also the Hérault and Rhône rivers are studied in ORME, as it is one of the main project objectives to examine the role of the inputs by small coastal rivers in comparison with those from big rivers.

The monitoring of the Têt started in 2000 with a pilot study on the material transport in the basin, from the headwaters down to the river mouth. This was done through weekly sampling at its major water gauging stations (Figure 1), combined with high frequency sampling (up to hourly time steps) during floods at the downstream stations and seasonal sampling of the major tributaries. The study allowed a detailed quantification of the natural and anthropogenic material sources that contribute to the dissolved material transport in the river, and to propose a model for the sediment and organic carbon supply to the Mediterranean Sea (Serrat *et al*., 2001; Garcia-Esteves and Ludwig, 2003; Ludwig *et al*., 2005). As this is typical also for many other Mediterranean rivers, the water flow of the Têt River is highly variable and strongly dominated by the occurrence of short and violent flash-floods. The average water discharge of the river is about 10 m^3/s, but it can increase by more than two orders of magnitude during major floods (Ludwig *et al*., 2004). Serrat *et al*. (2001) estimated the annual mean sediment discharge to 53,000 ±16,000 tons/yr for the reference period of 1980-1999. Also here, this value is accompanied by a very high inter-annual and seasonal variability, since in some years about 2-3 times this amount was discharged during only three days (e.g., in 1996, see Serrat *et al*., 2001).

Because the particulate material transport is strongly dominated by flash-floods, which are difficult to sample through manual techniques, the river was equipped in 2004 with an automatic sampling station close to its mouth. The station collects samples in daily time steps during normal hydrological conditions, and in hourly time steps during floods. In addition, a multi-parameter sonde has been installed in the river upstream the sampling station and continuously registers the physical and chemical properties of the river water. The overall data allow a precise estimation of the total suspended sediment (TSS) transport in the river, and a detailed understanding of the different material sources (erosion, waste-waters, primary production, etc.) that contribute to the material fluxes.

2.2. Monitoring of the delta sediments

In order to follow the terrestrial inputs once they entered the sea, the Têt River system is also regularly monitored off-shore its mouth. A buoy has been moored in its outer estuary in a water about 25m-deep. Since 2003, it measures online the hydro-climatic properties of the water column and delimitates an experimental zone that is regularly visited for sediment coring and for the deployment of various instruments (ADCP, altimeters, etc.) for the in-situ monitoring of the sedimentary system at the sea bottom. Further off-shore, close to the shelf break where the submarine canyons discharge the platform sediments to the deep sea, regular coring and sediment trap samples complete our monitoring strategy.

The delta system of the Têt River is also compared with other river systems in the Gulf of Lions. Surface sediments on the entire platform were sampled in 2002, with higher spatial sampling resolutions in the river deltas. This study focussed, beside grain size distributions, carbonate and organic carbon contents, on the concentrations of trace metals. As many of them are introduced by rivers into the coastal zone, they are useful indicators not only for the detection of potential risks for the marine ecosystems due to pollution, but also for the identification of the distribution pathways of the riverborne sediments (Roussiez *et al*., 2005a,b; Roussiez *et al*., in press) in the coastal environment.

3. RESULTS

3.1. Organic carbon

The carbon content in the total suspended solids of the Têt River clearly decreases with increasing TSS concentrations (Figure 2a), as is commonly observed in rivers. Scatter in the plot of both parameters is reduced when only analysing the fine sediment fraction (silt and clays), which accounts for about 80-90% of the total suspended sediments close to the river mouth (Ludwig *et al*., 2005). Carbonate minerals contribute to the total carbon contents in samples with

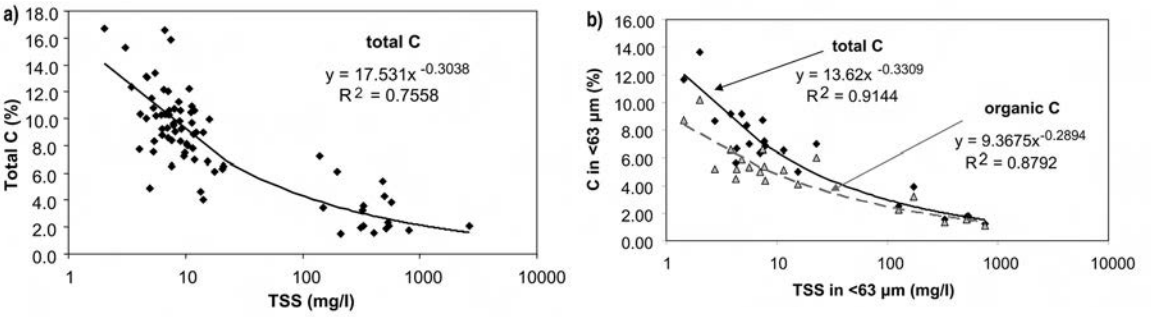

Fig. 2a,b. Relationships between carbon and total suspended sediments in the Têt River (Garcia-Esteves and Ludwig, 2003): (a) total carbon in total suspended solids; (b) total (black dots) and organic carbon (grey triangles) in the silt and clay fraction only based on a subset of samples from (a). Notice that on average, the TSS concentrations of > 100 mg/L account for 85% of the total sediment transport by the river.

low TSS concentrations (Figure 2b). Above TSS concentrations of 100 mg/l, however, when by far most of the TSS transport occurs and when clay contents are highest (ca. 35%), carbon in the river sediments is almost exclusively organic. Here, the organic carbon content rarely falls below 2%, and in some samples with high clay content, the percentage of organic carbon even increases with increasing TSS concentrations. This is indicating that a major part of the organic matter transport in the Têt is associated with clays.

In the outer estuary around our monitoring buoy, the average organic carbon content in the sediments is clearly lower than in the river sediments and lies in the rage of 0.4 - 0.8%. The values increase further off-shore to about 1% at water depths of 60-80m, and the gradient hence decreases towards the river mouth (Figure 3). This is in disagreement with the idea of a dominant terrestrial origin of the organic carbon in the sediments, and in-situ primary production might be an important source.

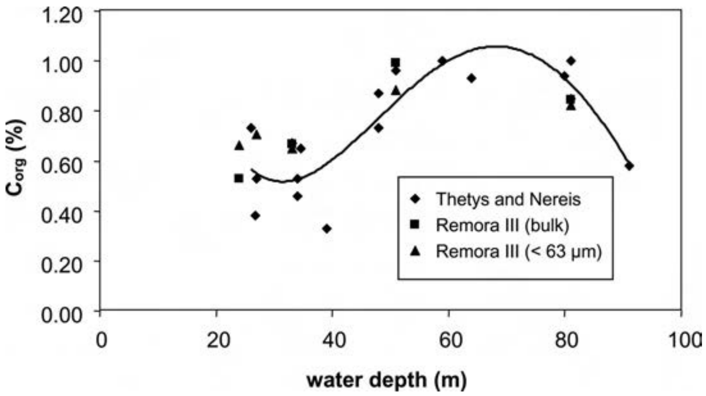

Fig. 3. Distribution of organic carbon contents in surface sediments along an off-shore gradient out of the Têt estuary (Ludwig *et al.,* 2005). Samples were collected during three different cruises (Thetys, Nereis and Remora III cruises).

However, when normalizing the organic carbon contents to a clay mineral indicator element, such as stable Cs (Roussiez *et al*., 2005b), the sense of the gradient is now opposite and points to greatest values in the Têt River. Clays in the vicinity of the mouth are richer in organic matter, which might indicate their terrestrial origin. Also for the other rivers of the Gulf of Lions, a similar pattern is obtained. Whereas the bulk organic matter distribution in the surface sediments does not clearly allow the identification of the deltaic systems close to the coast, the Cs normalized distribution shows enrichment in front of all river mouths (Figure 4).

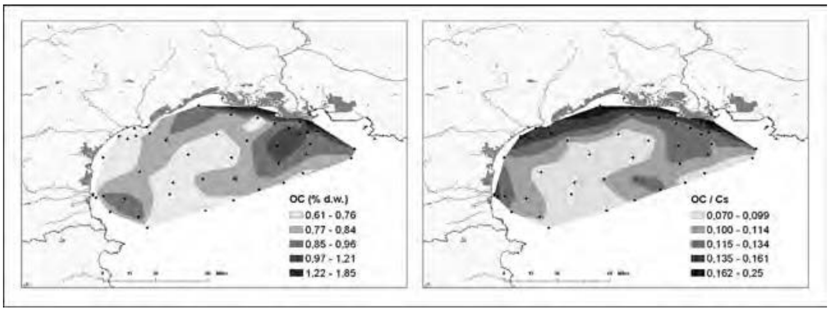

Fig. 4. Distributions of C_{org} (left side) and Cs-normalized C_{org} (right side) in surface sediments (<63 µm) of the Gulf of Lions (Roussiez *et al.,* in press).

The analyses of different biomarkers in the surface sediments off-shore the Têt River confirm their terrestrial nature close to the mouth. ^{13}C isotope ratios, C/N ratios and the newly developed BIT index reveal here a dominant terrestrial origin of the organic matter in the sediments.

Nevertheless, certain tracers show clear differences in the range of the measured values between the river and the delta sediments. These differences are especially important for C/N ratios, which increase up to 30 in the shallowest sediments (Ludwig *et al*., 2005), whereas they mostly remain ≤ 10 in the river sediments (Garcia-Esteves and Ludwig, 2003). One plausible explanation for this is that the riverine particulates were fractionated with respect to their grain size after they enter the marine waters. The coarser silt fraction, often more enriched in relatively fresh vascular plant material with elevated C/N ratios, might concentrate in the delta sediments, whereas the finer clay fraction, often characterized by more degraded organic matter with lower C/N ratios, might be remobilized and transported further off-shore. Once notes a particularity of the deltaic systems in the Gulf of Lions in that deposition of fine-grained sediments occurs above the storm wave base (Roussiez *et al*., 2005a), subjecting them to cyclic resuspension through storms and increasing wave heights.

3.2. Trace metals

The behaviour of trace metals is particularly interesting in this context. Because of pollution, many of them are principally introduced by rivers into the marine environment, in strong association with clays and organic matter. In the suspended sediments of the Têt, the associated metal abundances are rather constant, as this is also found for most other rivers in the Gulf of Lions. In the delta sediments, however, the metal distribution is variable in space and in time, being controlled both by the riverine inputs and the hydrodynamic conditions that control the outwash of fine-grained sediments.

When following the temporal evolution of the metal concentrations in the surface sediments at our buoy site, we found the highest concentrations directly after a major flood in December 2003 (Figure 5). The concentrations are in the same range than what is found in the river sediments, indicating that these deposits were the result of the settling of riverborne sediments after the flood. Also the general sediment core description, C/N ratios and/ or other geochemical and sedimentological parameters confirmed this. During the following months, however, the successive outwash of the fine sediments provoked a clear decrease in the heavy metal concentrations. A second flood occurred in April 2004, but the riverborne sediments did not settle at our monitoring site (F. Bourrin, pers. com.). Consequently, the concentrations in the sediment remained at about the same levels as before.

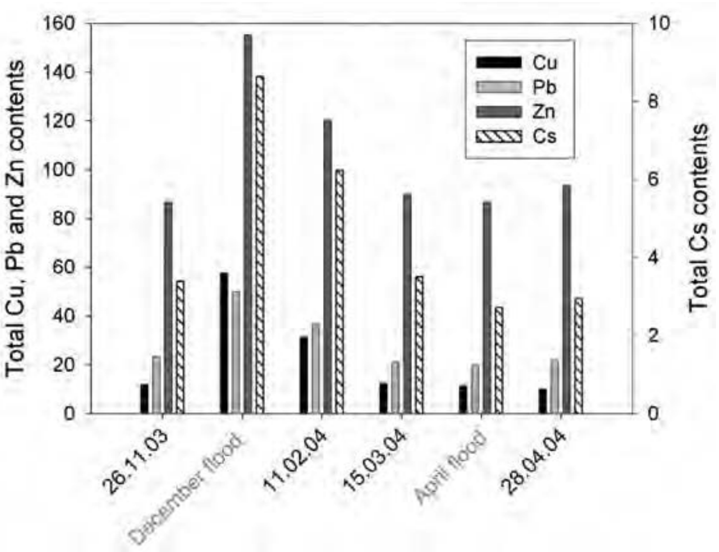

Fig. 5. Temporal variation of Cu, Pb, Zn and Cs total contents in surface sediments of the monitoring buoy off-shore the Têt River. Units are ppm (data from Roussiez).

Nevertheless, the April flood was interesting too because it allowed studying the spatial distribution of the heavy metal concentrations in the surficial platform sediments along an off-shore transect from the river (Figure 6). The concentrations of Pb and Zn were lowest in the direct vicinity of the mouth, although both metals are typical indicators for riverborne pollution (Roussiez *et al*., 2005b). Further off-shore, however, they increased continuously and reached the typical river values at a distance of about 20 km from the mouth. Here, below the storm-wave base, the hydrodynamic conditions are much less energetic and therefore allow the settlement of also the finer river sediments.

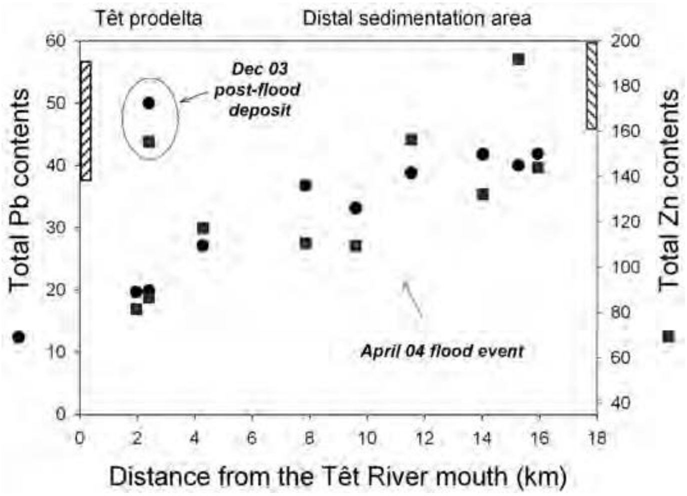

Fig. 6. Spatial evolution of Pb and Zn contents in surface sediments collected during the April 04 flood event off the Têt River in comparison with their selective contents in the post-flood deposit of December 03. Riverine references are illustrated by hatched bars along the Y axes, and are expressed as the standard deviation intervals around the means (n = 10). Units are ppm. (data from Roussiez).

4. CONCLUSIONS

Our results clearly show that the deltaic sedimentation of the particles and associated elements from the Têt River is not a continuous process, as is often thought when speculating about the fate of terrestrial materials in the marine environment. Sedimentation and subsequent burial of these materials are highly dynamic and include the combination of several phenomena, such as the sediment delivery by floods, their temporal storage in the estuary, their remobilisation during storms and their deposition in proximate and distal sedimentation zones, depending on the prevailing hydrodynamic conditions. In the case of the Têt River, riverine supply and deltaic deposition of great amounts of riverborne sediments only occur during floods, often accompanied by storms and hence highly energetic conditions in the coastal environment close to the river mouth. Even if these flood sediments are deposited on the delta sediments after returning to calmer conditions, they are rapidly subjected to regular resuspension and further offshore transport.

The weight of human activities on the basin-coast system: the case of Emilia-Romagna region (Northern Adriatic)

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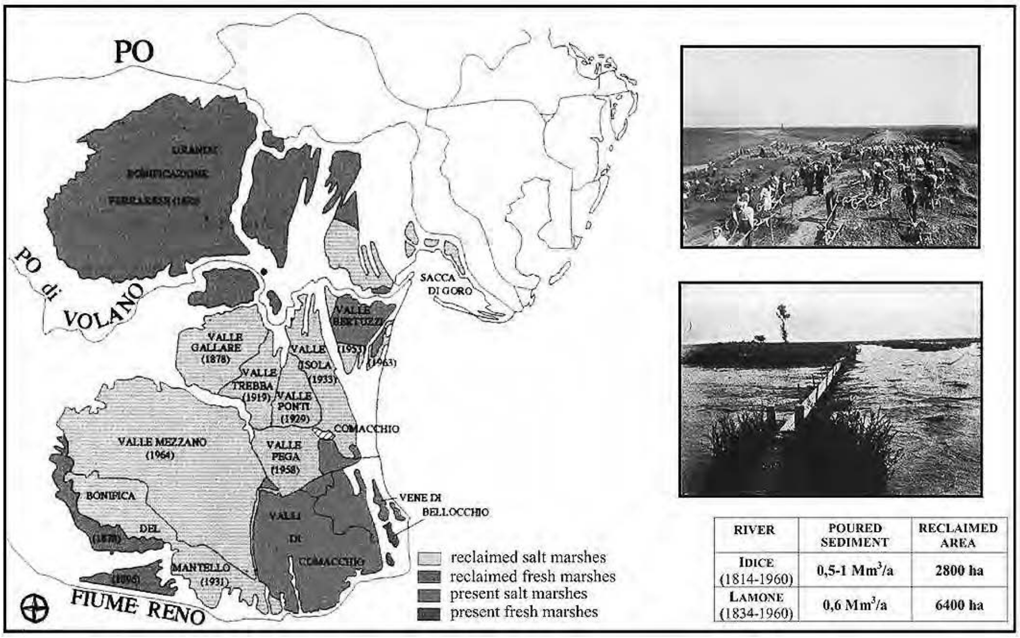
The role exerted by man on the modern evolution of the Adriatic littoral and, especially, in the Emilia-Romagna, has grown in importance through time until it reached a critical point during the last century. Modifying the fluvial courses and supplies and modifying the littoral hydro-sedimentary dynamics, man has altered in a short-time secular natural equilibrium (Simeoni and Bondesan, 1997).

Climatic variations during the "Little Ice Age" (between about 1500 and 1850) have modified significantly the hydrographical conditions of the Po plain, inducing the swamping of wide coastal areas of the Emilia-Romagna (Veggiani, 1982). The drainage by reclamation of these territories, initiated during the 19th century, have removed important quantities of material from the beach budget, and consequently have heavily affected the evolution of some coastal stretches (Figure 1).



RIVER	POURED SEDIMENT	RECLAIMED AREA
IDICE (1814-1960)	0,5-1 Mm^3/a	2800 ha
LAMONE (1834-1960)	0,6 Mm^3/a	6400 ha

Fig. 1. Reclaimed lands in the Po Delta Territory. The two pictures describe the drainage operations. The table shows the extension of the reclaimed areas belonging to the basins of two small rivers (Simeoni *et al.*, 2003a – mod.).

Even while damaged and without important supplies, the beaches of Emilia-Romagna were characterised by a substantial positive evolutive trend until the end of the 1940s. It is only during the last 50 years, that the area presents rapid and common erosion phenomena, especially intense between the 1960s and the 1970s. These retreats are probably related to the important supply reductions of the regional rivers during these period. Studies (IDROSER, 1996) suggest that the turbid supply of the Po decreased from $12.8.10^6$ t/yr during the period 1918-43 to $4.7.10^6$ t/yr during the period 1945-1972, while the other rivers of Emilia-Romagna have suffered a reduction of their supply of by a factor ranging from 2 to 4. During this period no relevant climatic variations have been observed, the causes of fluvial supply reduction are probably related to the numerous human activities realised on this territory. It is enough to remember that, during the period 1955-92, 21 Mm^3 of inert extraction from the riverbed of the Emilia-Romagna region (except the Po) have been officially allowed. At the same time some other human induced modifications occurred in the river basins (IDROSER, 1996), such as different land uses, dikes construction and a very low maintenance of the river beds that have been invaded by arboreous plants, able to strongly reduce the solid discharge.

Furthermore, during the last decade, the coastal evolution has also been greatly "influenced" by the accelerated increase of the subsidence that naturally presents high rates (2-3 mm/yr), due to methaniferous water extraction and to intense drainage of the ground-water for agriculture. This phenomenon, together with an unsuccessful natural compensation, are the principal causes of the actual altimetry of the eastern Po plain, characterised by 2365 km^2 of territory situated below the mean sea level. Considering low-gradient beaches, like those of Emila-Romagna, the subsidence induces not only a shoreline retreat (several meters compared with few centimetres of subsidence) but also an increase of the gradient of the "shoreface", and consequently a reduction of the coastal sand body.

The necessity to contrast the erosion has induced the construction of numerous defence structures, especially during the 1970s and 1980s, that have stiffened the coastal system and strongly altered its hydro-sedimentary dynamics. Some simple data suffice to highlight the importance and impact of these interventions on the coastal system: 48.9 km of detached breakwaters, 8,7 km of attached breakwaters, 1.6 km of groins, 27 km of dykes, walls and artificial dunes have been constructed; 4.2 km of Longard pipe have been placed and millions of cubic meters of sand have been deposited along 13.8 km of coast (Figure 2). These interventions, even if they have controlled and/or reduced the erosion, have neither resolved the problem, or significantly reversed the still observed negative trends.

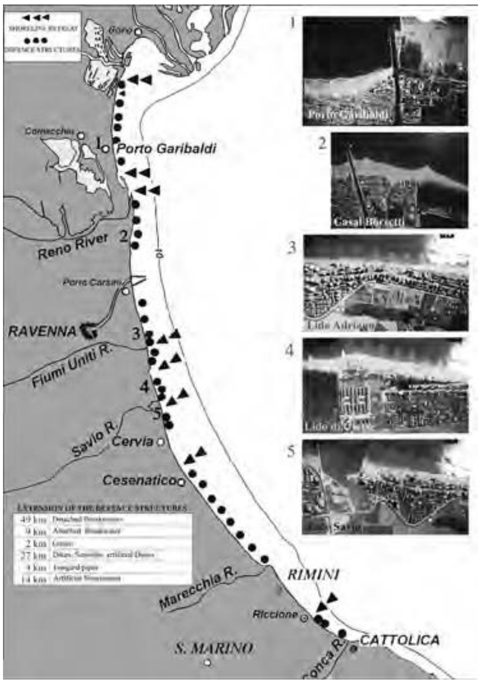


Fig. 2. Present configuration of the Emilia-Romagna coast (Simeoni *et al.*, 2003a – mod.).

Non-optimist scenarios can be elaborated for the future in relation with the accelerated global sea level rise (more than 20 cm for 2050). Adding this rise to the subsidence we may assume a worsening of the coastal disequilibrium in the short term. Significant indication of this phenomenon comes from the study performed in the Ravenna territory based on the extrapolation and projection of topographic data from 1986 and 1992 (Comune di Ravenna, 1996). The territory, that already in 1992 was below the mean sea level, will continue to subside so that, according to the worst hypothesis, more than 62% of the territory will reach a level close to zero in 2050. Another scenario points out how the 2025 forecasted territory altimetry could be worrying (Table 1).

Table 1. Short time variation of the most significant topographic classes (in meter) of the Ravenna coast (territorial extension of 195 km^2) expressed in percent.

Years Level m	1992 %	2025 %	2050 %
-3/-2	0	0	0.1
-2/-1	0.5	1.1	2.4
-1/-0.5	1.5	4.3	8.5
-0.5/+0.5	34.9	53.1	62.7
+0.5/+1	34.3	24.6	16.4
+1/+2	24.7	14.3	7.4
+2/+3	3.3	2.1	1.5

The sea level rise could have particular "fatal" consequences on the coastal dune systems, with present level ranging from +1 and +2 m, and will dramatically reduce their extensions: 25% in 1992; 14% in 2025 and only 8% in 2050. The damages are obvious considering that dunes represent a natural reservoir of sediments for the re-equilibrium of the coastal budget and constitute a natural defence against marine floodings. The sea level rise will induce other negative impacts such as: loss of drainage system efficiency of the reclaimed areas; progressive diminution of the coastal defence structures efficiency and disequilibrium of the harbour area, increase of the salinity rates of the more superficial ground freshwater due to the landward migration of the salt wedge.

All these consideration need to be taken in consideration either for eventual management programme or for possible application of evolutive model of the coastal zone at short time. As the hard defence structures appear inefficient due to their hardening, it is now obvious that management politicise must be based on soft defence solutions like nourishment, dune reconstruction, submerged bars or spits construction (see CIESM, 2002). In such sense, the Emilia-Romagna region has adopted during the last years an integrated intervention politicy. Some nourishment interventions have been realised with sand deposited near the fluvial mouths or near the anthropical channels outlets (ex: Po di Goro, Logonovo channel, Gobbino channel) in order to improve the hydraulic efficiency of the mouths or outlets. Sometimes these nourishment have been carried out with material deposited on the updrift side of the jetties, which have interrupted the natural longshore sediment transport. For instance, in 2003, the Emilia-Romagna Region realised an artificial nourishment of about 214,000 m^3 of sand through a by-pass system that pumps the materials from the southern side of the harbour, transports and distributes over a maximum distance of 9 km at the northern side (Simeoni *et al*., 2003b).

Formation of the Krka river estuary in Croatia and the travertine barrier phenomenon

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The Krka River is a medium sized water course in the Dalmatian karst area. It has formed in a typical karstic area, - however, some characteristics and features make this river unique among other rivers belonging to the Adriatic watershed. Its canyon-like appearance is a consequence of the geological setting of the entire catchment area with its suite of tectonically formed faults and crevices within limestone of Cretaceous and Palaeogene age.

Fig. 1. The Krka River.

The geological setting of the Krka river catchment area is the outer Dinaride formation, whose tectonic evolution is closely associated with the recent and historical seismicity of the circum-Adriatic region. The Adriatic microplate lies within a collisional environment caused by the northward motion of the African tectonic plate and its subduction under the Eurasian plate. A key question is whether the Adriatic microplate is a rigid promontory of the African plate mirroring its behaviour, or if it is moving independently, either rigidly in one or more parts, or with some distributed deformation (Chanel *et al*., 1979). This movement is thought to have begun in Cretaceous time and has built the present Alpine mountain belt (Dewey *et al*., 1989). Recent data on lower seismicity levels in the Adriatic sea and eastern Italy relative to their surroundings implies that the Adriatic microplate rotates with respect to Eurasia around a pole in the northern Po plain. Hence, neotectonic processes in the Apennines, showing dominantly but not exclusively normal faulting, reflect extensions between western Italy south of the Po plain (presently considered to part of Eurasia) and Adria, whereas the thrust faulting mechanisms in the Dinarides and Venetian Alps reflect Adria-Eurasia convergence. The pole's proximity to the microplate illustrates a common pattern for microplates in the boundary zone between major plates, in which the pole for the relative motion between the major plates is far away. Thus motion between them varies slowly along the boundary, whereas those for the microplate's motion with respect to the major plates are nearby and so describe rapidly varying motion (Engeln *et al*., 1988). However, geologic data show that Adria was subducting southwestward beneath Italy during Mio-Pliocene time. This is consistent with a recent spatio-temporal evolution of a multiplate system. It may therefore be assumed that during Mio-Pliocene time Adria was no longer a part of Africa and had become an independent microplate. Convergence occurred as Adria moved northeastward with respect to Eurasia. The transition from convergence to extension in the Apennines in the past 2 Ma resulted from the cessation of subduction in the Apennines accompanied by a breakoff of the subducting Adria slab, and the cessation of back arc spreading in the Tyrrhenian sea (Geiss, 1987). As a result, western Italy became part of Eurasia, while Adria's northeastward motion produced a new extensional boundary along the Apennines.

On the western side of the Adriatic sea, the Gargano subaqueous delta formed on the eastern and southeastern side of the Gargano promontory. This subaqueous deposit represents the southernmost portion of the late-Holocene highstand systems tract (HST) growing along the western side of the Adriatic as an extensive wedge of deltaic and shallow-marine mud. This late-Holocene HST rests above a regional down lap surface which marks the period of the maximum landward shift of the shoreline, at the end of the last Pleistocene – Holocene sea level rise. The late-Holocene mud wedge, of which the Gargano subaqueous delta is a significant component, reaches up to 35 m in thickness and has a cumulative volume of ca. 180 km^3. The Gargano subaqueous delta is characterised by a submarine topset in waters shallower than 25-30 m, and accounts for ca. 15% of the total volume of the late-Holocene mud wedge, despite the absence of direct river supply to the Gargano area (Cattaneo *et al*., 2003). The overall process dynamics seems to be in accordance with the climate changes during the last glacial-Holocene transition (Asioli *et al*., 1999).

Four major stratigraphic depositional systems crop out at the seafloor and within surface and near-surface deposits of the area crossed by the Krka river, defining the general geologic framework for this region: (1) lower and middle Jurassic limestones, (2) upper Cretaceous (Cenomanian and Turonian) limestones and dolomites, followed by Senonian limestones, (3) lower and mid-Eocene foraminiferal limestones, and (4) mid-Eocene flysh deposits comprising mainly marls. Quarternary deposits consist mainly of red soil (*terra rossa*) on limestone, and yellow clayey soil on the flysh. During the late Pliocene and early Pleistocene time, a wide northdalmatian karstic plain was formed as a result of upper-Plesitocene glaciation. There are several theories as to how the canyon of the Krka river formed and developed, but the process appears to have been a single phase development. This is evident from the absence of mappable river terraces. Recent, neotectonic movements resulted in north-south faulting which controlled the directional formation of the canyon in areas where the canyon crossed dominant geologic features. The rate of erosion during the last glacial period (Würm) was ca. 4 mm per year as the volume of the continental icesheet increased until some 25,000 years before present, when sea level was about 97 meters below present. The canyon of the Krka river extended into today's coastal area and may be observed to the southern side of the island of Zlarin. Subsequent Holocene sea level fluctuations resulted in a net rise in sea level of 65 m (i.e. ca 30 m below present) leading to the development of the barrier estuary (Colantoni *et al*., 1979).

One further phenomenon of karst areas in the Adriatic region is the occurrence of numerous submarine freshwater springs along the present coastline, indicating subterranean riverine flow.

The canyon forming processes in the Krka river area were particularly intensive throughout the glacial and interglacial periods during the upper Pleistocene. At that time, massive travertine (calc tufa) barriers appeared at certain sections along the river course, and the rising of sea level resulted in the formation of the contemporary estuary in the lower reaches of the Krka river. The creation of travertine layers in the post-Würm period led to the creation of Skradinski buk, the Roški slap waterfall and the remaining waterfalls along the course of the river, as well as the formation of Visovac Lake and other water reservoirs in the canyon section of today's Krka river. The travertine barriers of the Krka river form waterfalls which are a unique natural phenomenon, not present in other karstic rivers of the eastern Adriatic coastline. They were formed during the last ten thousand years, after the last glacial period, when favourable climatic conditions occurred for the development of vegetation and the deposition of calcium carbonate from the river water. It was then that the magnificent works created by water in the rough karst landscape began. Travertine was formed by this carbonate sedimentation creating theresholds, covers, beards, curtains and other geomorphological forms. Travertine is the basic phenomenon of today's hydrological and landscape image of the "Krka" National Park (Marguš and Menđušić, 2003).

The creation of travertine formations was attributed primarily to mosses and algae. Pevalek (1953) described in detail that the moss *Cratoneurum* is a strong travertine-builder, as its youngest and uppermost sections in the tufts are free of travertine, the middle sections are covered in limestone and the lower sections of this travertine-builder are completely turned to stone. In 1971, Matoničkin and associates drafted the hypothesis that plants and animals serve passively as a foundation upon which travertine is deposited. In 1985, a group of researchers from the Ruđer Bošković Institute in Zagreb studied the travertine-building in the Black River in the Plitvice Lakes water system (Srdoč *et al.*). They found that there was no travertine formation in the segment of the Black River downstream from the source, even though the moss *Cratoneurum commutatum* was widely distributed on the rocky surface. All research agreed, however, that the process of travertine formation and the growth of travertine barriers is a highly complex process and that the community of travertine-forming biota participates in the creation of travertine barriers.

If we consider all the knowledge to date on the extraction of calcium carbonate crystals, travertine-building and the creation of travertine formations, then the hypothetic model of travertine-building in the Krka River is ambiguous and is closely tied to the living world. Therefore, in the area of Krčić creek, the source of the Krka river, the concentration of calcium bicarbonate in the river water is significant, in equilibrium with the equivalent concentration of carbon dioxide. Due to the differing partial pressures, carbon dioxide escapes into the atmosphere and causes the breakdown of the bicarbonate molecules into water and calcium carbonate. The beginning of this reaction and the creation of calcium bicarbonate molecules occur when plants consume carbon dioxide for their photosynthetic activities. Water, by a physico-chemical or biogenic path, then becomes supersaturated with calcium carbonate, thus fulfilling the first condition required for the precipitation of microcrystals and the beginning of the crystallization of calcium carbonate.

It is well known that travertine barriers grow along fault lines or in places of stepwise underwater relief in zones of intensive water splashing. In such locations, development of certain mosses is observed, which flourish in strong water currents and withstand erosion processes. These include: *Cratoneurum commutatum*, *C. filicinum, Bryum ventricosum, Didymodon tophaceus, Cinclidotus aquaticus, Platyhypnidium rusciforme, Fissidens crassipes, Pellia fabbroniana, Fontinalis antipyretica, Mniobryum calcareum* and others. Rich communities of attached algae develop on these species and participate in the process of travertine formation. Of the blue-green algae in the travertine barrier habitats, the most widely distributed are species from the *Phormidium* family, while the green algae are represented by the families *Stigeoclonium, Cladophora, Vaucheria, Spirogyra* and *Zygnema*. The vegetation of attached algae on mosses and filamentous algae and rock surfaces are composed of the diatoms *Cymebella affinis*, *C. ventricosa*, *Cocconeis placentula, Melosira varians* and others. Recent research confirmed the key role of attached algae in the process of extracting and forming calcium carbonate crystals, not only on the mosses and filamentous algae, but also on all submerged objects.

In the area of the previous waterflow in the vicinity of Knin, ancient travertine formations, ca. 125,000 years old are present. These are referred to as "dead travertine". They were formed during the last Riss/Würm interglacial period. The active travertine barriers of the Krka are biodynamic formations and are described as "living travertine". Due to the permanent process of travertine formation, the river Krka represents a unique karst phenomenon.