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RESEARCH ARTICLE

River delta shoreline reworking and erosion in the Mediterranean and Black Seas: the potential roles of fluvial sediment starvation and other factors

Manon Besset*, Edward J. Anthony* and François Sabatier*

The Mediterranean basin (including the Black Sea) is characterized by a plethora of deltas that have developed in a wave-influenced setting. Many of these deltas are sourced in sediments by river catchments that have been variably dammed. The vulnerability status of a selection of ten deltas subject to different levels of reduction in fluvial sediment supply following damming was analysed by quantifying changes in delta protrusion area and protrusion angle over the last 30 years. The rationale for choosing these two metrics, which do not require tricky calculations of longshore bedload transport volumes and river 'influence', is that as sediment supply wanes, increasing relative efficiency of waves leads to longshore redistribution of reworked sediments and progressive 'flattening' of the delta protrusion. The results show that eight of the ten deltas (Nile, Rhône, Ebro, Ceyhan, Arno, Ombrone, Moulouya, Medjerda) are in erosion, whereas two (Danube, Po) show stability, but the statistical relationship between change in delta protrusion area and sediment flux reduction is poor, thus suggesting that the role of dams in causing delta shoreline erosion may have been over-estimated. But this poor relationship could also be due to a long temporal lag between dam construction and bedload removal and transport to the coast downstream of dams, and, where the delta protrusion is being eroded, to bedload trapping by shoreline engineering structures and by elongating delta-flank spits. Other potential influential factors in shoreline change include subsidence, sea-level rise, storminess, exceptional river floods, and managed sediment releases downstream of dams. A longer observation period and high-resolution sediment-budget studies will be necessary to determine more definitively to which extent continued trapping of sediment behind dams will impact overall delta stability in the Mediterranean and Black Seas. Mitigation of delta erosion is likely to become costlier under continued sediment starvation and sea-level rise.

Keywords: river deltas; delta vulnerability; delta erosion; delta subsidence; river dams; Mediterranean Sea; Black Sea

Introduction

The Mediterranean basin (including the Black Sea) is characterized by a plethora of deltas that have formed as a result of favourable catchment, hydrodynamic and climate conditions, and human-induced changes (Vita-Finzi, 1975; Maselli and Tricardi, 2013; Anthony et al., 2014). The marine hydrodynamic context of Mediterranean river mouths has been largely conditioned by waves, and the alongshore supply of fluvial sediment has been fundamental to the geomorphic development of open-coast beach, dune and barrier systems in situations where coastal morphology and wave fetch conditions favour unimpeded longshore drift. Apart from the eastern seaboard of Tunisia and the Adriatic Sea, the Mediterranean continental shelf

is relatively narrow (a few km to about 50 km), and this has favoured weak tides (microtidal regime: mean spring tidal range of 0.5 to 1 m). The wave climate is dominated by short-fetch wind waves (periods of 4–6s), sometimes intermixed with longer waves (8–9s) where fetch conditions are more favourable. Wave approach directions are very variable. Storms can attain extreme intensities (Lionello et al., 2006), despite the limited fetch. Shaw et al. (2008) have reported destructive historical and pre-historical tsunamis.

Mediterranean deltas range from a few km² in area, associated with small catchments (tens to hundreds of km²), to major protuberances at the mouths of the larger rivers, the most important of which are the Danube, the Po, the Nile, the Ebro and the Rhône (**Figure 1**). Several of these large open-coast deltas, notably the Danube and the Rhône, started their development as bay-head deltas in embayments and rias. Numerous smaller deltas, especially in the Central and Western

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Figure 1: Map showing most of the Mediterranean and Black Sea river deltas (a) and Google Earth images of the ten deltas (b). Deltas selected for this study are represented by red dots in (a). The common deltaic plain of the Ceyhan and Seyhan deltas is referred to as the Ceyhan in this paper. Circles in (b) show arbitrarily delimited area around the delta mouths (see Materials and Methods). Arrows show wave-induced longshore transport directions: Danube-Stânfu Gheorghe (Vespremean-Stroe and Proteasea, 2015), Nile (Morhange et al., 2005; Ubeid, 2011; Ghoneim et al., 2015), Po (Simeoni et al., 2007; Simeoni and Corbau, 2009), Rhône (Sabatier et al., 2009) Ebro (Jimenez et al., 1997), Medjerda (Amrouni et al., 2014), Moulouya (Dakki, 2003), Arno (Anfuso et al., 2011), Ombrone (Pranzini, 2001). Directions for the Ceyhan are derived from delta plan-shape morphology in relation to the dominant local wave direction. DOI: <https://doi.org/10.1525/elementa.139.f1>

Mediterranean, also developed in these embayed settings under conditions of high fluvial sediment supply, notably rich in sand and gravel, and locally impeded longshore drift between bedrock headlands (Anthony et al., 2014).

The history and development of deltas in the Mediterranean basin, one of the cradles of civilization, has been strongly intertwined with the rise and demise of cultures and societies, as well as with major cultural and economic changes, especially over the last

two millennia (Anthony et al., 2014). The 23 countries bordering the Mediterranean have a total population of 498 million in 2015 (World Population Prospects, United Nations, 2015), with a relatively high density of 96 inhabitants per km² on the coast (Benoit and Comeau, 2005). Anthropogenic pressures are, therefore, consistently high on the Mediterranean's coast and deltas. Mediterranean deltas, like many other deltas, commonly have highly productive soils, rich and biodiverse ecosystems, and offer a wide range of ecosystem services such as coastal defence, drinking water supply, recreation, green tourism, and nature conservation. These deltas are home to millions of people, notably the iconic Nile delta, and host important agricultural and industrial activities as well as transport and communications infrastructure. But, like many deltas world-wide today, Mediterranean deltas are becoming increasingly vulnerable to catastrophic river floods, subsidence, global sea-level rise, and erosion (Anthony et al., 2014).

The vulnerability of modern deltas strongly depends on fluvial sediment supply that is increasingly impacted by human activities, leading notably to accelerated subsidence and erosion. Many deltas in the Mediterranean are linked to river catchments that have been dammed over the last few decades. Whereas accelerated subsidence has received a lot of attention in recent years, notably synthesized in the benchmark papers by Ericson et al. (2006) and Syvitski et al. (2009), delta shoreline change, especially erosion, also recognized as an important corollary of the diminution of sediment supply to deltas, has been treated in numerous case studies rather than in a synthetic approach.

In this paper, we analyse the current vulnerability status of a selection of ten Mediterranean deltas (**Figure 1**) by looking at shoreline erosion. The choice of these deltas was based on the following two criteria: a large delta size and/or availability of data. The problem of delta shoreline erosion and the underlying driving mechanisms are examined with reference to quantified variations in *delta protrusion area*. The ten selected deltas are open-coast deltas more or less exposed to waves and longshore currents that can redistribute, alongshore, reworked deltaic sediments, rather than bay-mouth deltas still encased in wave-sheltered ria-type embayments that have been more or less infilled by coastal aggradation and progradation under conditions of impeded alongshore sediment transport. The protrusion area is defined as the area of delta protuberance relative to a straight (theoretically hitherto open-coast) shoreline running across the delta plain and linking the delta to the adjacent non-protruding non-deltaic shoreline (**Figure 2**). The rationale for analysing the protrusion area is that as sediment supply wanes, the relative wave and current influence increases, leading progressively to 'flattening' of the delta protrusion and shoreline straightening as reworked deltaic sediments are redistributed alongshore (Anthony, 2015). Whereas the fluvial dominance ratio of Nienhuis et al. (2015) provides a prediction of the protrusion angle according to the change in river sediment flux, variation of the protrusion angle can be used to predict a change in protrusion area. Thus, the results could give an indication of the capacity of wave-influenced deltas to maintain their plan-view shape notwithstanding more or less significant sediment reduction. Protrusion reworking can also include the formation

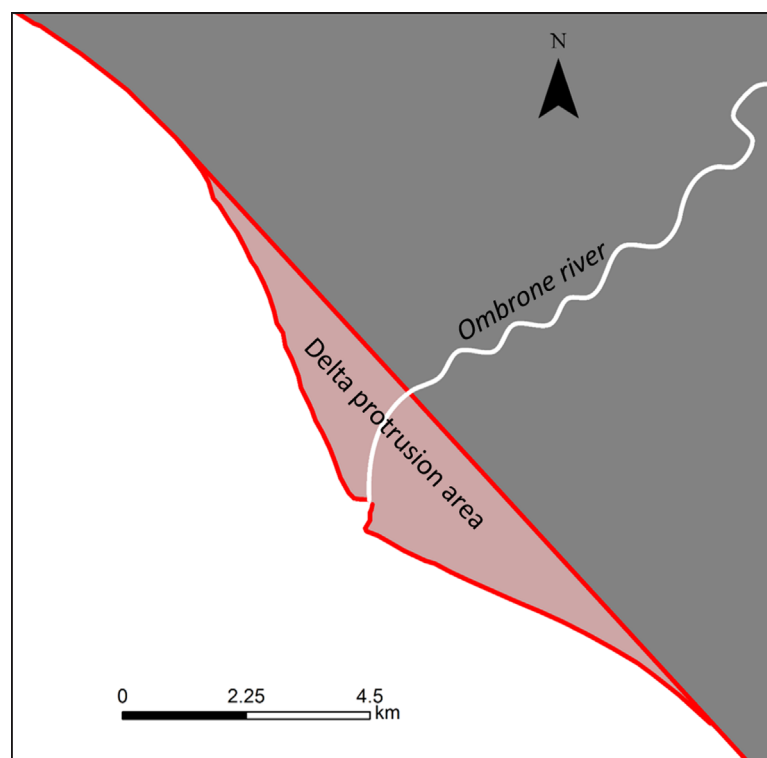


Figure 2: Schematic delimitation of the delta protrusion, using the example of the Ombrone. DOI: <https://doi.org/10.1525/elementa.139.f2>

of flanking spits on both active deltas (Anthony, 2015) and abandoned lobes (Nienhuis et al., 2013). Protrusion flattening and the attendant shoreline straightening may involve increasing asymmetry of the delta as part of the trajectory of delta destruction (**Figure 3**), although asymmetry may be an intrinsic attribute of many prograding deltas, expressed by a more or less skewed delta plan shape that expresses an uneven distribution of sediment on either side of the central axis of the delta (Bhattacharya and Giosan, 2003; Li et al., 2011; Korus and Fielding, 2015). Anthony (2015) showed that many Mediterranean

deltas presently exhibit a symmetrical or near-symmetrical plan shape that represents mutual adaptation between river flux, delta morphology, and wave approach. Thus, in instances where the deltaic coast at the mouth is indeed asymmetric, this could reflect an imbalance involving strong unidirectional longshore drift, as in the case of the Sfântu Gheorghe lobe of the Danube, characterized by the asymmetric Sacalin barrier (Vespremeanu-Stroe and Preoteasa, 2015). Some of the characteristics of the ten selected deltas, which are also among the largest in the Mediterranean, are shown in **Table 1**.

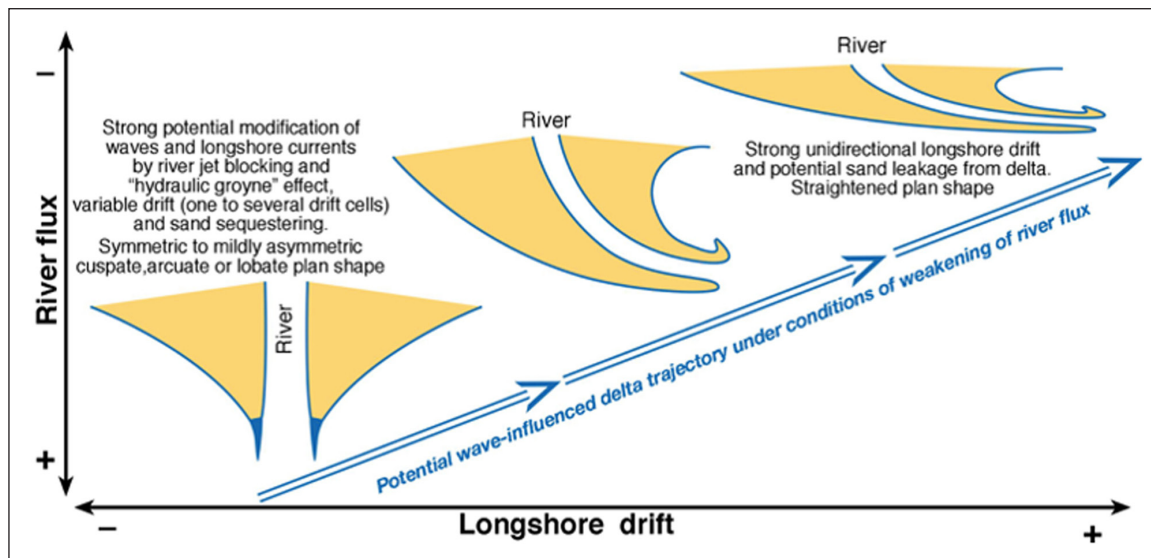


Figure 3: Schematic continuum of delta morphology and potential net long-term trajectory of evolution. The morphology ranges from symmetric to strongly longshore-deflected and asymmetric, as a function of river influence relative to wave-induced longshore transport. Delta destruction occurs as river influence becomes weakened by a variety of natural (changes in catchment climate and vegetation linked to the Little Ice Age, for instance, avulsion) and human-induced changes (catchment land-use and reforestation, catchment engineering, dams). From Anthony, 2015. DOI: <https://doi.org/10.1525/elementa.139.f3>

Table 1: Selection of data on the ten deltas and on their catchments and river discharge. Danube (Coleman and Huh, 2004; Preoteasa et al., 2016), Ebro, Nile and Po (Coleman and Huh, 2004), Arno, Ceyhan (Syvitski and Saito, 2007), Rhône (Provansal et al., 2014), Ombrone (Syvitski et al., 2005), Medjerda (Meybeck and Ragu, 1996), Moulouya (Snoussi et al., 2002; Milliman and Farnsworth, 2011). DOI: <https://doi.org/10.1525/elementa.139.t1>

Deltas	River basin area (km ²)	River length (km)	Fresh water discharge (m ³ /s)	Sediment discharge (kg/s)	Delta area from apex (km ²)	River mouth number	Protrusion area (km ²)
Arno	9200	240	57	72	437	1	6
Ceyhan-Seyhan	34210	380	222	173	150	2	1243
Danube	779500	2536	6499	630	5560	3	2302
Ebro	85100	624	240	34	935	1	304
Medjerda	15930	370	18	297	209	2	16
Moulouya	51000	520	21	151	787	1	2
Nile	3038100	3878	2778	3876	12512	2	1366
Ombrone	3480	130	32	60	37	1	19
Po	87100	691	1514	561	948	1	512
Rhone	90000	820	1700	167.54	3194	2	523

Materials and methods

The methodological approach involved three types of complementary analyses: (a) variations in delta protrusion area, (b) changes in delta protrusion angles, and (c) the degree of spit development in deltas where one or more spits are present, as an indicator of shoreline change.

(a) Delta protrusion area

In order to highlight recent deltaic shoreline changes and variations in delta protrusion area, we selected available satellite images of high (pixel size: 1.5 to 2.5 m) to moderate (pixel size: 30 to 60 m) resolution made available by the USGS and the French IGN, as well as aerial orthophotographs and, for the Rhône, field data (Table 2). The spatial data were chosen to cover the entire 'delta-influenced' shoreline for each year of analysis and with a cloud cover not exceeding 10%. We limited our choice to images taken at low tide and systematically in January of every year to minimize seasonal and tidal distortions (tides induce very little variability in the microtidal context of the Mediterranean and Black Seas). For each delta, the change in protrusion area between 1985 and 2015 was determined. The deltas were classed in terms of net area loss, net area gain, and stability. The shoreline was identified as the external limit, when observable, of vegetation between land and sea. Whenever the use of the vegetation marker was not feasible, we identified a variety of lasting indicators such as engineering structures to delimit the shoreline. Although the satellite data resolution varies, we chose to attribute a common error margin, incremented for deltas with moderate-resolution data. The error margin of the protrusion area for each delta was calculated from the errors due to satellite image resolution and operator uncertainty in manually delimiting the shoreline, given by the following equation:

$$E = \frac{L * E_l}{S} \quad (1)$$

where E is the error margin (in km), L the total shoreline length (in km), E_l the error relative to the resolution of the satellite images and operator uncertainty (in km), and S the protrusion area (km²). The result was then multiplied by the 30-year period of delta protrusion shoreline change. The area differentials have a mean error margin of 0.0092 km²/yr. E_l is expressed by a value increment of two pixels per km: one pixel to compensate for shades of colour of the satellite images and the other for operator errors in delimiting the shoreline, i.e., 0.018 km² per km.

The overall area differentials of the deltas are, with regards to the error margins, significant for all the deltas when expressed against delta protrusion area. We calculated the relative percentage error of change in protrusion area using the following equation:

$$E_{\%} = \frac{L * E * 100}{S} \quad (2)$$

where $E_{\%}$ is the percentage error of change in protrusion area.

$E_{\%}$ ranged from $\pm 5.4\%$ for the Moulouya delta to $\pm 0.1\%$ for the Ceyhan and Danube deltas. Deltas exhibiting gains or losses of less than the computed value were considered as stable, with negligible evolution over the 30-year period.

In complement to the overall delta shoreline change, the area change affecting the vicinity of the mouth(s) of each delta was also calculated using arbitrary limits depicted in Figure 1b. The reason for this operation is that the mouth zone is the primary receptacle of bedload exiting from the river, such that significant changes in this zone may be a good indicator of changes in fluvial bedload supply and/or in the intensity of reworking by waves and currents.

(b) Changes in delta protrusion angles

We used as a marker of shoreline change the variation in the mean angle of the protrusion shoreline on either side of the mouth of the delta. In wave-influenced deltas commonly characterized by a cusped protrusion morphology, the mouth is, theoretically, the zone most exposed to incident waves, although, in the presence of sustained sediment inputs, this zone is also subject to sedimentation and formation of mouth bars that dissipate wave energy. The larger the angle of the shoreline relative to the mouth, the 'flatter' the delta protrusion, and the straighter the shoreline subjected to alongshore redistribution of fluvial and reworked delta sediment on either side of the mouth. The mean angle was measured from linear regression lines of points at a regular interval of either 80 m (for images of 1970s) or 30 m (for 2015) along the shoreline on either side of the delta mouth at two dates (Figure 4). This analysis was carried out for all deltas for the year 2015 and the angle variation calculated relative to the year for which the earliest images, starting from the 1970s, were available: 1972 for the Ombrone and Ebro deltas, 1973 for the Ceyhan and the Nile, 1974 for the Moulouya, 1975 for the Po and Arno, 1977 for the Rhône and 1978 for the Danube. We postulated that an increase in this angle from one date to the other signified that the delta protrusion had become relatively flatter and more influenced by incident waves and longshore currents that redistribute reworked sediments away from the confines of the mouth, and potentially beyond the deltaic shoreline.

To estimate the error margins related to the measured offset river mouth angles (Θ), we computed the errors associated with satellite image resolution and operator measurements (Figure 4). The theoretical shoreline on either side of the mouth was produced from a linear regression of points along the shoreline at the regular intervals defined above. The distances between the coordinates of each point and its projection in the linear regression yielded negative or positive residuals (R_y) (in km) relative to the regression line (Figure 5). The absolute value of each residual was extracted and considered as the distance from the regression of each point. The arithmetic average of the residuals was calculated for the shoreline on each side of the mouth. These values were summed up with those of E_l . The result therefore corresponded to the error envelope of shoreline delimitation (Figure 5).

Table 2: Satellite and aerial photograph data used in the statistical analysis of deltaic shoreline change. DOI: <https://doi.org/10.1525/elementa.139.t2>

DELTA	DATE	Type	# shots	Resolution (m)	Provider	DELTA	DATE	Type	# shots	Resolution (m)	Provider
RHONE	1977	Aerial photography	23	1	IGN	MEDJERDA	1972	Landsat 1		60	
	1987		14				1984				
	1998	BD ORTHO®	4	0.5 à 1	IGN ; AERIAL		1988	Landsat 5			
	2002	DGPS Field survey + SPOT5	1	2.5	CEREGE; CNES		2000		1		USGS
	2003	SPOT 5 + BD ORTHO®	7	0.5 à 2.5	CNES; IGN		2005	Landsat 7		30	
	2005	DGPS Field survey	–	–	CEREGE		2010				
	2011	BD ORTHO® + Ortho littoral V2®	2	0.5	IGN ; MEEM		2015	Landsat 8			
	2015	SPOT 6	64	1.5	USGS						
	1965				IGM		1974	Landsat 1		60	
	1975				Toscany region		1980	Landsat 3			
ARNO	1982				Toscany region + IGM	MOULOUYA	1984	Landsat 5			
	1986	Aerial photography	nc	nc			1988	Landsat 4	1		USGS
	1990	(Cite Bini et al., 2008)					2000			30	
	1996				IGM		2005	Landsat 7			
	2003						2010				
	2004				Province of Pisa		2015	Landsat 8			
	2015	Landsat 8	2	30	USGS		1973	Landsat 1	5	60	USGS
							1990	Landsat 4 et 5	7	30	

(contd.)

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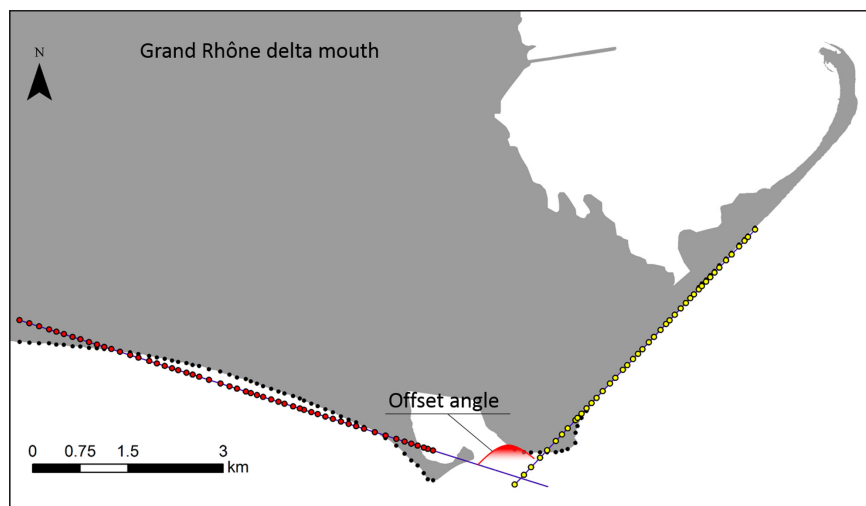


Figure 4: Method of quantification of the shoreline protrusion on either side of the delta mouth. The protrusion is delimited by the red arc with the example of the Grand Rhône mouth (Rhône). Black dots show shoreline delimitation points every 30 m (for images of the 1970s) or 80 m (for images of 2015), purple lines the regression lines of the generated linear model, and red and yellow dots the projection of points indicating shoreline position on the linear regression line, respectively on either side of the mouth. DOI: <https://doi.org/10.1525/elementa.139.f4>

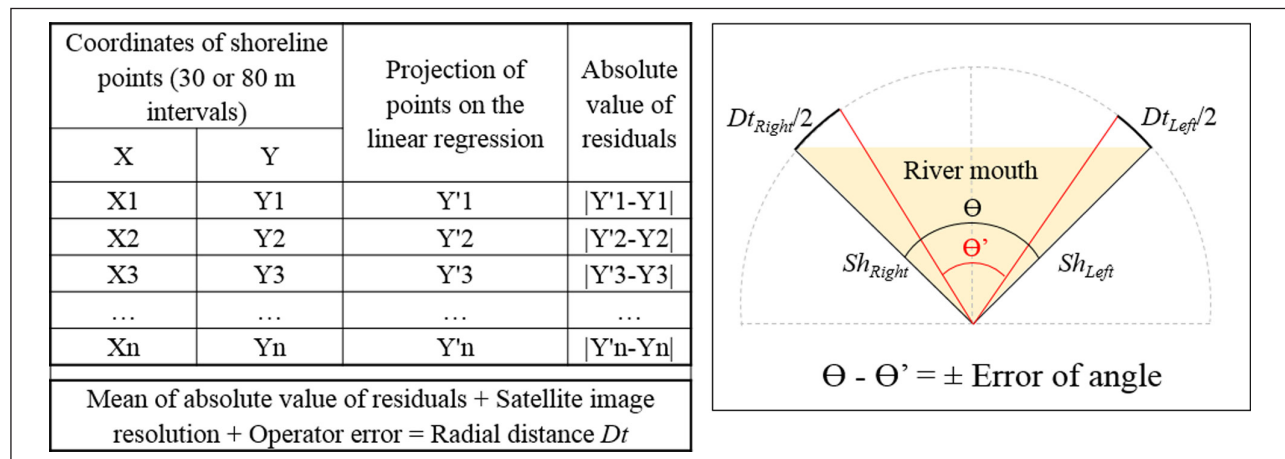


Figure 5: Method for calculating error margins of the offset river mouth angles. DOI: <https://doi.org/10.1525/elementa.139.f5>

In calculating the error margin of Θ , the down-mouth end of each shoreline Sh was offset by the angular distance $Dt_{(left\ or\ right)}/2$, expressed by:

$$D_t = \left| \overline{R_y} \right| + E_t \quad (3)$$

By subtracting the measured value of Θ' from Θ , as shown in **Figure 5**, we obtained the average error margin of the angle for each delta.

(c) Spit growth

For deltas characterized by one or more spits, spit lengthening over the 30-year period has been used as a geometric marker of shoreline change. The speed of spit lengthening has been calculated for each delta up to the year 2015.

Results

The results show that eight out of the ten studied deltas in the Mediterranean and Black Seas have lost protrusion area over the last 30 years, with a maximum, respectively,

of 34.4% and 16.3% for the Moulouya and Medjerda deltas in North Africa (**Figure 6**). However, changes are relatively weak in the other deltas (**Figure 6**). Although the Danube shows a large apparent gain in area compared to the other deltas, this gain is insignificant when compared to the protrusion area of the delta, of the order of 2,300 km², i.e., 0.1% in 30 years, equivalent to the error margin. This is also the case of the Po delta, one of the three largest deltas in the Mediterranean, the area gain of which has been negligible over the last 30 years. These results are coherent with trends reported in the literature for several deltas (**Table 3**). A close scrutiny of the data shows that much of the area loss has occurred in the vicinity of the river mouths (**Figure 7**). Only the mouths of the Arno, the Sulina and the Chilia show area gain.

In terms of temporal trends in shoreline change, most of the deltas show fluctuations over the 30-year period (**Figure 8**), with the Danube being the only delta with a clearly affirmed recent (since 2008) upswing in protrusion area gain. The Nile delta shows a long-term trend of

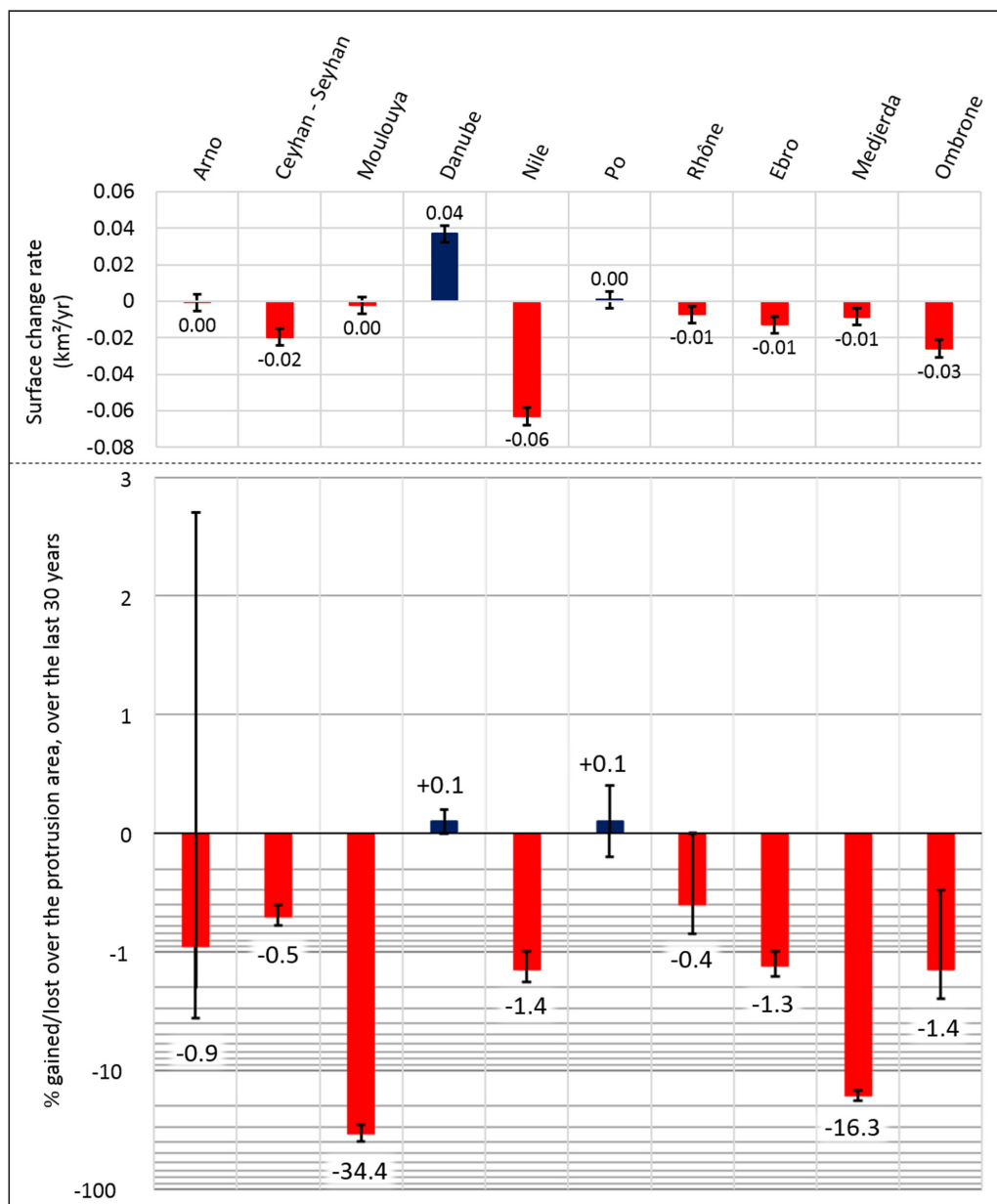


Figure 6: Statistical analysis of rates of shoreline area change. Rates of area change along the shorelines of the ten deltas (top graph). Percentage of delta protrusion area change for each delta over 30 years (bottom graph). Negative values (red columns) represent delta protrusions subject to erosion, and positive values (blue columns) prograding delta protrusions. DOI: <https://doi.org/10.1525/elementa.139.f6>

Table 3: Published references on delta shoreline change for the Arno, the Ombrone, the Rhône, the Nile, the Moulouya, the Medjerda and the Ebro deltas. DOI: <https://doi.org/10.1525/elementa.139.t3>

Delta	Reference for comparison	Comparison	Period
Arno	Bini et al., 2008	Surface area change	1965–2004
Ombrone	Cipriani et al., 2013	Metric area change	1973–2005/2006
Rhône	Sabatier and Suanez, 2003	Metric area change	1987–2000/2002
Nile	Torab and Azab, 2006	Surface area change (between Rosetta and Damietta mouths)	1973–2001/2005
Moulouya	Mouzouri et al., 2011	Observations	1988–2006
Medjerda	Louati et al., 2014	Metric area change	1987–2000/2002
Ebro	Jimenez et al., 1997; Jimenez and Sanchez-Arcilla, 1993	Metric area change and trends	1985–1990

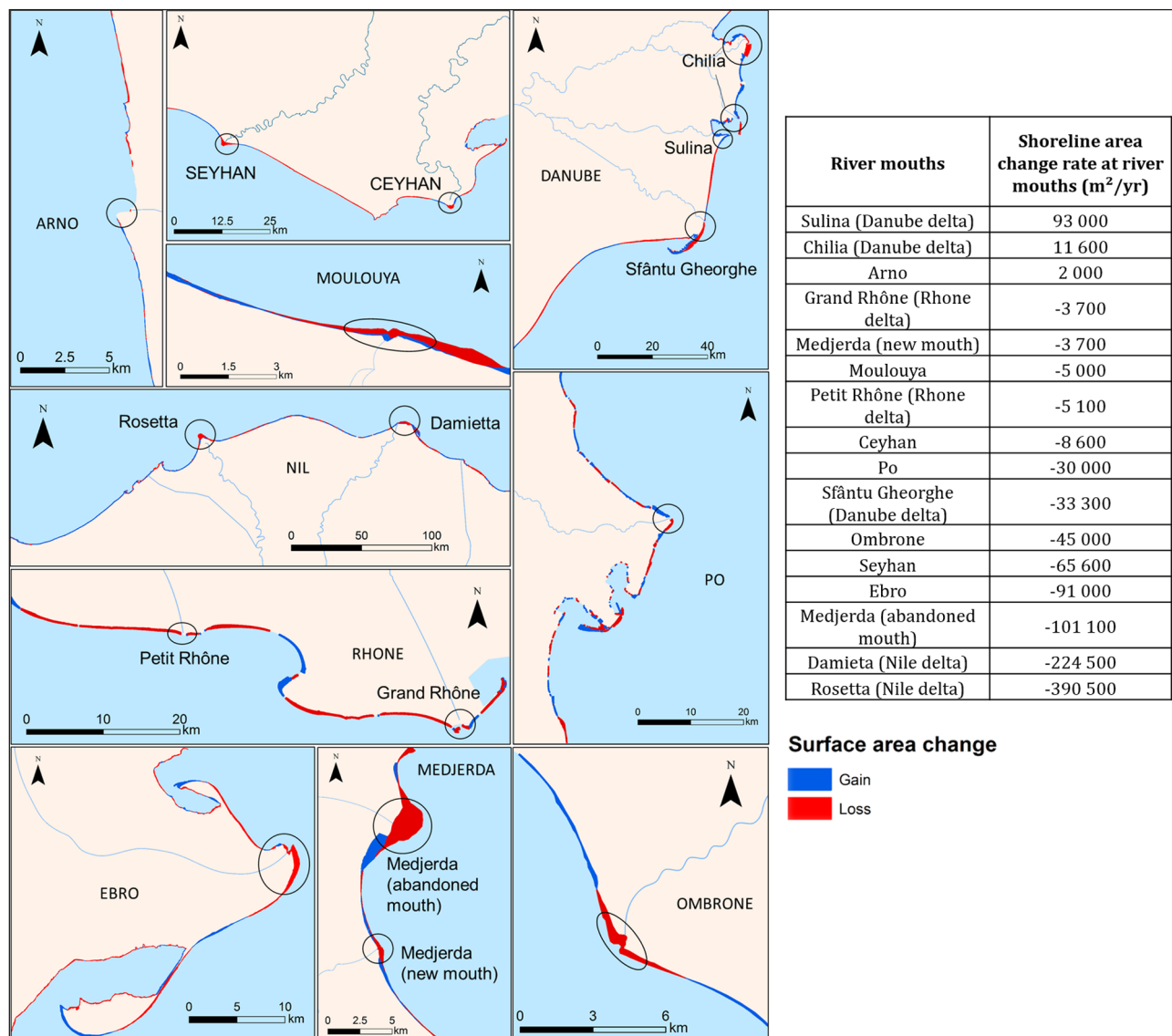


Figure 7: Surface area change in the immediate vicinity of the delta mouths. Area change, in m²/year, corresponds to the circled area. Losses are depicted in red and gains in blue. Note that the Medjerda underwent a major avulsion in 1973 following an important flood, leading to a new mouth in the south and abandonment of the historical mouth in the north. DOI: <https://doi.org/10.1525/elementa.139.f7>

erosion in the wake of the construction of the Aswan High Dam in 1964 that attained a peak in 1990, with erosion waning and replaced by relative stability over the last decade. The Po, Ceyhan and Ombrone deltas show a decline in area gain, and even a shift towards increasing loss over the last few years. Area losses have increased over the last 15 years for the Ombrone, Po, Rhône, Medjerda, Ceyhan, and Ebro deltas.

Regarding protrusion angles of the deltas, 9 delta mouths exhibit an increase in angle from the 1970s to 2015, with a maximum change for the abandoned mouth of the Medjerda, after a diversion canal built in 1939 resulted in flow division. The initial river mouth became abandoned (Figure 7) in March 1973 after an exceptional flood (Guen, 1988). The mouths of the Arno, Po, Rhône, and the Sfântu Gheorghe mouth of the Danube show a slight decrease or negligible increase not exceeding their respective error margin values over the study period. With the exception of the Arno, all of these delta mouths are also characterized

by wave-constructed spits. The results show extensions of the spits, already extant in the 1970s, flanking the mouths of the Ebro, Po, Rhône, Danube (Sfântu Gheorghe) and Nile (Damietta) deltas, ranging from 7 m/year to more than 160 m/year (Figure 10). The comparison between the evolution of the protrusion angle at the mouth and the change in lengths of these spits shows that the absence of coastal flattening, for the majority of the deltas, is compensated by important spit elongation. The Damietta protrusion of the Nile is an exception characterized by a progressive increase in shoreline angle together with spit lengthening of 3.15 km between 1990 and 2015.

Discussion

The impacts of human activities on Mediterranean river catchments and sediment flux have been documented in several case studies and in basin-scale syntheses (e.g. Bravard, 2002; Poulos and Collins, 2002; Hooke, 2006; Milliman and Farnsworth, 2011). Engineering works aimed

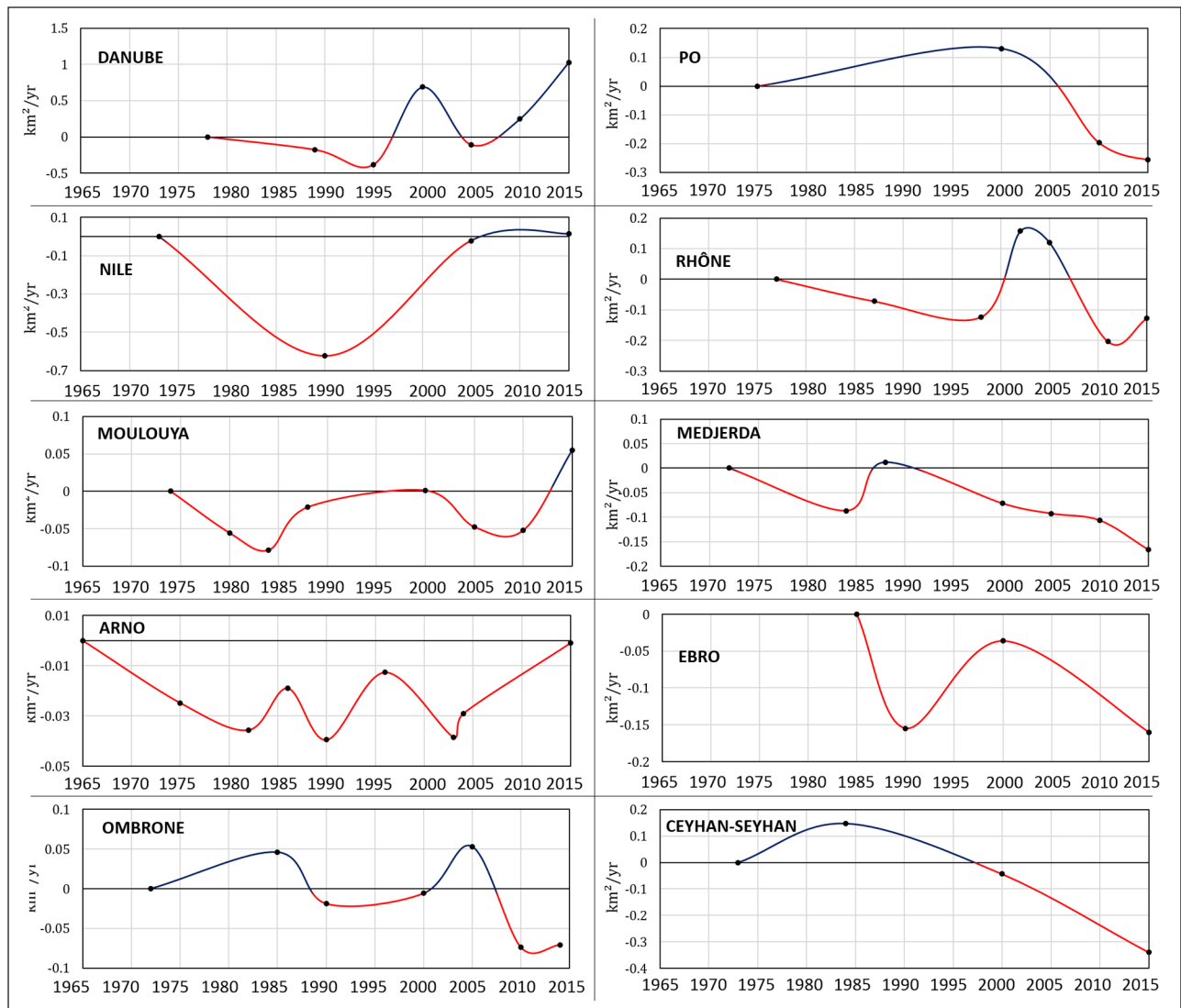


Figure 8: Temporal evolution of shoreline area change for each delta over 30 years. DOI: <https://doi.org/10.1525/elementa.139.f8>

at torrent management and channel embanking to assure flood control and navigation, as well as in-channel gravel and sand extractions, have significantly affected fluvial sediment supply to the coast. Over the last fifty years, dams intercepting and storing much of the fluvial sediment flux appear to stand out, however, as the dominant cause of reduction of river sediment to coastal sinks (e.g. Surian and Rinaldi, 2003). Hundreds of dams constructed across rivers draining into the Mediterranean Sea are deemed to have generated significant reductions in fluvial sediment loads, and none of the river catchments feeding the ten deltas selected for this study has been spared. Eight of the ten deltas are associated with catchments that have lost more than 60% of their sediment flux (**Figure 12a, b, c**). The Ombrone, Rhône, Ebro, Moulouya and Nile deltas have lost more than 80% of their fluvial loads following the construction of dams, this figure attaining 98% in the iconic case of the Nile. The sediment load of the Danube is still relatively high at 19.9 Mt/yr, despite a 70% drop after the construction of dams. The Ceyhan catchment, the latest to be affected by dams, has also lost a significant amount of its fluvial sediment flux, although this loss has

been much less severe than in several other catchments such as the Arno, Ombrone, Ebro, Moulouya and Nile, that now supply less sediment to their deltas than the Ceyhan. Although the relationship between dams and river sediment flux reduction appears, as expected, to be the overarching element of river catchment management in the Mediterranean and Black Seas in recent decades, there is a spatial and temporal variability in this relationship that implies that other factors need to be taken into account (Anthony et al., 2014). Land-use changes in Mediterranean catchments, especially the abandonment of farmland in the mountainous hinterlands, have led to reforestation, and concomitant reductions in fluvial sediment yields.

Although eight out of the ten deltas show both an erosional tendency and important decrease in fluvial sediment load, the statistical relationship between these two variables is not significant (**Figure 11**). This relationship is, in fact, only strongly expressed for the Moulouya and Medjerda deltas, which have significantly retreated over the study period. All the other deltas show very little loss or relatively mild gain (cases of the Danube and Po), notwithstanding significant decreases in fluvial

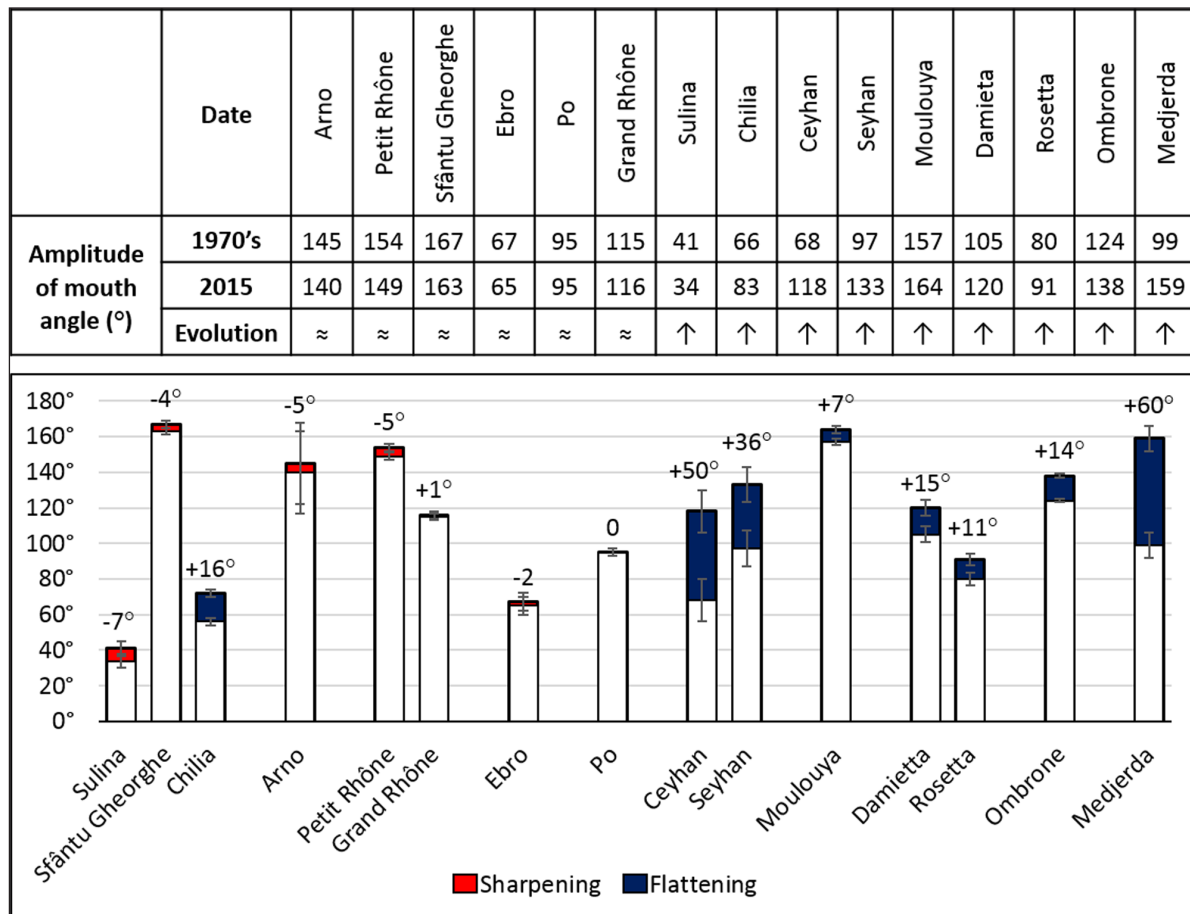


Figure 9: Changes in angles of delta protrusion between the 1970s and 2015. A decrease in protrusion, corresponding to delta shoreline straightening, is denoted by higher 2015 angles. DOI: <https://doi.org/10.1525/elementa.139.f9>

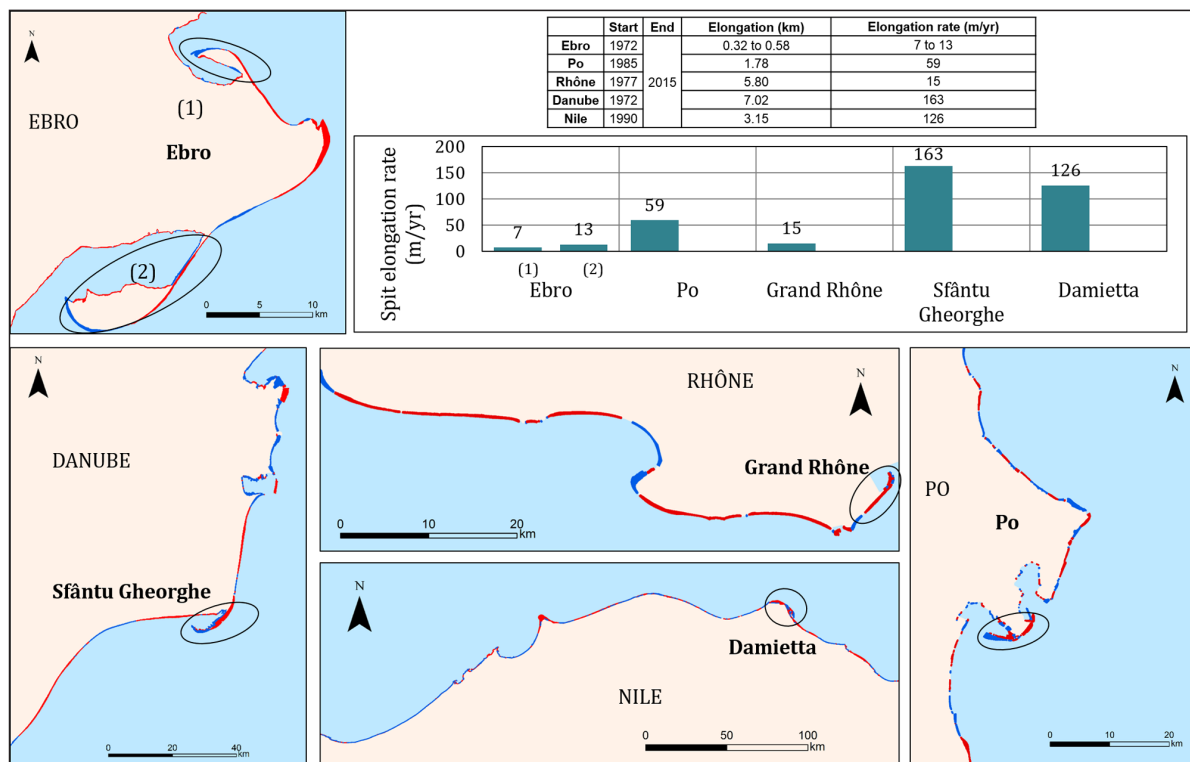


Figure 10: Rates of elongation of spits flanking the Ebro, Danube, Rhône, Nile and Po deltas. Blue shoreline indicates accretion and red erosion. DOI: <https://doi.org/10.1525/elementa.139.f10>

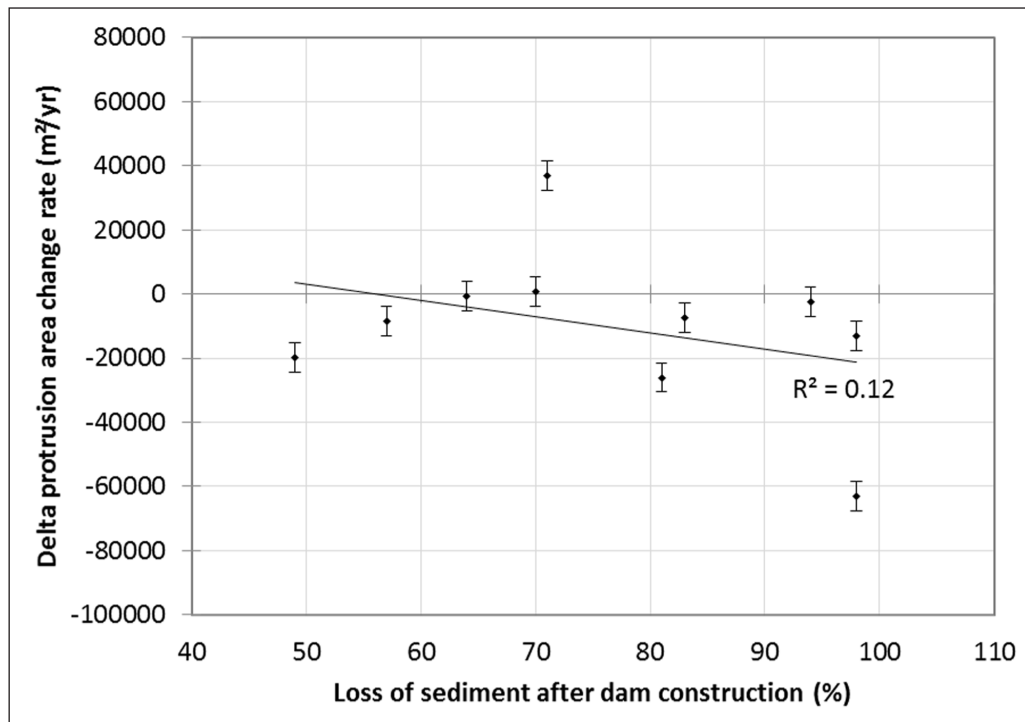


Figure 11: Scatter plot of delta protrusion area change rate versus loss of sediment after dam construction.

DOI: <https://doi.org/10.1525/elementa.139.f11>

sediment flux, notably in the Nile, Ebro, Arno and Rhône deltas (**Figure 12d**). The poor relationship could suggest that: (1) the negative effect of dams on sediment supply decrease to deltas in the Mediterranean is presently overestimated, (2) the relative shoreline stability reflects a lag in the downstream propagation of the effect of dams on the reduction of bedload transfer from river channels to delta shorelines. Lique et al. (2005) noted that sediment load reduction effects have, to date, had, little effect on many of the deltas of the small, steep rivers and torrents of the coast of Andalusia. Elsewhere, deltas have actually accreted as a result of land-use changes, a fine example being the Meric in Turkey (Ekercin, 2007). Although the Ceyhan delta shows a net loss of area, much of this loss is attributed to significant retreat of its twin Seyhan lobe following dam construction (Alphan, 2005). The first major dam on the Seyhan was constructed only in 1984 (Ataol, 2015), and since then, nine other dams have been constructed between 1989 and 2013. The less-dammed Ceyhan has shown net delta area gain following deforestation (Kuleli, 2010).

Although dams are incriminated as the primary cause of modern fluvial sediment retention, with the consequent negative feedback effects on coastal sediment budgets and shoreline erosion in the Mediterranean, very few studies have actually attempted to disentangle decreases in sediment flux caused by natural and land-use changes from those generated by dams (Anthony et al., 2014), a fine exception being that of the well-documented Rhône River budget over the last 130 years published by Provansal et al. (2014). These authors concluded that dams constructed on the river over the last thirty years have had little or no impact, the river having already been transformed by navigation and flood control works before upstream dam

installations could impact the downstream reach and the coast. The sources of sediment, torrential in origin, had already been exhausted before the dams were constructed. In their review of research progress and future directions in the relationship between dams and geomorphology, Petts and Gurnell (2005) showed that river relaxation downstream of dams can occur over very long periods of time, except for semi-arid systems, where changes can be initially rapid. This observation is in agreement with the significant erosion that has affected the Moulouya and Medjerda deltas over the 30-year period of study following damming of these two rivers. Only the Danube delta shows net advance over the 30-year period, notwithstanding a drop in fluvial sediment supply. Whereas the sediment load has decreased significantly (70%), the liquid discharge exiting at the mouths of the Danube has hardly varied, and this could be a significant factor in the relationship between river flux and its 'hydraulic-groyne effect' in mitigating wave reworking and evacuation of river-mouth deposits away from the delta confines (Anthony, 2015). Another factor could be the long relaxation time of the large Danube catchment after construction of the Iron Gate dams, with a bedload supply, from downstream of the last dams, to the coast at still practically pre-dam values, but this is an unresolved issue. A longer observation period, and high-precision river sediment-budget studies, of the type carried out by Provansal et al. (2014) on the Rhône, will be necessary to determine more definitively to which extent continued sediment trapping behind dams will impact delta shoreline change and overall delta stability in the Mediterranean and Black Seas.

Since our shoreline analysis covers the delta protrusion area, and assuming that reductions in sediment flux have affected delta shoreline sediment budgets, the poor

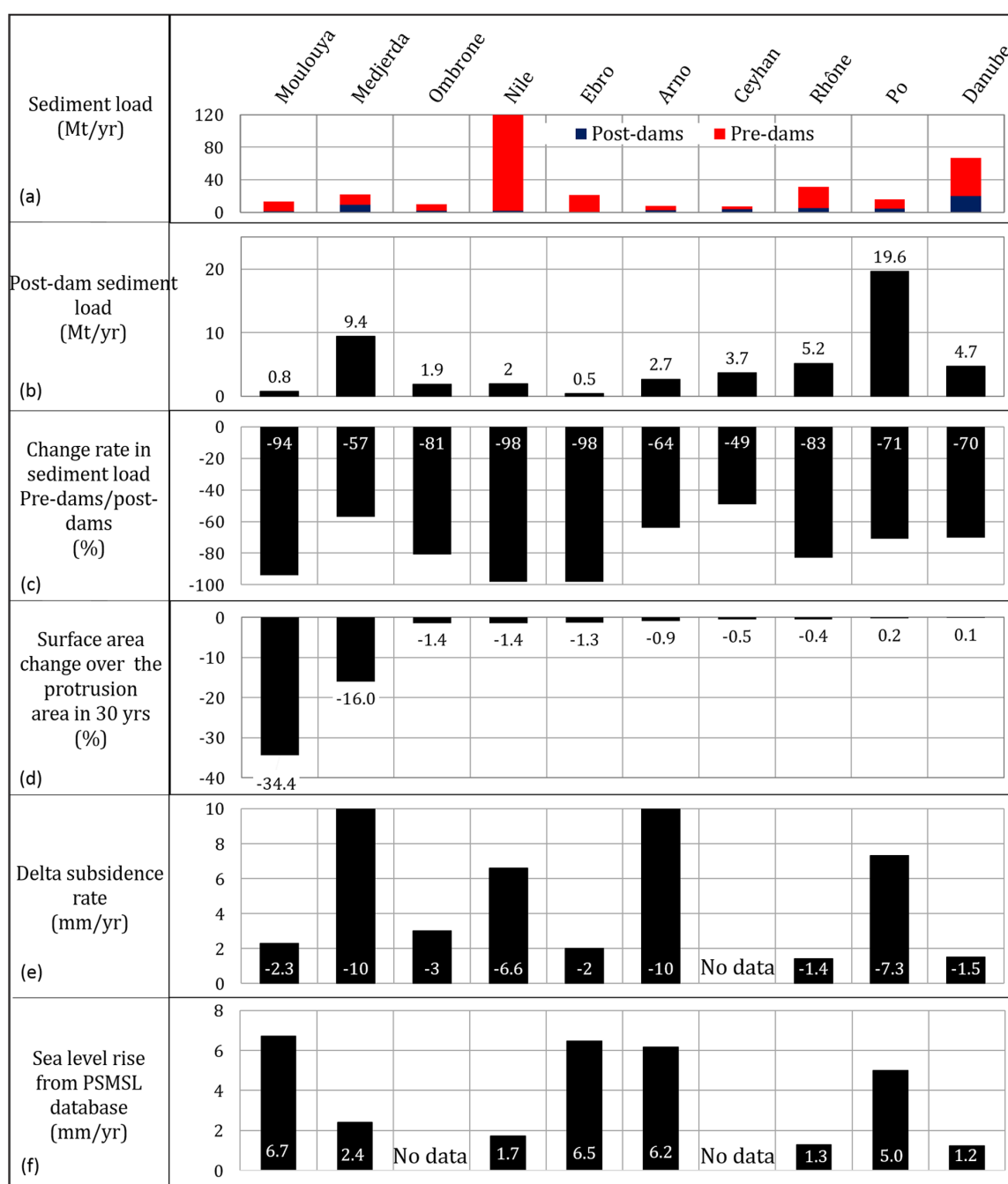


Figure 12: Graphs depicting changing river sediment loads and delta-plain subsidence confronted with changes in delta protrusion area for the ten deltas. (a) Pre- and post-dam sediment loads in Mt/year for the Arno River (Billi and Rinaldi, 1997), the Medjerda River (Sliti, 1990; Rand McNally Encyclopedia of World Rivers, 1980; Meybeck and Ragu, 1996; Tiveront, 1960; Milliman and Farnsworth, 2011), the Ebro River (Palanque et al., 1990; Vericat and Batalla, 2006), the Po River (Idroser, 1994 cited in Simeoni and Corbau, 2009; Syvitski and Kettner, 2007), the Ceyhan River (EIE, 1993, cited by Cetin et al., 1999), the Rhône River (Milliman and Meade, 1983; Ollivier et al., 2010; Dumas et al., 2015; OSR, 2016), the Moulouya River (Snoussi et al., 2002), the Ombro River (Milliman and Farnsworth, 2011), the Nile River (Syvitski and Saito, 2007; Milliman and Farnsworth, 2011), and the Danube River (Milliman and Farnsworth, 2011; Preoteasa et al., 2016); **(b)** Post-dam sediment loads in Mt/year (note difference in scale between (a) and (b)); **(c)** Percentage change in fluvial sediment loads following dam construction; **(d)** Percentage change in surface protrusion area over 30 years; **(e)** Mean delta-plain subsidence rates in mm/year: Arno (CNR, 1986), Danube (Vespremeanu et al., 2004), Moulouya (Church et al., 2004), Nile (Becker and Sultan 2009; Marriner et al., 2012; Stanley and Clemente, 2017), Po (Bondesan et al., 1995), Rhône (Vella and Provansal, 2000), Ebro (Ibáñez et al., 1997), Ombro (Pranzini, 1994), Medjerda (World Bank, 2011; Louati et al., 2014). Note that sediment loads in the European rivers have also undergone reductions related to catchment reforestation during both the pre-dam and the recent to present post-dam periods, as shown by the budget calculations of Provansal et al. (2014) for the Rhône. DOI: <https://doi.org/10.1525/elementa.139.f12>

relationship between shoreline area change and river sediment flux could also be explained by spatial and temporal variations in shoreline dynamics. Although the immediate vicinity of the river mouths is potentially the primary receptor of fluvial sediment, virtually all of the deltas showed a loss of area at their mouths (**Figure 7**). There is a probability that bedload losses that could arise from wave reworking of the delta protrusions, especially at the mouths, are mitigated by: (1) intrinsic sediment sequestering alongshore, within the confines of the deltas, (2) delta shoreline stabilization structures, and/or (3) delta spit lengthening. Intrinsic sediment sequestering alongshore could be a shoreline self-stabilization mechanism that counters sediment loss from the confines of the delta, especially in settings, such as the Mediterranean and Black Seas, where the influence of waves and wave-generated currents is important in delta shoreline reworking (Anthony, 2015). The old classification proposed by Fisher et al. (1969) distinguished, from a stratigraphic point of view, between 'highly constructional' river deltas in settings of strong fluvial influence and weak wave and current activity, and 'highly destructional' deltas which occur where wave reworking removes a significant part of the fluvial load. More recently, Nienhuis et al. (2013) numerically explored modes of wave reworking of abandoned delta lobes via longshore transport, while Anthony (2015) showed the potential for some wave-influenced deltas to sequester reworked shoreline sand through self-organized behaviour involving changing gradients in longshore sediment transport and notably counter-longshore drift patterns at the confines of the deltas. Nienhuis et al. (2015) further proposed a 'fluvial dominance ratio' expressed by river sediment input versus the potential maximum alongshore sediment transport away from the delta mouth to quantify the balance between river inputs and what they rightly considered as the largely overlooked ability of waves to spread sediments along the coast.

The longshore transport patterns of the ten deltas, culled from the literature, with the exception of the Ceyhan, are summarized in **Figure 1**. The dynamics of these delta mouths highlight both 'open' unidirectional longshore transport of bedload, and bi-directional transport from the mouths. The cases of the Arno, the Sulina and the Chilia seem to correspond to situations where sediment blocking at the mouth has been favoured. The Chilia is currently the main mouth of the Danube, capturing about 58% of the liquid and sediment discharge of the entire Danube basin (Bondar and Panin, 2001; Tatui and Vespremeanu-Stroe et al., 2016). The mouth of the Arno has been strongly engineered, and this results in bedload trapping in its vicinity (Anfuso et al., 2011).

The protrusion angles and their variations in time shown in **Figure 9** may be used to gauge the impact of wave reworking in a context of decreasing water and sediment discharge. Nine delta mouths (for a total of 6 deltas) exhibit an increase in angle from the 1970s to 2015 that is tantamount to a general flattening tendency of their protrusion, and alongshore leakage of reworked mouth sediments, among which the Moulouya exhibits the highest

change in angle. Where this angle change has been minimal, shoreline change is probably compensated by both spit lengthening, as in the cases of the Sfântu Gheorghe, Ebro, Po and Grand Rhône (**Figure 9**), and engineering structures designed to trap bedload. In the former situation, bedload exiting from the mouths is transported along the spits by waves. This mechanism assures wave energy dissipation through spit elongation. The role of shoreline engineering is further evoked below.

The results also show variability in shoreline change trends. The Nile, Moulouya and Arno deltas tend to show decreasing erosion, whereas the Po, Rhone, Ebro, Medjerda, Ceyhan and Ombrone deltas show a pronounced downswing with increasing erosion (**Figure 8**). Given the poor relationship between delta shoreline erosion and post-dam sediment reduction (**Figure 11**), the pattern in the former group may be due to a large range of factors. Engineering works along the Nile (Ghoneim et al., 2015; Ali and El-Magd, 2016) and the Arno delta shorelines (Anfuso et al., 2011) may explain the reduction trend, but such engineered mitigation of delta shoreline erosion is likely to become costlier in the face of sea-level rise and continued sediment starvation. In the case of the Moulouya, strong erosion at the mouth (**Figure 7**) and increasing flattening of the delta protrusion by wave and current reworking (**Figure 9**) may be leading to shoreline straightening and decreasing alongshore transport rates that also imply lesser erosion. Imassi and Snoussi (2003) calculated an area loss at the mouth of the Moulouya delta of 800,000 m² between 1958 and 1986, following commissioning of the first dams, the largest of which was constructed in 1967, and which led to a reduction in water and sediment discharge of up to 94% (Snoussi et al., 2002). The mean area loss rate calculated in our study over the period 1986 to 2015 corresponds to less than 20% of the mean annual net loss calculated by Imassi and Snoussi (2003), in agreement with a slow-down in alongshore bedload transport along an increasingly straightened shoreline.

The pattern in the latter group (Po, Rhone, Ebro, Medjerda, Ceyhan and Ombrone deltas) may be readily linked to the substantial recent decreases in fluvial sediment, notwithstanding the poor statistical relationship between shoreline change and fluvial sediment supply. Fluctuations in this trend, with temporary accretion pulses (**Figure 8**), may be related to exceptional sediment-supply conditions associated with larger river floods and/or engineered sediment releases from dams. This seems to be the case of the two small peaks evinced by the Rhône delta between 2000 and 2005, and between 2011 and 2015. The 2000–2005 peak no doubt corresponds to the effect, on sediment supply, of both engineered sediment releases from reservoirs on the Rhône, to the tune of 1.7 Mt by the firms running the dams, and a 1000-year return flood in December 2003. The 2011–2015 peak could be due to sediment releases from dams in 2012 of the same volume as in 2003. Maillet et al. (2006) calculated from bathymetric differencing a total of 600,000 m³ of sediment transferred from the Rhône catchment to the delta

and its inner nearshore zone following the December 2003 flood.

In other cases, phases of lower wave reworking associated with decreased 'storminess' may also have influenced the temporal pattern. Zainescu et al. (2017) have highlighted an unprecedented level of low storminess off the Danube delta since 2006 that has been matched by more fluvial deposition at the delta mouths and reduced wave reworking. Regarding the wave climate, however, analysis of ERA-40 and ERA-Interim hindcast data in the Mediterranean Sea generated by the Wave Atmospheric Model (WAM) model of the ECMWF (European Centre for Medium-Range Weather Forecasts) does not show any significant trend in wave height over the 30-year period of study of delta shoreline change.

Two final points of discussion concern the vulnerability of the deltas to subsidence and sea-level rise. Whereas some deltas such as the Nile and the Medjerda are affected by high subsidence rates, others, such as the Moulouya and Ebro, are more heavily impacted by sea-level rise (**Figure 12e, f**). Still others are exposed to both subsidence and rising sea level, as in the cases of the Po and the Arno. Deltas with the largest protrusion losses are not those currently exhibiting the highest subsidence rates, as shown by the Moulouya, probably a dominantly bedload delta, given its low subsidence rate of 2 mm/year (**Figure 12e**). In fact, there is no clear relationship between the 30-year loss in protrusion area and current subsidence rates. Compensation for subsidence no doubt takes up some of the still subsisting fluvial sediment supply to the deltas, especially the fine-grained over-bank sediment. The Medjerda probably illustrates the moderating effect of a still relatively sustained sediment supply following dam construction on a high subsidence rate of 10 mm/year. The Po exhibits a moderately high subsidence rate of more than 7 mm/year (**Figure 12e**), and shows only negligible shoreline change with regards to the large size of its protrusion (**Figure 6b**). This situation may be due to a combination of three factors: (1) the relatively low drop in fluvial sediment supply, compared to other deltas (**Figure 12a, c, d**), (2) the relatively wave-sheltered setting of this delta (**Figure 1**), and (3) changes in delta-plain depocentres associated with a net deceleration in human-induced subsidence. Subsidence from accelerated compaction generated by methane production in the Po delta from the late 1930s to the 1970s reached rates of 60 mm/year (Caputo et al. 1970, in Syvitski, 2008), but decreased by a factor of five after methane production ceased, and subsidence shifted to where sedimentation was more active (Bondesan and Simeoni, 1983, in Syvitski, 2008). Acceleration of subsidence and sea level rise in Mediterranean and Black Seas could lead to increasing delta vulnerability to erosion, as compensation of surface sinking and infill of accommodation space created by sea-level rise may not be sufficient under the currently prevailing sediment-supply conditions.

Conclusions

1. Delta protrusion area, defined as the area of delta protuberance relative to a straight shoreline running across the delta plain, and linking the

delta to the adjacent non-protruding non-deltaic shoreline, appears to be a useful criterion for analyzing river delta vulnerability to wave activity in the strongly wave-influenced setting of the Mediterranean.

2. Analysis of protrusion area loss for ten Mediterranean and Black Sea deltas show that eight are in erosion and two show negligible relative gain in protrusion area.
3. With the exception of the Moulouya and Medjerda deltas, the sediment loads of which are probably impacted by their semi-arid setting in addition to trapping behind dam reservoirs, the protrusion area loss has been moderate.
4. There is no statistically significant relationship between change in delta protrusion area and drop in river sediment supply following the construction of dams.
5. This poor relationship is probably due to: (a) over-estimation of the effect of dams on sediment supply decrease to deltas in the Mediterranean, and (b) a lag in the downstream propagation of the effect of dams on the reduction of bedload transfer from river channels to delta shorelines, with the exception of the Moulouya and Medjerda deltas, the semi-arid catchments of which appear to have responded rapidly to damming.
6. This poor relationship could also reflect the possibility that bedload losses that could arise from wave reworking of delta protrusions are: (a) mitigated by sequestering alongshore, within the confines of the deltas, (b) mitigated by delta shoreline stabilization structures, and/or (c) compensated by delta spit lengthening.
7. A longer observation period and high-precision river sediment-budget studies will be necessary to determine to which extent continued sediment trapping behind dams will eventually impact, in a more definitive way, delta shoreline change and overall delta stability in the Mediterranean and Black Seas.
8. Fluctuations in shoreline protrusion area over the 30 years involving temporary accretion pulses may be related to exceptional sediment supply conditions associated with larger river floods, phases of lower wave reworking associated with decreased 'storminess', or engineered sediment releases from dams.
9. There is no clear relationship between the 30-year loss in protrusion area and current subsidence rates.

Data Accessibility Statement

- The World Deltas Database Framework: <http://www.geol.lsu.edu/WDD>.
- Landsat satellite images: <https://earthexplorer.usgs.gov/>.
- Wave climate data: <http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/>.
- Tide data: <http://www.psmsl.org/>.
- The digitized shorelines and geometric processing can be available by contacting MB (besset@cerege.fr).

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: MB, EJA, FS
- Contributed to acquisition of data: MB, EJA, FS
- Contributed to analysis and interpretation of data: MB, EJA, FS
- Drafted and/or revised the article: MB, EJA, FS
- Approved the submitted version for publication: MB, EJA, FS

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