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Edward J. Anthony [(1)]

SAND AND GRAVEL SUPPLY FROM RIVERS TO COASTS: A REVIEW FROM A MEDITERRANEAN PERSPECTIVE

Abstract - E.J. Anthony, *Sand and gravel supply from rivers to coasts: A review from a Mediterranean perspective.*

Coasts composed of loose sand or gravel (bedload) are abundant in the Mediterranean and are built essentially from sediments supplied by river deltas. This bedload supply to the Mediterranean's clastic coasts has been favoured by river catchment characteristics and human influence. The plethora of pocket beaches in small embayments in the Mediterranean directly trap bedload supplied by small rivers, whereas fluvial bedload supply to more or less long open-coast shores, which include spits, and variably wide barriers and dunes, sometimes exhibiting more or less closely-spaced beach ridges, is conditioned by interactions between river jets, waves and wave-induced longshore currents, and river-mouth bars. Longshore currents redistribute mouth bar deposits to these adjacent, more or less distant, shores, assuring their stability or accretion. Sand, and more rarely gravel, has also been derived from nearby abandoned delta lobes or from older relict nearshore deposits, transported shoreward by wave reworking, and alongshore by longshore currents. Shoreline erosion by waves can also release sand and gravel that are redistributed alongshore to other portions of coast, or that accumulate offshore. Longshore transport from river mouths operates within the framework of one or several sediment cells with boundaries. Many such cells are now characterized by artificial boundaries that block bedload transport. These include harbours and terminal groynes, products of coastal urbanisation and economic development, especially over the last century. Human activities have also significantly affected river catchments and river mouths in the Mediterranean, thus impacting the capacity of rivers to supply sediments to coasts. The most important human interventions are flow regulation by dams and sediment entrapment by reservoirs, resulting in strong reductions in both river liquid and solid discharges, but fluvial channel engineering and harbour development have also affected rivers in the Mediterranean. These impacts were largely preceded in many Mediterranean river catchments by multi-millennial climate and land-use changes. Climate change and sea-level rise will further impact river sediment supply to coasts by affecting the ability of river mouths to trap or release sediment, and by modulating longshore bedload transport rates.

Keywords - Mediterranean coast, Mediterranean rivers, Mediterranean deltas, river dams, coastal urbanisation, artificial shorelines, coastal engineering.

Riassunto - E.J. Anthony, *L'apporto di sabbia e ghiaia dai fiumi alle coste: una review dal punto di vista del Mediterraneo.*

Le coste costituite da sabbia o ghiaia sono abbondanti nel Mediterraneo e sono costruite essenzialmente dai sedimenti trasportati dai delta dei fiumi. Questo apporto verso le coste del Mediterraneo è stato favorito dalle caratteristiche dei bacini dei fiumi e dall'influenza dell'uomo. La grande quantità di spiagge a tasca all'interno di baie nel Mediterraneo trattiene direttamente il carico solido fornito da piccoli fiumi che vi fluiscono, mentre il carico solido fluviale che raggiunge coste aperte di qualsiasi estensione, che includono *spit*, dune e barriere più o meno ampie, e che talvolta presentano cordoni di spiaggia con spaziatura variabile, è condizionato dall'interazione tra correnti dei fiumi, onde, correnti *longshore* indotte dalle onde e barre di foce. Le correnti *longshore* ridistribuiscono i depositi delle barre di foce lungo le spiagge adiacenti, più o meno distanti, garantendo la loro stabilità o accrezione. La sabbia, e più raramente la ghiaia, può anche derivare da vicini lobi deltizi abbandonati o da depositi costiero-prossimali relittuali più antichi, e poi trasportata verso costa dalle onde e lungo costa dalle correnti *longshore.* L'erosione delle spiagge a causa dell'azione del moto ondoso può anche fornire sabbia e ghiaia che sono poi ridistribuite lungo costa verso altri settori, o altrimenti accumulate *offshore.* Il trasporto lungo costa a partire dalle foci dei fiumi opera all'interno di un sistema di una o più celle litoranee con limiti ben precisi. Molte di queste celle sono adesso caratterizzate da confini artificiali che interrompono il regolare trasporto sedimentario: per esempio porti e pennelli ortogonali a costa, strutture legate all'urbanizzazione costiera e allo sviluppo economico, moltiplicatesi in particolare durante l'ultimo secolo. Le attività dell'uomo hanno inoltre significativamente influenzato i bacini e le foci dei fiumi nel Mediterraneo, finendo per modificare la capacità dei corsi d'acqua di fornire sedimenti alle coste. L'intervento dell'uomo si è esplicato principalmente attraverso la regolazione dei flussi d'acqua con la costruzione di dighe e l'escavazione di sedimenti dagli alvei fluviali, determinando forti riduzioni sia della portata liquida che di quella solida: l'ingegnerizzazione dei canali fluviali e lo sviluppo dei porti hanno influenzato i fiumi anche nel Mediterraneo. In tanti bacini idrografici Mediterranei, questo forte impatto antropico è stato comunque preceduto dai cambiamenti climatici e di uso del territorio avvenuti negli ultimi millenni. I cambiamenti climatici e la risalita del livello del mare continueranno ad influenzare l'apporto sedimentario dei fiumi modificando la capacità delle foci a intrappolare o rilasciare sedimento e modulando i tassi di trasporto al fondo lungo costa.

Parole chiave - Costa Mediterranea, fiumi Mediterranei, delta Mediterranei, dighe fluviali, urbanizzazione costiera, linee di costa artificiali, ingegneria costiera.

1. Introduction

The most important sources of sediment to the world ocean are rivers (Milliman & Farnsworth, 2011), and the redistribution of this sediment from rivers to adjacent coasts is primarily vested in waves and wave-generated longshore currents. The amount of sediment supplied annually by the world's rivers has been estimated at 10-20 billion metric tons (Milliman & Syvitski,

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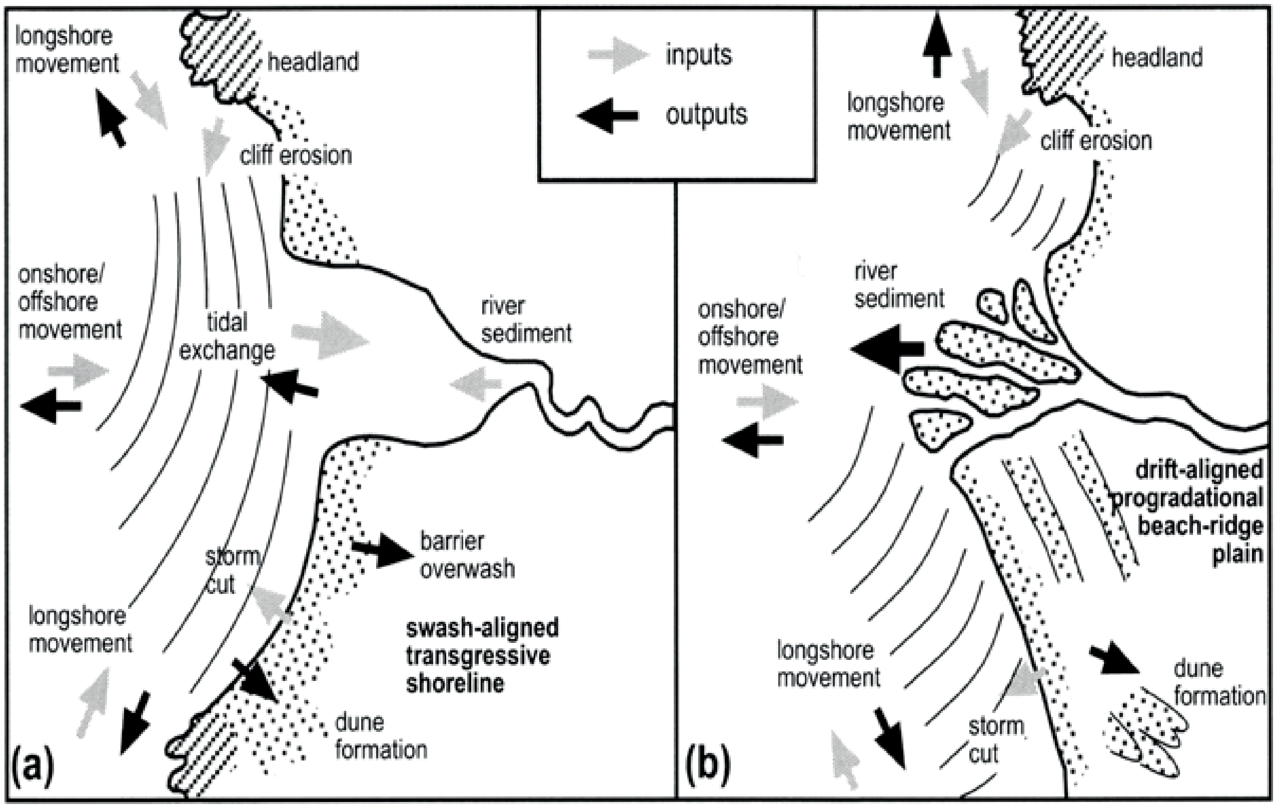

Fig. 1 - Sediment exchanges at river mouths. a) Infilling river mouths (estuary) tend to trap both terrestrial and marine-derived sediment. b) Infilled river mouths (delta) tend to supply sediment to adjacent shores that is redistributed through longshore transport. From Masselink & Hughes (2003).

1992), although there is considerable uncertainty concerning volumes, because of the effects of human intervention (Syvitski *et al.*, 2005; Ericson *et al.*, 2006), which are constantly on the increase. River sediment supply to the world ocean is largely dominated by fine-grained (mud) sediments, although the situation largely varies as a function of catchment climate and geology (Milliman & Farnsworth, 2011). Aggraded river mouths (deltas) commonly release fluvial bedload to adjacent coasts, whereas still infilling river mouths (estuaries) tend to trap bedload (Fig. 1). The sand and gravel fraction supplied by the world's rivers is important in the building up and stabilization of wave-built shorelines such as beaches, dunes and beach-ridge barriers. In addition to river supply, shoreline erosion by waves can also release sand and gravel that are redistributed alongshore to adjacent shorelines. Bedload is commonly redistributed downdrift following updrift beach erosion, cliff recession and coastal landslides, which may also be important local sources of sediment release to the shore. A third important source of bedload supply to the shore is the shoreface, especially in wave-dominated settings. Terrigenous and biogenic sediments accumulate on the shelf over short to geological timescales, and form superficial sediment sheets that can be reworked onshore by waves and wave-, tide- and wind-induced currents. Shoreline translation over the shelf during sea-level fluctuations has provided a long-term framework for further cross-shelf reworking of sediments.

This review concerns the supply and alongshore redistribution of coarse sediment (sand and gravel) from rivers to adjacent shorelines, based on a Mediterranean perspective. River bedload supply is particularly important in the Mediterranean basin where shorelines are mainly sourced by rivers, many of which are characterized by deltas (Fig. 2). The Mediterranean seaboard is relatively steep. As a result, the propensity for its coasts to benefit from sediment supply from the nearshore shelf is limited, in contrast to many oceanic coasts facing broad continental shelves (Anthony, 2009). 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 4-6 s), sometimes intermixed with longer waves (8-9 s) where

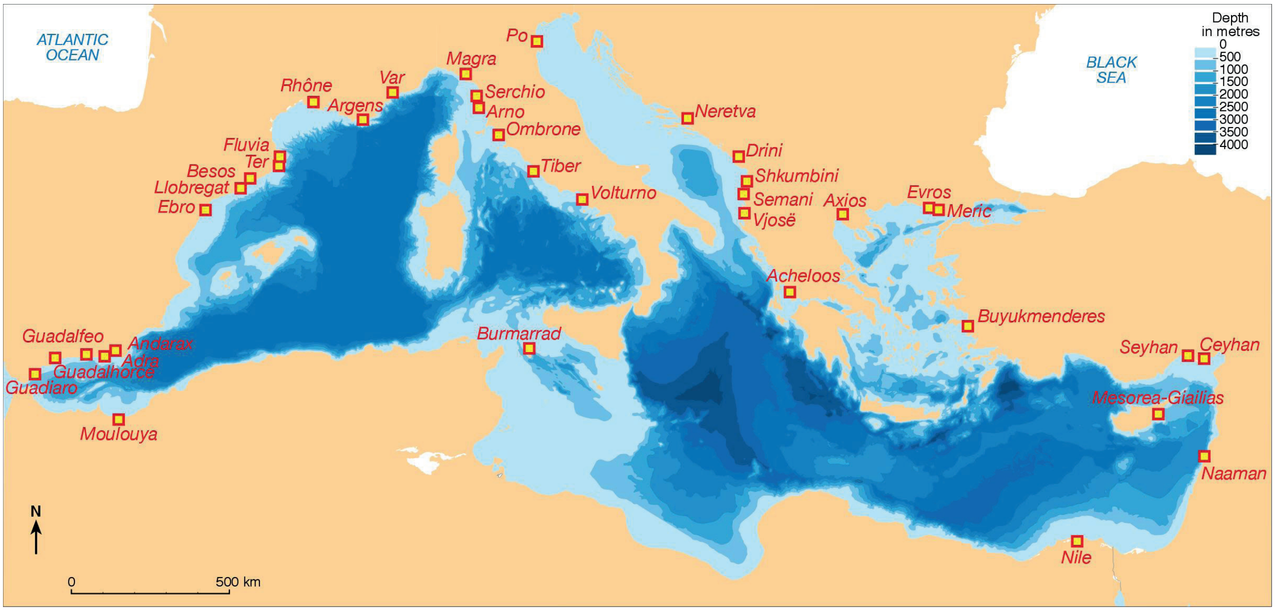

Fig. 2 - Map showing many of the rivers deltas of the Mediterranean. Note the abundance of deltas on the Spanish coast, the Italian Tyrrhenian Sea coast, and the Adriatic coast. From Anthony *et al.* (2014).

fetch conditions are more favourable. Wave approach directions are very variable. Storms can attain extreme intensities (Shah-Hosseini *et al.*, 2013), despite the limited fetch. Shaw *et al.* (2008) have reported destructive historical and pre-historical tsunamis.

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 (Fig. 3). Shoreline development in these cases has generally been sourced by rivers episodically subject to floods strong enough to flush sediments to the nearshore zone, where they form a sediment reservoir for wave-induced alongshore supply to adjacent beaches. Along the relatively arid southern and eastern shores of the Mediterranean, aeolian activity has also commonly generated large aeolian dune systems. Such dune systems are much less developed on the western shores of the Mediterranean. In addition to open-coast barriers, the Mediterranean comprises a plethora of more or less deeply embayed shores of all lengths (< 10 m to 10 km) locked between bedrock headlands (Anthony *et al.*, 2014). These embayments are associated with dominantly rocky shores and are rimmed by rocky bluffs and/or sandy/gravelly pocket beaches or barriers (Grottoli *et al.*, 2015). They commonly have limited space for sediments to accumulate and are sediment supply-limited, with little or no progradation, but some are sourced by episodic sediment inputs from ephemeral streams, especially on high-relief coasts (Pranzini *et al.*, 2013) in the Western Mediterranean. Other embayments developed as

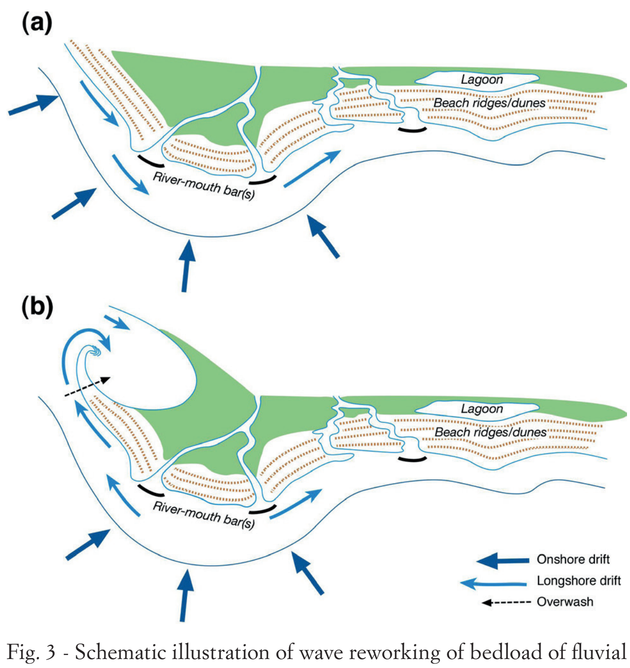

Fig. 3 - Schematic illustration of wave reworking of bedload of fluvial origin and/or derived from the nearshore shelf to feed the accretion of distant barrier shorelines composed of beach ridges, dunes and spits with unidirectional longshore transport from the mouth in panel (a), and divergent, bi-directional longshore transport in panel (b), the classical situation of river delta supply of bedload to adjoining coasts. From Anthony (2015).

rias since sea level stabilized in the mid-Holocene. High fluvial sediment supplies, sand- and gravel-rich bedload, and locally impeded longshore drift between bedrock headlands have favoured an abundance of infilled bay-head deltas in some rias, in addition to the numerous open-coast deltas, especially in the Central and Western Mediterranean. Small coarse-grained so-called Gilbert-type or fan- and braid-deltas fed by short streams debouching from steep mountainous hinterlands (McPherson *et al.*, 1987) are a possibility along parts of the steep margins of the Western Mediterranean. Along these steep Alpine margins, the shelf is dissected in many areas by deep fossil canyons inherited from the Messinian Salinity Crisis (Clauzon *et al.*, 1996).

2. River mouths in the Mediterranean: the preponderance of deltas

River mouths are geomorphologically expressed as estuaries or deltas. Estuaries drowned as Post-Glacial sea level rose and stabilized tend to trap both fluvial and marine sediment, progressively filling up, and eventually evolving into deltas as a function of time and adequate sediment supply (Stanley & Warne, 1994). Although there are small steep-catchment rivers with limited coastal plain development in the Mediterranean, many river mouths are commonly associated with low-lying coastal plains, and are, thus, highly sensitive to changes in relative land and sea levels. Such changes determine the base level to which river mouths adjust. A rising sea level creates 'accommodation space' for sediments. This river-mouth accommodation space needs to be filled with sediments brought down by rivers, but sometimes also transported from the nearshore area and nearby shores by waves and currents. As sea level rise commonly outpaced sediment supply before 9000 yr BP, this favoured the development of estuaries, rather than deltas. Modern river deltas around the world started developing more or less simultaneously from infilling estuaries following the slowing down of the postglacial sea-level rise between about 9000 and 6000 years BP (Stanley & Warne, 1994). Since sea level stabilized about 5-6000 years ago and accommodation space was no longer created, many deltas have developed from infilling estuaries where rivers provide abundant sediment. This is particularly the case in the Mediterranean where there is a plethora of deltas (Fig. 2) of all sizes related to large sand and gravel supplies over the last 5000 years as a result of favourable catchment conditions, climate changes and human-induced changes (Anthony *et al.*, 2014). Mediterranean river deltas range from a few km^2 in area, associated with small catchments (tens to hundreds of km^2), to major subaerial deltas at the mouths of the larger rivers, the most important of which are the Po, the Nile, the Ebro and the Rhône (Fig. 2). Delta area is not, however, proportional to river basin area (or river length in Fig. 4), as many small rivers, such as the Acheloos, Fluvia and Ombrone, are characterized by disproportionately large deltas, whereas the Nile delta, which has shrunk in size over the last four millennia, is characterized by a small ratio (Fig. 4). Ratios of delta area to river size vary as a function of geological setting and inheritance, climate, exposure to waves, and human influence (Marriner *et al.*, 2015). The Po subaerial delta, which has an area of about the same size as that of the Nile, stands out with an exceptionally high ratio, fed by a fluctuating but large supply of sediment from its steep Alpine setting, and located in an area that excludes strong wave export of sediment. Deltas are particularly abundant on the steep mountain ranges bordering the coasts of Spain, Italy and the Adriatic (Fig. 2). On the 400 km coast of Andalusia in southeastern Spain, Liquete *et al.* (2005) identified no less than 26 rivers ranging in basin size from 3120 km2 (the Guadalhorce) to 3.8 km2 (the Dos Hermanas), all with deltas.

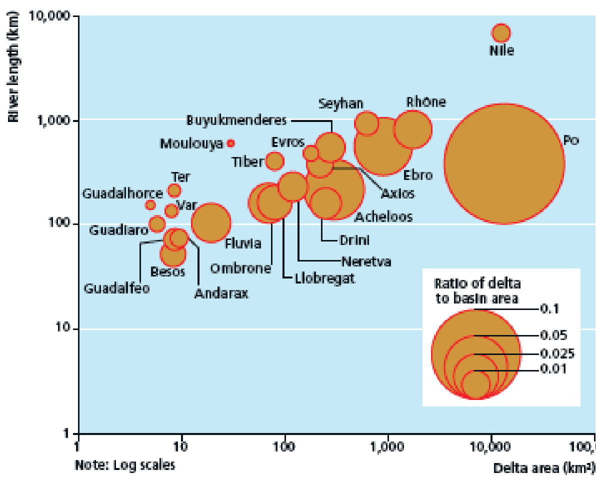

Fig. 4 - Graph showing river length, delta area and the ratio of delta area to river length for a selection of Mediterranean deltas. From Marriner *et al.* (2015).

3. River-mouth sedimentary processes: a brief synopsis

River mouths occupy a coastal transitional zone that has been deemed by Dalrymple & Choi (2007) as representative of one with some of the most profound spatial changes in depositional conditions that can be found anywhere on earth. This is because of the strong variations in many factors that influence the nature of the deposits (Fig. 5). These are, following Dalrymple

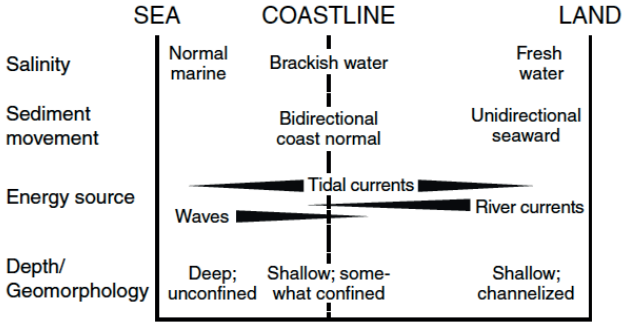

Fig. 5 - Variations in controls on sedimentation in the complex river-mouth transition from purely fluvial settings (land), through the tidally-influenced coastal zone, to shelf environments (sea). From Dalrymple & Choi (2007).

& Choi (2007): (1) the bathymetry and geomorphology, which change from relatively shallow-water, channelized environments landward of the coast, to deeper, unconfined settings on the shelf; (2) the source of the physical energy responsible for sediment movement, which ranges from purely river currents to tidal, wave, and/or oceanic currents on the shelf; (3) the resulting frequency, rate, and direction of sediment movement, which is unidirectional and continuous, to seasonal or flashy in the river, or reversing, with mutually evasive transport pathways in tidal settings, with a tendency for landward-directed residual transport, and onshore-offshore transport on the adjacent shoreface; and (4) the salinity of the water, which ranges from fresh, through brackish, to fully marine on the shelf. These variations are particularly marked in open-mouthed estuaries and deltas potentially subject to significant marine influence.

The majority of the world's river mouths, including most deltas in the Mediterranean, are characterized by dynamic processes involving interactions between fresh and salt water and a variable influence of tides, which, together, dominate the spectrum of 'estuarine' processes. This hydrological criterion is quite distinct from the afore-mentioned geomorphic distinction between infilling river mouths (estuaries) that continue to trap sediment from all sources, and largely infilled river mouths (deltas) that tend to export fluvial sediment to the sea (Fig. 1). Because of the weak tidal ranges in the Mediterranean, the tidal influence is quite limited. As a result, river-mouth processes mainly hinge on interactions between river discharge and waves (Fig. 3). Estuarine processes may be completely excluded from Gilbert-type deltas. More commonly, seawater penetrates up-river, either mixed to varying degrees with the freshwater discharge, or as a salt wedge beneath the overlying river discharge. Mixing may range from vertically homogeneous, under high-turbulence conditions, to salinity-induced density stratification in lower-turbulence situations, associated with 'estuarine circulation' in which denser, more saline bottom water tends to move landward at the bottom, whereas fresher water moves seaward at the surface. Water and bedload generally move seaward in the river-dominated portion of the fluvial-marine transition, whereas in the marine-dominated portion the net movement may be either seaward or landward depending on river discharge, on the neap-spring tidal stage, and sometimes on wind forcing. The tidal flows in the estuarine reaches of rivers may be characterized by mutually 'evasive' flood- and ebb-dominated transport pathways around elongate tidal banks. This condition is, however, much less developed in Mediterranean river mouths because of the commonly steep gradient of terminal channels and the weak tidal range.

The hydrodynamic processes prevailing in river mouths generally act to trap fluvial sediment in estuaries, and to limit its export to the sea (Fig. 1), a condition that can cause rapid river-mouth silting and navigation problems where yachting and fishing harbours are housed in river mouths, a common situation in the Mediterranean. As far as bedload is concerned, this trapping occurs essentially through the large-scale effects of water mixing or salt-wedge development and landward-directed residual tidal flow. The transported bedload tends to accumulate in a bedload convergence (BLC). The farther the salt intrusion into the estuary, the more likely sediment is to be trapped in the BLC. Bedload trapping efficiency depends on the position of the convergence zone, the strength of convergence and, for the fine sand fraction which may be temporarily suspended during strong flows, the settling velocity. The BLC in estuaries tends to lie landward of the shoreline trend, whereas, in deltas, it generally lies in the vicinity of the mouth protrusion. In the latter situation, the BLC is extremely important in storing and supplying bedload to adjacent shores away from the confines of the delta (section 5), but also in river-mouth management for purposes of navigation. The location of the BLC can vary strongly with tidal range, the neap-spring tidal cycle, and river discharge fluctuations, but as shown below, where wave influence is strong, the tidal range low, and sediment supply adequate, which is the case of many Mediterranean deltas, the position of the BLC commonly corresponds to the meeting zone between fluvial discharge and waves, somewhere offshore of the mouth, where it is expressed as river-mouth bars (Fig. 3, see also section 5). This critical river-mouth area from where bedload is transported to build up adjacent shores (beaches, barriers, dunes) is also, as stated above, one of the most complex of hydrodynamic environments because of the diversity and space- and time-varying intensity of fluvial water discharge, tides, and wind and wave activity (Fig. 5). Fluvial supply of bedload to the coast is particularly important in the course of strong river flood events. Under such strong fluvial discharge, complete river domination of the river-mouth dynamics may occur, and estuarine processes that may be involved in the formation of mutually evasive bedload transport pathways within the main delta channel(s) and non-tidal (density) circulation can be suppressed, such that bedload is transported directly offshore of the confined river to form river-mouth bars.

At the interface between down-flowing freshwater and up-flowing salt wedge, tidal and density current activity in delta channels can generate alternating deposition and resuspension of fine suspension-sized material (mud) in an estuarine turbidity maximum, a zone exhibiting generally very high suspended sediment concentrations. Salt-wedge intrusion, a fundamental mechanism in the infill of estuaries, can lead to the re-introduction into delta channels of sediment deposited by a river in the nearshore or offshore zone.

4. Methodological approaches in monitoring bedload dynamics in river mouths

Bedload supply from river mouths to adjacent coasts is primarily assured by waves and the longshore currents they generate. Additional currents may be generated by winds, as in the Mediterranean, and tides, but the latter are weak in the Mediterranean. Wave activity in the vicinity of river mouths is, however, strongly modulated by river discharge. Understanding of the processes at play when waves interact with river mouths is still poor. This complexity resides, in a nutshell, in hydrodynamic interactions involving more or less sediment-charged river plumes, waves, wave-induced currents, wind-induced stress, tides and tidal currents, salinity differences and density currents, bottom friction and bedload transport, commonly under energetic conditions, in addition to morphodynamic feedback among mouth and inner shoreface morphology, bathymetry, bedforms and flow. Despite this complexity, an understanding of river-mouth processes is fundamental if we are to better elucidate the pathways of river-mouth bedload dynamics in the presence of waves, as well as the long-term development of deltaic and adjacent shorelines. These processes are also of considerable importance in the engineering and management of river mouths for navigation and other purposes.

A fair understanding of these processes, which are involved in bedload sequestering at river mouths, and especially bedload mobilization by waves and currents for redistribution to adjacent shores, is still hampered by the inadequacy of conventional equipment to provide measurements in this highly dynamic environment, but also by the commonly large area and spatial and temporal variability inherent to processes and bedforms. In addition to recourse to successive bathymetric surveys, from which bottom terrain models can be generated to determine change, bedform monitoring and current and suspended sediment concentrations using acoustic Doppler current profilers have also been employed. Other complimentary approaches include the use of bathymetric Lidar (Light Detection and Ranging) data and other remote sensing methods that detect suspended sediment concentrations (such as the use of MERIS and MODIS satellite images) and bedforms (SPOT and other high-resolution optical satellite images), and, in the near future, drone-derived photogrammetry-based shallow bathymetry. As an alternative, or complement, to these field experimental and remote sensing approaches, numerical modelling has been used extensively in recent years to predict river-mouth hydro-morpho-sedimentary patterns, but such efforts are still far from achieving their objectives. Numerical modelling efforts, aimed, for instance, at elucidating the possibility of formation of river-mouth bars (section 5), fundamental to longshore bedload redistribution towards adjacent beaches by waves and currents, are generally based on the DELFT3-SWAN wave model that simulates the propagation and dissipation of organized wave energy at the river mouth. Wave heights have, however, been shown to be significantly overestimated in SWAN modelling of strong gradients in opposing, partially blocking currents (Westhuysen, 2012; Dodet *et al.*, 2013), and this is potentially a source of bias in estimating the impact of waves on mouth bars. Furthermore, modelling is hampered by scale and time constraints, especially as far as river influence is concerned. River influence varies significantly between large and small rivers, whereas the wave background is essentially similar whatever the size of the river. Bar formation is also likely to be associated with strong river discharge, whereas the wave influence relative to river discharge is more likely to be greater during periods or seasons of low river discharge. In an estimate of longshore bedload transport in the mouth of the Rhône, Sabatier *et al.* (2009) used the NMLong-CW model (Numerical Model for simulating Longshore Current-Wave Interaction), a 2D model that calculates wave characteristics (height and direction), longshore currents (velocity) and longshore sediment transport rate in the surf zone with an externally imposed current (Larson & Kraus, 2000). They found that wave height was directly affected by the presence (case 1) or absence (case 2) of river flow, since the breaking waves were significantly lower in case 1 than in case 2, with longshore transport being less active when river flow blocked the waves in the mouth sector (Fig. 6).

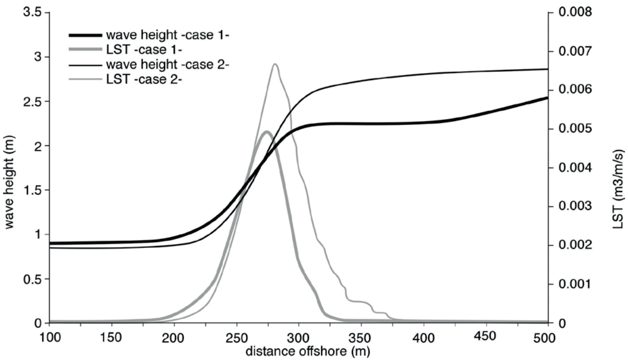

Fig. 6 - Simulation of the longshore sediment transport (LST) at the mouth of the Grand Rhône river delta using the NMLong-CW model. From Sabatier *et al.* (2009).

5. Bedload supply from river mouths to the coast: river-mouth bars

If we leave aside the afore-mentioned complexity of river-mouth dynamics and the underlying logistic and methodological difficulties involved in monitoring the fate of bedload, the river mouth basically plays the role of destabilizing waves and longshore currents, leading to deposition in the BLC zone and the eventual formation of mouth bars. River-mouth bars are commonly sandy to gravelly shallow-water deposits where subject to wave action, which inhibits mud deposition. Bars are also commonly poor in mud where rapid muddy sedimentation between the river mouth and the bar occurs. Figure 7 is a simplified sketch of interactions between river mouths and waves under different potential wave incidence contexts (Anthony, 2015). Ideally, the river flux just needs to generate a destabilization of waves that ensures that the necessary amount of bedload trapped is sufficient to foster aggradation at the mouth, leading to delta growth. Excessive bedload accumulation, tantamount to nearly total wave dampening, could indeed result in massive aggradation of the mouth of the river, with feedback up-river on channel instability that eventually contributes to generating channel avulsions. Avulsions, which can lead to delta lobe switching and abandonment, have been generated in some large Mediterranean deltas by pulses of massive sediment supply and accumulation in their terminal channels and mouths, inducing wave dampening to the extent where wave-generated currents become too weak to assure longshore evacuation of sediment, thus generating disequilibrium. Fine examples have been documented in the Po (Correggiari *et al.*, 2005) and the Rhône (Provansal *et al.*, 2015). The interactions between the river and wave action at the mouth may concern both unidirectional and bidirectional longshore transport, depending on wave direction. Bi-directional transport is characterized by divergence from the mouth, and is essential in feeding adjacent shores on either side of the river mouth (Fig. 7).

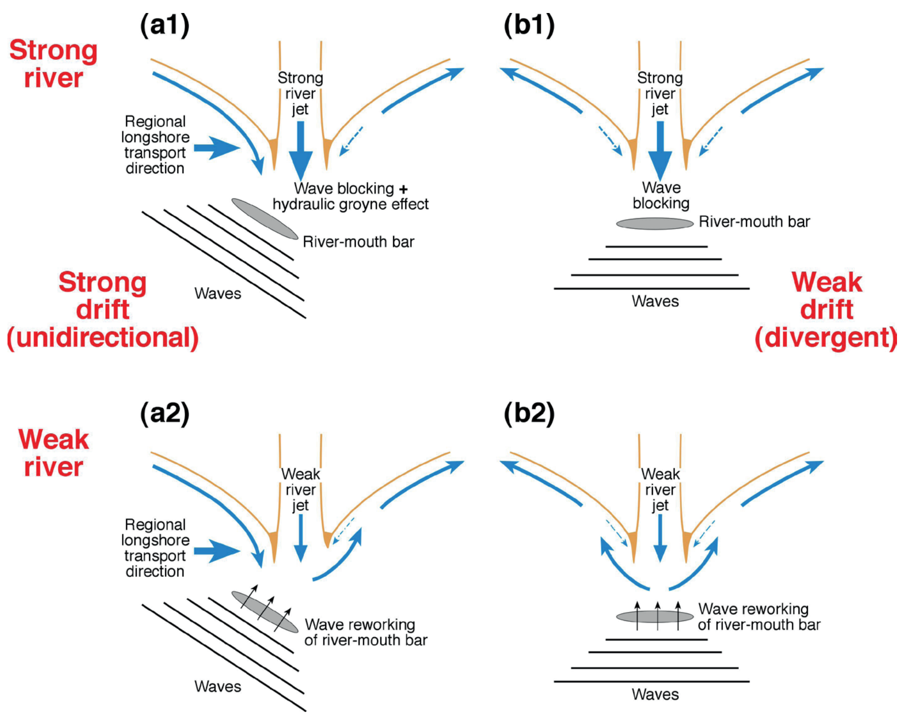

Fig. 7 - Simplified interactions between a deltaic river mouth and waves under conditions of strong (a) and weak (b) longshore drift and strong (1) and weak (2) river influence. Strong river influence is expressed by wave blocking in (a1) and (b1) and by the hydraulic groyne effect of the river jet on the longshore current in (a1), resulting in both (a1) and (b1), as well as by the formation of a river-mouth bar, whereas wave reworking and established longshore currents, strong in (a2) and weak in (b2), prevail under conditions of weak river influence. Counter-drift may locally prevail near the river mouth in all situations as a result of gradients in wave dissipation between the mouth zone and the adjacent coast. River-mouth asymmetry occurs in (a2) as a result of the strong unidirectional longshore drift. From Anthony (2015).

Insight on the dynamics of river mouths can be gained from measurements and modelling of tidal inlets. Tidal inlets are generally much smaller than river mouths, and unlike the latter, which are more complex and logistically harder to monitor, have been commonly studied for decades, especially from an engineering point of view. In tidal inlets, the ebb discharge plays the role of fluvial discharge. River flow is expected, as in the case of strong ebb flow through tidal inlets, to generate energy dissipation through wave blocking and refraction (e.g., Ris & Holthuijsen, 1996; Sabatier *et al*., 2009; Westhuysen, 2012; Dodet *et al*., 2013), resulting in disorganization of a wave-driven longshore current caused by the so-called hydraulic groyne effect (Fig. 7). The hydraulic groyne effect refers to the effect of the ebb jet on longshore currents across tidal inlets (Todd, 1968), and the term was later employed by Komar (1973) to describe the strong river outflow in his model of river delta growth under the influence of longshore currents. Both wave blocking and longshore current disorganization enhance in-situ bedload accumulation. The dissipative effect of the river jet on wave energy may be enhanced by viscosity associated with a significant charge in suspended sediment, which is likely to be the case in many river mouths during events or seasons of strong liquid discharge (Anthony, 2015). Bedload accumulation at the mouth resulting from interactions between river flow and wave blocking should lead to the formation of river-mouth bars, but the mechanisms involved are hard to demonstrate, whether by experimental work or by recent numerical modelling efforts. Using the 3-D Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system to numerically analyze the interaction between currents, waves, and bathymetry in idealized inlet configurations, Olabarrieta *et al.* (2014) further demonstrated that the mouth bathymetry (ebb shoal in tidal inlets) is a dominant controlling variable. In river mouths, the mouth bar thus corresponds to an accumulation of bedload (the BLC, section 3) at a variable distance offshore of the confinement of the river channel banks (Fig. 8). The mouth bar may be linked to the river channel banks by subaqueous levees that act as additional bedload transport conveyors toward the former. Several conceptual and numerical efforts have been devoted to the genesis and dynamics of river-mouth bars, from the early synthesis of Wright (1977) to the recent work of Canestrelli *et al.* (2014). Edmonds & Slingerland (2007) found from modelling that the distance between the river mouth and the mouth bar was proportional to the river jet momentum flux and inversely proportional to grain size, but this only concerned river-dominated mouths in the absence of waves. The larger the momentum flux and finer the grain size, the larger this distance. Where waves are significant, the locus of bar formation must be an adjustment between the momentum flux of river (and ebb tidal) discharge, grain size, and wave characteristics such as height, period and incidence angle (Anthony, 2015). The relationship between the formation and growth of mouth bars and wave influence is still not clear, however, especially with regards to the inhibiting role of waves on mouth bar formation found from some modelling studies such those of Geleynse

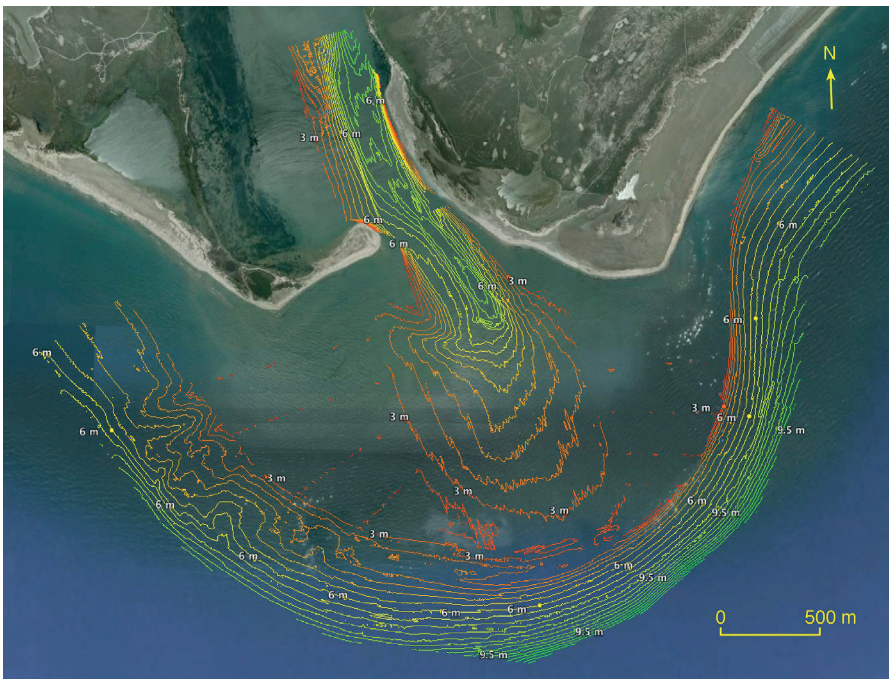

Fig. 8 - Lidar and side-scan sonar bathymetric image of the mouth bar of the Grand Rhône, the main distributary of the Rhône delta and engineered to channel almost all of the river's present discharge. The bar is a quasi-permanent feature. Flanking levees along the river channel are linked to the bar (3 m contour) at an offshore distance of about 1 km. From Anthony (2015).

et al. (2011) and Nardin *et al.* (2013). This finding is in contradiction with the abundance of bars associated with wave-influenced river mouths. River-mouth bar deposition has been a commonly described feature of many bedload-rich deltas in environments where wave action can be significant, such as those of the Ombrone (Pranzini, 2001), the Rhône (Sabatier *et al.*, 2009), and the Seyhan (Evans, 2012), to cite but a few Mediterranean examples. River delta mouths are extremely complex entities, and concerns may be raised about how representative numerical modelling efforts on river-mouth bar interactions with waves are of real-world deltas. Datasets on river-mouth bar deposits in real-world deltas are lacking, with very few exceptions (e.g., Vassas *et al.* (2007), Rhône; Traini *et al.* (2012), Sao Francisco in Brazil).

For bedload, and keeping wave height constant, the stronger the relative river-mouth jet effect, both in terms of wave blocking and longshore transport disruption, the farther offshore of the mouth bar deposits are likely to be. Anthony (2015) has shown that where the regional drift is unidirectional, strong wave energy dissipation at the mouth should reinforce transport on the updrift side towards the mouth (Fig. 7) because of the resultant alongshore wave energy gradient. However, this gradient can also theoretically generate local counter-drift towards the mouth on both flanks in situations of transport divergence at the mouth, thus further enhancing bedload concentration in this zone (Fig. 7). Under conditions of weak river influence, active wave reworking of the mouth bar may be expected to simply lead to downdrift bedload transport in the former case, probably involving bedload bypassing from the updrift to the downdrift flanks across the river mouth. In contrast, in the latter case, longshore transport redistributes the wave-reworked bar deposits towards the delta flanks. Minor and limited counter-transport in the immediate vicinity of the mouth may still occur, however, on the basis of the wave energy gradients involved in bar reworking (Fig. 7). River-mouth bars are, thus, important as sources of sediment and as initial forms for the construction of wave-built deltaic and adjacent shorelines. Longshore currents play an important indirect role by mediating mouth bar development, in addition to their more fundamental role in redistribution of sediment alongshore that contributes to shaping shorelines (Fig. 3).

6. River influence and longshore bedload transport configurations

Anthony (2015) proposed schematic large-scale delta plan-shape configurations reflecting the relationship between river influence and wave-induced longshore transport for single-mouth deltas or individual delta lobes (Fig. 9). The trajectory shown in this figure presupposes that river influence is more prone to last-

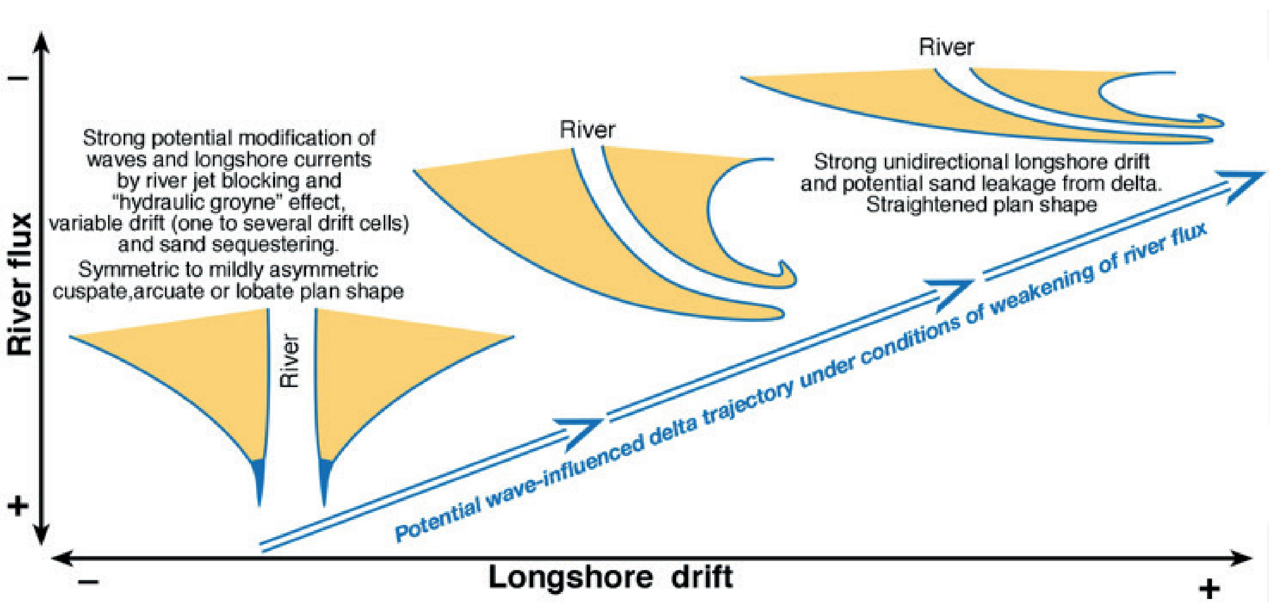

Fig. 9 - Schematic continuum of delta morphology ranging from symmetric to strongly longshore deflected, as a function of river influence relative to wave-induced longshore drift, and potential net long-term trajectory of delta evolution as river influence becomes weakened by natural (changes in catchment climate and vegetation linked to the Little Ice Age, for instance, avulsion) and human-induced changes (catchment land-use and reforestation, catchment engineering, dams). For symmetric deltas on the left side of the diagram subject to divergent drift, the trajectory may dominantly involve simple recession through redistribution of delta lobe sediments towards the flanks, leading eventually to delta shoreline straightening. From Anthony (2015).

ing fluctuations than the offshore wave climate, and thus predicts the evolution towards an increasingly drift-dominated delta configuration as the fluvial influence progressively decreases. Deltas that are morphometrically relatively symmetrical and subject to opposed or bi-directional drift, such as the Ebro and the Ombrone (Fig. 9) are, theoretically, the ideal sediment suppliers to adjacent shorelines on both sides of the river mouth. The drift divergence leads to redistribution of mouth deposits on both flanks of the delta. Other examples of this potential relationship between longshore transport and the delta mouth probably include the main Pila lobe of the Po, the Rosetta lobe of the Nile, the Shkumbini, Tiber, Arno and Volturno deltas. Pranzini (2001) argued that delta symmetry is a product of progressive delta growth despite an initial dominant regional transport direction. The terminal courses of the Arno and Ombrone rivers face the dominant waves, a configuration induced by rapid delta progradation as a result of increased river sediment supply following widespread catchment deforestation in Tuscany from the Early Middle Ages to the 18th century (Pranzini, 2001). The rivers maintained their directions as a result of higher accretion rates on the less exposed downdrift sides of the deltas. On the more exposed updrift sides, delta growth caused the shoreline to gradually evolve as to face directly approaching waves. Here, due to lower refraction, wave energy per unit of shoreline increased whilst the shoreline accretion rate decreased. This rotation of the shoreline led to longshore inversion on the updrift side, whereas present-day erosion of the cuspate mouth under an increasingly deficient sediment supply is leading to restoration of the original transport direction. These changes are depicted in Fig. 10 for the Ombrone.

It is interesting to note that all of these deltas are, with the exception of the Rosetta lobe, on the northern Mediterranean seaboard, and have been reported by Anthony *et al.* (2014) to have developed under a particular set of conditions that include: (1) pulses of large sediment supply mediated by human activities over the last two thousand years, and by Little Ice Age (LIA) changes from the 16th to the 19th centuries that favoured rapid delta formation and changes in delta morphodynamics, (2) a commonly single terminal channel, (3) relatively fetch-limited conditions and a large directional spread of wave energy, potentially limiting wave removal of fluvial sediment, but with, nevertheless, one dominant wave window, (4) high winter river discharges that also coincide with the most energetic waves, thus potentially fostering the rapid growth of cuspate-type deltas facing the energetic wave window and subject to divergent transport from the mouth.

Regional net unidirectional drift is probably the most common drift configuration on the world's coasts. For delta symmetry to prevail, strong river flow needs to act as an efficient hydraulic groyne on bedload transport. This presupposes that abundant bedload is supplied from updrift by wave-induced longshore transport, and intercepted by the fluvial jet exiting through the river mouth (Anthony, 2015). The stronger the groyne effect and larger the sediment supplied alongshore from updrift the larger the deltaic growth likely to result from this interception, except where through-transport occurs when river discharge is low. With time, an increasingly prominent delta lobe growing relatively perpendicular to the general coastal trend would tend to reduce the net sediment transport towards the mouth as the waves assume a more normal approach direction (Bhattacharya & Giosan, 2003; Ashton & Giosan, 2011). This type of delta configuration is probably rare (Anthony, 2015). More commonly, under conditions of regional unidirectional transport, mutual adjustments between the river flow and wave approach angle can result in variably skewed river mouths and delta lobes (asymmetric deltas) that highlight a more or less strong influence of longshore

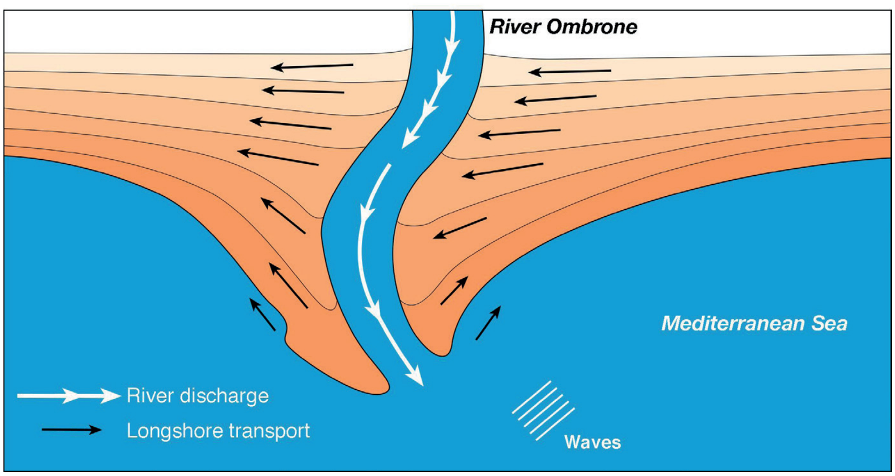

Fig. 10 - Changes in the Ombrone river delta illustrating the shift from unidirectional longshore drift to divergent drift from the mouth (modified after Pranzini, 2001). This growth mode has involved gradual rotation of the updrift flank in a way as to generate the drift divergence from the mouth. Several other deltas in the Mediterranean appeared to have developed in the same way. From Anthony (2015).

drift relative to river influence (Fig. 9). The sediment transported along the flank updrift of the mouth may be derived from erosion of deltaic strand-plain deposits as in the case of the Ombrone (Pranzini, 2001), or from abandoned delta lobes, as in the Rhône (Sabatier & Suanez, 2003; Sabatier & Anthony, 2015). Connected sediment cells (section 8) along deltaic coasts subject to strong longshore transport are likely where several active or abandoned lobes coexist. Apart from the Rhône, the Nile delta with its active (Rosetta and Damietta) and abandoned (Burullus) lobes provides fine examples of such connected cells (El Banna & Frihy, 2009).

7. Calculation of longshore bedload transport rates

The upper shoreface, and notably the surf zone, are affected by longshore transport under the joint effects of sediment stirring by wave breaking and advection by currents induced by waves. Wave forcing may be reinforced or weakened in certain environments by currents generated by wind forcing and by tides. Under breaking wave conditions, transport rates are commonly two to three orders of magnitude higher inside than outside the surf zone (Wright *et al*., 1991), although such transport can also be pronounced in the swash zone (Masselink & Puleo, 2006), but swash zone transport has been much less investigated. Predicting shoreline evolution typically requires reliable calculations of the volume of sediment transported alongshore that may be fed into models of long-term shoreline development. The difficulties of measuring bedload in the breaker, surf and swash zones, where longshore transport operates optimally, has led to a profusion of modelling approaches based on transport formulations that are more or less calibrated by optical and acoustic backscatter sensors, complemented by current meter recordings of current speeds, bedload trapping using traps or estimates from accumulation rates behind engineering structures, or bedload accumulation deduced from more or less accurate estimates of shoreline trends from remote sensing datasets. Among these, Lidar data and aerial photogrammetry data, obtained through drones or other airborne sources, also enable the establishment of digital elevation models of short-term shoreline change from which potential longshore transport rates over time may be deduced (eg., Brunier *et al*., 2016).

The ability to predict surf zone hydrodynamics has improved over the last decades, but at the same time the need for better and reliable resolution of the longshore sediment transport rate has increased, necessitated by the imperative of establishing reliable shoreline management plans in a world where development stakes in the coastal strip are constantly increasing. This necessity has spawned various sediment transport formulae concerning both the cross-shore distribution of the transport rate and the concentration distribution through the water column. Among these formulae, coastal dynamicists tend to have a preference for energetics-based models such as that of Bailard (1981). Several formulae, deemed to be more or less skilful, have been devised and used by coastal engineers (e.g., van Rijn, 1993). Pinto *et al.* (2006) showed that slight variations in the physical parameters commonly used in these sediment transport formulae, such as velocity, depth and grain size characteristics, can induce significant uncertainty in estimating longshore transport rates. Long-term rates of longshore bedload transport may be calculated using hindcast wave datasets such as those of ERA-Interim or WaveWatch III that are fed into models as long-term driving wave inputs (e.g., Almar *et al*., 2015). Cooper & Pilkey (2004) have severely criticized present approaches to longshore transport modelling.

8. The coastal sediment transport cell

Apart from bedload sequestering in sediment traps that form hollows along the shore (river mouths and inlets) and behind the shore (overwash into back-barrier lagoons), longshore sediment supply is reflected in shoreline morphological change as the sediment balance of the shoreface profile adjusts. The shoreface retreats (erosion) under conditions of a negative longshore sediment input relative to output, and advances (accretion) when the input exceeds the output. Longshore transport operates within the framework of one or several sediment cells with natural or artificial boundaries (Carter, 1988). Each cell contains an erosional (sediment source) and a depositional (sediment sink) segment. The sediment cell notion is particularly pertinent to coastal management issues (e.g., Bray *et al*., 1995; van Rijn, 2011), but it is also an important concept to be kept in mind as far as long-term shoreline accretion or erosion are concerned because of the relevance of cell boundaries to sediment flux continuity alongshore. Note that the same concept applies to sediment transport across the entire shoreface, which sometimes involves a strong longshore component. The distinction between swash and drift-alignment, which designates, respectively, shores associated with weak and strong longshore drift (Davies, 1980), is also a useful basis for considering process variations and long-term shore development patterns.

The coastal cell concept is commonly used in a sediment budgetary framework and to delineate eroding, stable and accreting sectors (Fig. 11), with or without consideration of the processes. The emphasis is

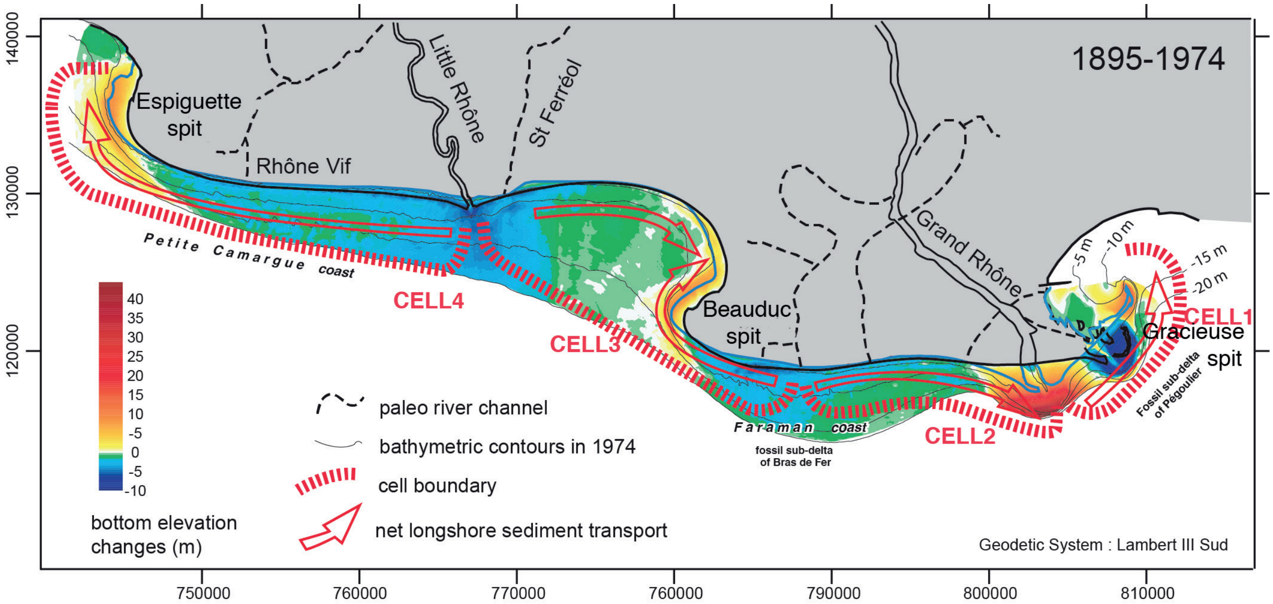

Fig. 11 - Sediment cells and sediment budget of the Rhône delta shoreface over 80 years (1895-1974) based on bathymetric chart differencing and analysis of shoreline trends. The four major cells are associated with three major spits: La Gracieuse (western, downdrift end of cell 4), Beaduc (western, downdrift end of cell 3) and Espiguette (eastern, downdrift end of cell 1). Beauduc and La Gracieuse spits terminate in drift convergence zones (embayments) where significant accretion prevails. The cells associated with these spits are sourced by eroding abandoned (Bras de Fer) and quasi-abandonded (Little Rhône) lobes, whereas Espiguette spit derives much of its sand supply from the important bedload reservoir and bar (Fig. 8) off the mouth of the Grand Rhône. Modified after Sabatier & Suanez (2003) and Sabatier & Anthony (2015).

thus, commonly, on identification of each coastal cell, its segments and net sediment gains and losses (e.g., Anfuso *et al.*, 2011). The cell approach is useful, but even where coastal cell definition may appear simple, the task of simply delineating the shoreline and constraining the processes operating both across shore and alongshore in such cells may turn out to be difficult (Gelfenbaum & Kaminsky, 2010). However, Mediterranean shores, with their limited tidal range and their highly indented rocky shores and embayments, are less prone to problems of cell delimitation compared to alluvial coasts subject to large tidal ranges. In such settings, potentially strong tidal currents, modulation of wave action by tides, and large variations in the shoreline controlled by tidal range, can lead to complex shoreface and shoreline sediment circulations, especially where large stocks of loose mobile sediments are available on shallow shorefaces and are constantly reworked by waves and currents, as in the English Channel and the southern North Sea (Sedrati & Anthony, 2014).

9. River-mouth sediment supply and shoreline barriers

Delta mouth bedload deposits (especially mouth bars) are the building blocks of most wave-exposed deltaic and adjacent barrier shorelines in the Mediterranean. Such deposits are generally subject to two modes of development under wave action: (1) they are built up by waves to form longshore barriers that provide shelter for contained fine-grained sedimentation in back-barrier plains and lagoons, and (2) serve as sources of, and longshore transport pathways for, sand and coarser-grained deposits that contribute to the development of adjacent beaches and barriers or spits (Anthony, 2015). Whatever the source of the bedload that accumulates in the delta lobe (fluvial, reworking of abandoned delta lobes), the seaward portion of these deposits may be built up by classical wave processes in the surf and swash zones that lead to the accretion of beaches, beach ridges and spits, sometimes complemented by aeolian processes (Anthony, 2009).
Distributary-mouth bar deposits probably evolve into more or less longshore-continuous nearshore barriers. The bars build up to subaerial shoreline forms under the influence of waves, and notably swash processes, to finally isolate back-barrier spaces and lagoons (Fig. 3). Shoreline progradation commonly occurs as successive beach ridges, as in the Ombrone and Arno deltas, and parts of the Rhône delta, sometimes decorated by small aeolian dunes. Deltaic beach-ridge plains are commonly organized into various sets that reflect abundant sand (and less commonly gravel) supply. Such sets also commonly exhibit truncations that

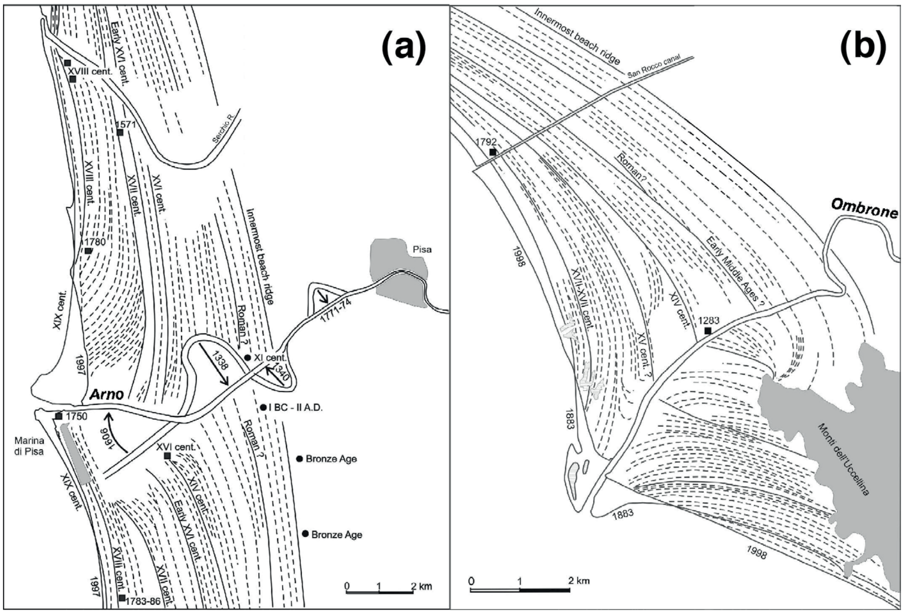

Fig. 12 - Beach-ridge sets and their truncations displayed by the Arno (a) and Ombrone (b) river deltas, two small, sand-rich deltas (from Pranzini, 2007).

reflect past delta shoreline reworking associated with a diminution, or rerouting of bedload in another deltaic channel, as in the Ombrone and Arno (Pranzini, 2001; Pranzini, 2007) deltas (Fig. 12), or lobe abandonment as in the Rhône (Vella *et al.*, 2005). Such patterns thus illustrate joint responses of incident wave angles and gradients, longshore currents and changing shoreline configurations, sediment loads, delta channel switches, and possibly deepwater wave directional changes. River deltas with abundant sand supply may, in fact, exhibit delta plains dominated by beach ridges, as in the afore-mentioned cases of the Arno and Ombrone (Fig. 12). Delta plains may, therefore, span a wide range of progradational types in terms of beach-ridge sets, from tightly packed sets, to episodic beach ridges. Cheniers, found in more mud-dominated settings, are not typical of Mediterranean shores. Variations in the abundance of beach ridges may also occur over time, as in the case of the Rhône (Vella *et al.*, 2005). Beach-ridge patterns have been used by Pranzini (2007) to reconstruct variations in processes of wave reworking and deposition during the growth of the Arno delta.

Spits, such as those of the Ebro (Fig. 13) and the Rhône (Fig. 11), are common features of Mediterranean deltas. They are diverse in morphology and genesis. Large spits reflect various shades of longer-term morphodynamic adjustments involving river influence, bedload supply, longshore transport, and shoreface bathymetry and gradient. Infilling lagoons behind perennial spits may commonly sequester alongshore drifting bedload supplied by washover events or through breaches across spits. Sabatier *et al.* (2009) have suggested a lag between Rhône delta lobe and spit development. Sediments are initially trapped in the lobe off the mouth, leading to a pronounced delta mouth protuberance, and are then reworked by waves to form spits when the mouth location shifts and the lobe is abandoned. This is in agreement with the modelling observations by Nienhuis *et al.* (2013), according to which well formed, spatially extensive recurved spits, which they considered as generally diagnostic of wave reworking of sediment promontories, are likely to be generated following abrupt lobe abandonment after a previous phase of strong progradation.

It is not clear why spits (Ebro), rather than strand-plains with more or less closely spaced beach ridges (Ombrone), (Fig. 13) form on the flanks of: (1) some delta distributary mouths or (2) abandoned lobes. In the case of still active distributary mouths, this is likely to be a sediment supply criterion, with successive mouth-flanking strand-plain deltas sourced by significant sand or gravel supply, and mouth-flanking infilling embayment systems bound by large spits associated with deltas with a lesser sediment supply. Flanking spits are also likely associated with: (1) entrenched single-mouthed (or with non-bifurcating mouths) delta systems subject to high but episodic liquid and solid discharges, rather than regular discharges over time, or (2) frequent lobe switches wherein bedload supply is not perennial. But a lobe switch is also associated with a new mouth that captures much of the discharge, resulting in a strong fluvial jet that pushes mouth-bar formation offshore, a condition favourable to flanking spits. The Ebro delta spits (Fig. 13) are probably a reflection of the former case, the development of this delta having been particularly accelerated

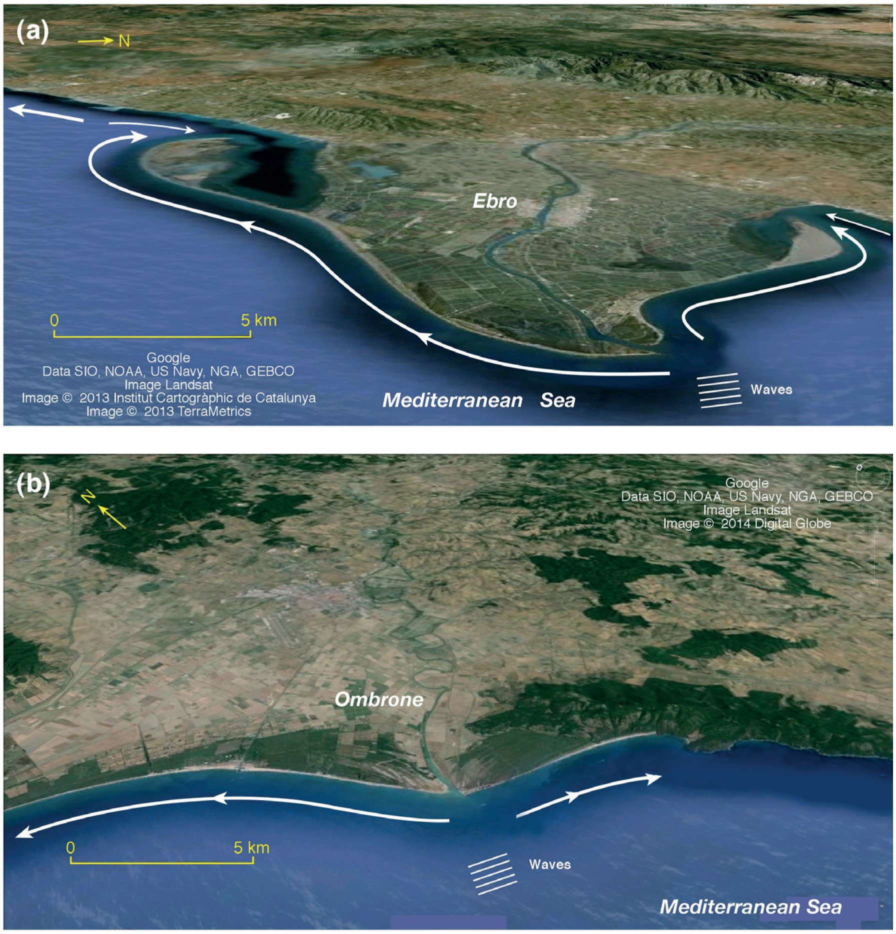

Fig. 13 - The Ebro and Ombrone river deltas. These morphometrically relatively symmetrical deltas are characterized by divergent drift from the mouth following a pattern of progradation wherein delta growth has occurred to face the dominant wave direction. The Ombrone exhibits successive beach ridges whereas the Ebro is characterized by two prominent spits that end in embayments characterized by counter-transport as a result of high wave angles, a process that contributes to sand sequestering within the confines of the delta. From Anthony (2015).

by major but pulsed sediment supply during the Little Ice Age (Guillén & Palanques, 1997), whereas the frequent avulsions and lobe switches of the Rhône delta, recently synthesized by Provansal *et al.* (2015), probably reflect the second case.

10. River sediment supply and coastal erosion

The question of the vulnerability of deltas and coasts resulting from various human activities, and in the face of sea-level rise associated with climate change, has been abundantly addressed in the literature (e.g., Ericson *et al.*, 2006; Syvitski *et al.*, 2009; Evans, 2012; Anthony, 2013; Anthony, 2016; Ibáñez *et al.*, 2014). Human activities affect river catchments down to the river mouths, thus impacting on the capacity of the latter to maintain morphosedimentary equilibrium and to supply sediment to adjacent coasts. Chief among these human interventions are flow regulation by dams and sediment entrapment by reservoirs, resulting in strong reductions in both river liquid and solid discharges (Syvitski *et al.*, 2005; Milliman & Farnsworth, 2011). The Mediterranean provides eloquent examples of the plethoric growth of dams, although environmental and other concerns have seen these tailing off since the 2000s (Fig. 14). Dams are, however, relatively recent in the history of rivers, unlike other human alterations of landscapes that have been ongoing since the advent and expansion of agriculture and catchment engineering (Provansal *et al.*, 2014). Many deltas in the Mediterranean have been formed or have grown considerably in the wake of human interventions that liberated large amounts of sediments in the catchments, such as those of the Ebro, Ombrone, Po, Rhône and Tiber (Anthony *et al.*, 2014; Besset *et al.*, 2017). By reducing river liquid discharge, sediment supply and the potential for river-mouth bar formation and accretion of the delta lobe, human activities favour the sinking of deltas (Syvitski *et al.*, 2009), invariably enhance the potential influence of waves in washover processes and in dispersing deltaic bedload and fine-grained sediment, but also in exacerbating coastal erosion. Many of the Mediterranean's deltas have been affected by reductions in liquid and solid discharge (Fig. 15).

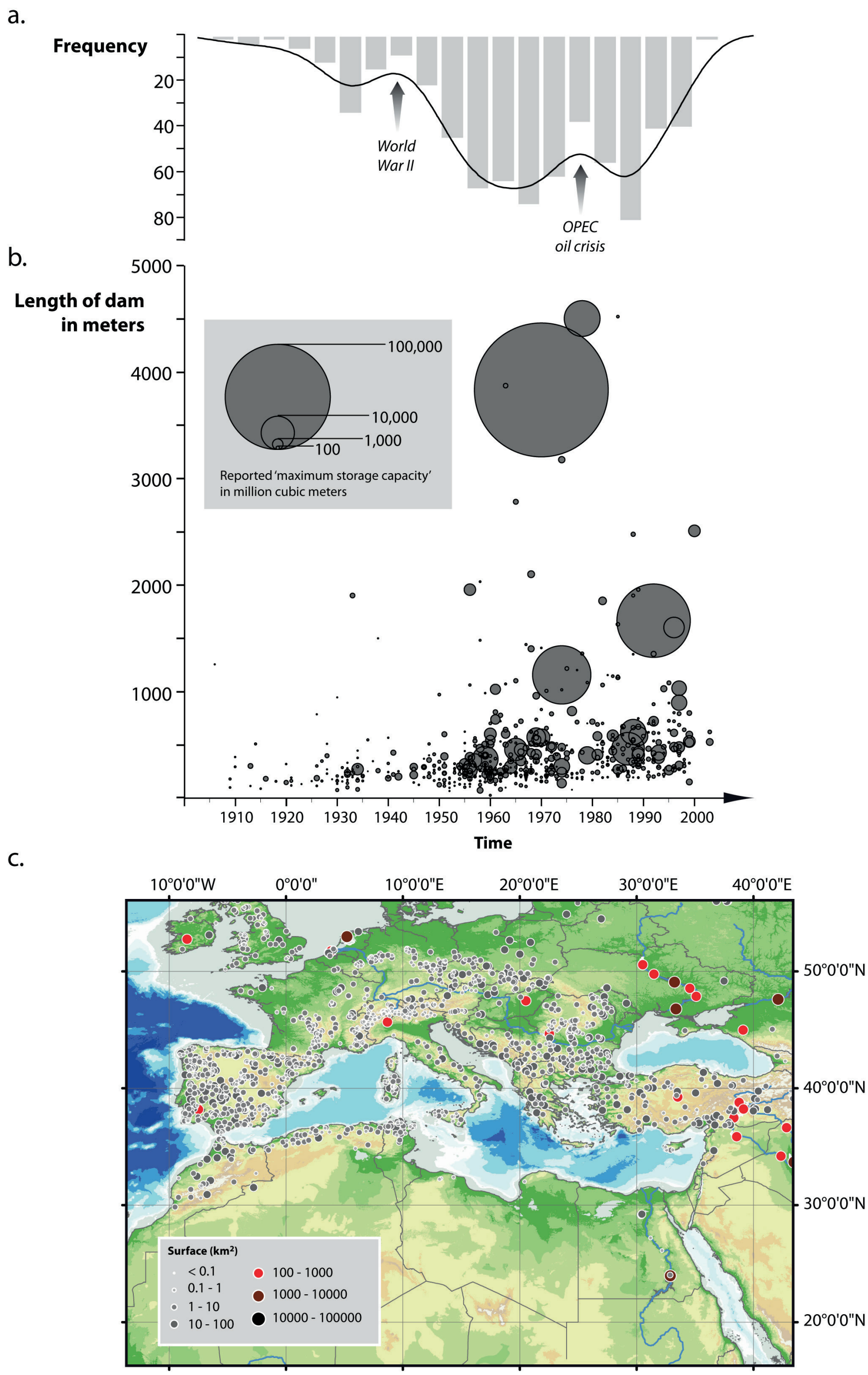

Fig. 14 - Mediterranean dams and reservoirs. (a) Upper plot is a histogram showing the construction date of dams in the Mediterranean and Europe (5-year bins) from 1900 to present. Solid line denotes the kernel density. (b) Bottom plot shows length and storage capacity of European and Mediterranean dams. (c) Surface area of reservoirs rimming the Mediterranean and Europe (in square kilometres). All data adapted from the Global Reservoir and Dam Database (Lehner *et al.*, 2011). From Anthony *et al.* (2014).

The reworking of abandoned delta lobes by waves is a common manifestation of delta erosion. In addition to lobe abandonment and reworking, Anthony (2015) identified two potential trajectories of delta morphological change associated with wave reworking following the weakening of river influence. Symmetric deltas facing the dominant waves may retreat while keeping their plan shape, although over time positive feedback effects may lead to a dominant transport direction. This type of situation is typical of the eroding Rosetta lobe of the Nile (Hereher, 2011) and the Ombrone (Pranzini, 2001). Variations in longshore sediment transport rate associated with the retreat of the Ombrone delta (Fig. 10) have been numerically modelled

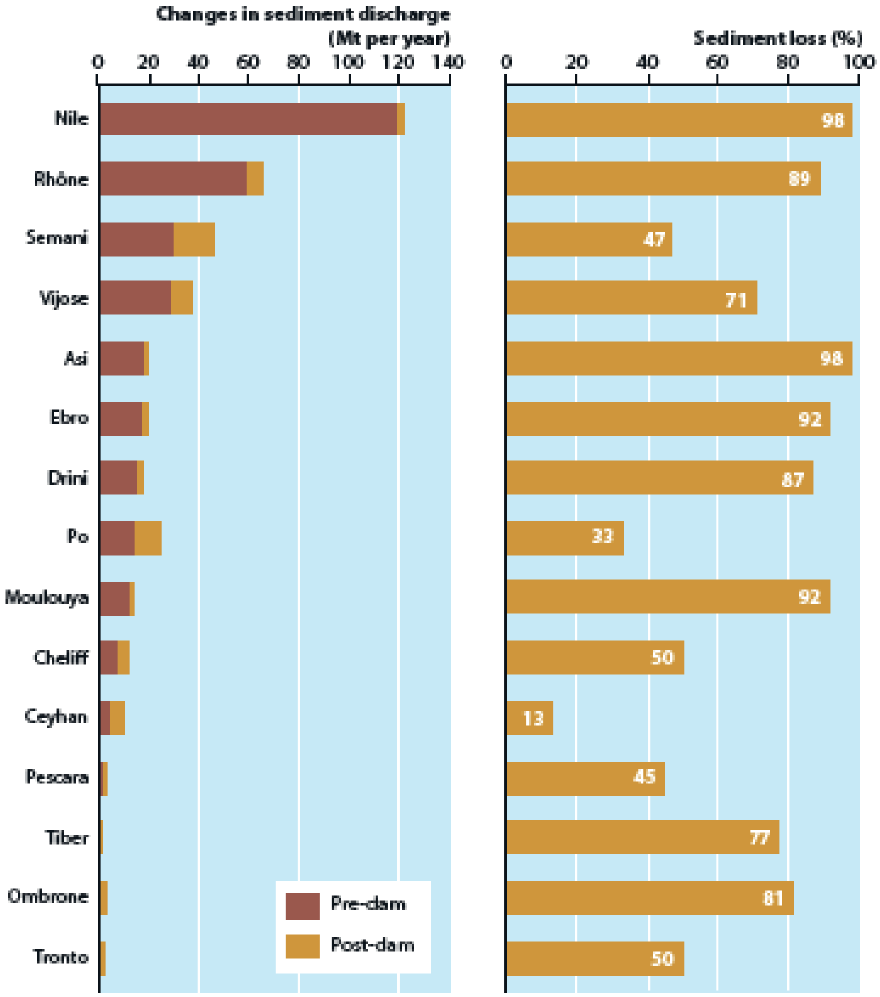

Fig. 15 - Pre- and post-dam changes in sediment discharge for selected Mediterranean deltas. From Marriner *et al.* (2015).

by Aminti & Pranzini (1990). They showed an almost symmetrical sediment distribution in 1883, with a drift divergence involving approximately 200000 $m^{3/yr}$ of sand moving in opposite directions on either side of the delta. Results for 1977 yielded 150000 m3/yr of sand moving northward of the river mouth and only 65000 $m^{3/yr}$ southward.

The other direction may be represented by the continuum shown in Fig. 9, from symmetric deltas to skewed or asymmetric and finally deflected or straightened deltas, as net river strength decreases over the long term whereas the wave climate is likely to become more energetic in response to climate change and greater storminess (Anthony, 2015). This situation is illustrated by the example of the Moulouya River delta in the semi-arid setting of western Morocco. Prior to dam construction, the sediment supply of the Moulouya River was significant enough to have generated the progradation of a small asymmetric delta of about 30 km2 skewed eastwards by longshore drift (Snoussi *et al.*, 2002). Since the construction of a major dam on the river, the fluvial sediment input has been reduced by 93%, leading to straightening of the shoreline and narrowing of the mouth (Snoussi *et al.*, 2002). This situation has resulted in the gradual destruction of the small Moulouya delta, with the reworked delta sediments evacuated eastwards by longshore drift.

A likely future outcome of excessive human modification of rivers in the Mediterranean is that many deltas will be eroded and some of the smaller ones may even revert to estuaries. This appears to be the case of the Magra River (catchment size: 1400 km2) in Italy (Pratellesi *et al.*, 2018). Like many rivers in the Mediterranean, the mouth of the Magra evolved over the last 2-3000 years into a delta from a primitive estuarine embayment. The river mouth and adjacent delta-front area have lost about 3 Mm3 of sediment over the last 100 years, especially due to channel dredging and aggregate extraction, and this trend is characterized by a transformation from a river-dominated delta into an

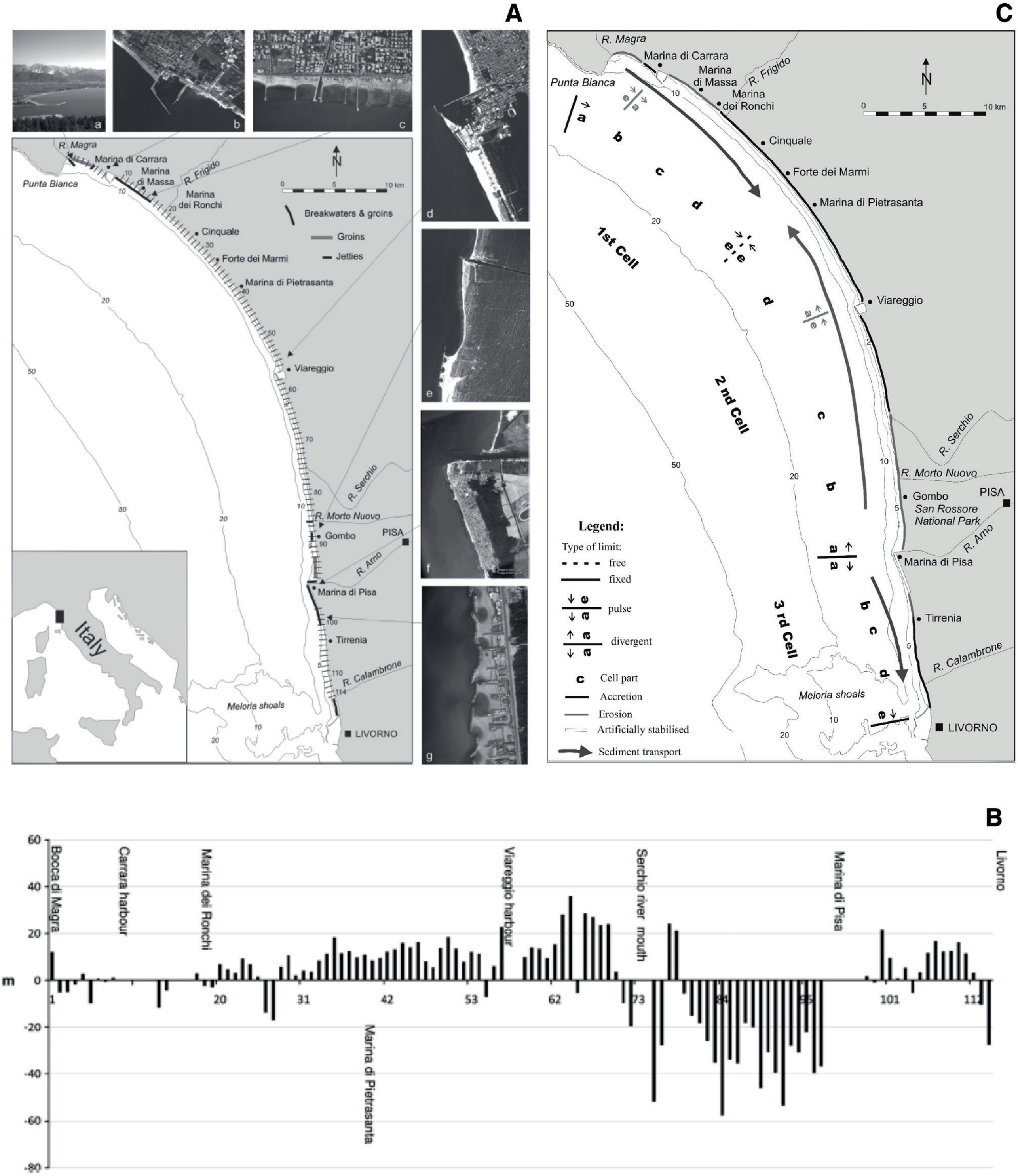

Fig. 16 - An example of large-scale shoreline modifications along a 64 km-long stretch of the Tuscany coast near Pisa, northern Italy. (A) Map and photographs depicting the profusion of shoreline engineering works (Magra river mouth (a), Marina di Carrara harbour (b), Marina di Massa (c), Viareggio harbour (d), Gombo and Morto Nuovo river mouths (e), Arno river mouth (f), and southern area of Marina di Pisa (g)). (B) Shoreline changes (erosion/accretion) from 1997 to 2005. (C) Net sediment transport directions (black arrows), and segments (accretion/erosion) and boundaries (natural/artificial, free/fixed/divergent/pulse; see Carter (1988) for definition of cell terminology) of major cells, with boundaries of secondary cells in grey. Compiled from Anfuso *et al.* (2011).

increasingly wave-dominated and sediment-depleted river mouth. The mouth of the Magra is increasingly exhibiting a morphology typical of an estuary. This example, wherein massive modern sediment withdrawal has led to river-mouth geomorphic reversal to a more primitive estuarine state that initially characterized the Magra delta, probably illustrates the potential fate of increasingly sediment-depleted deltas in the Mediterranean and elsewhere (Pratellesi *et al.*, 2018).

11. Perturbations of longshore transport and coastal erosion

Human engineering on the shores of the Mediterranean dates back to several millennia and especially concerned ancient harbours (Marriner & Morhange, 2007). Massive engineering interventions with far-reaching consequences on coastal sediment transport and coastal stability are, however, products of coastal urbanisation and economic development over the last century (Anthony, 2014). The expansion of coastal urban fronts, leisure ports and tourism in the course of the 20th century has been the main driver of large-scale modification of the coast in the Mediterranean, the world's most important tourism basin. Large-scale planned and unplanned development involving joint state and private capital ventures has, in many cases, exacerbated coastal instability, while endangering coastal ecosystems. The growth of urban fronts has commonly led to a drastic reduction in beach width and to dune degradation. The construction of marinas, leisure harbours and artificial beaches has resulted in the emergence of veritable artificial shorelines. These shores generally blend entirely with urban fronts. Urban tourism in the Mediterranean over the last four decades has been marked by a significant development of artificial beaches, especially in the dominantly rocky sectors of the Mediterranean coast of France (Anthony, 1994) and Spain (Ojeda & Guillèn, 2008), and in Italy (Bertoni & Sarti, 2011).

Some of the causes of, and the responses to, shoreline destabilization have been essentially a matter of 'hard' engineering, for both historical and cultural reasons. The construction of groynes, breakwaters and seawalls in response to development pressures, and notably to cater for tourism, has perturbed the longshore transport of sediment from river mouths and cliffs, leading to local-to-regional sediment budget deficits and erosion on shores downdrift of such structures (and surpluses and accretion on updrift coasts). Commonly, this has involved a vicious cycle of further construction of beach protection structures, in addition to generally costly beach nourishment schemes. A fine example of such effects is that of the 64 km-long Tuscany coast between Livorno and Punta Bianca (Fig. 16) where beach erosion threatens tourism, a primary activity on this stretch of coast (Anfuso *et al.*, 2011; Bertoni *et al.*, 2016). Here, as on many other beaches in the Medietrranean, seawalls, groynes, rip-rap revetments, detached breakwaters, and submerged structures have been constructed over the last century in order to fix sediments within a framework of declining bedload supply from rivers. Anfuso *et al.* (2011) identified the cell patterns and boundaries generated by these structures in addition to natural cell boundaries, and the future engineering works and nourishment that are planned to maintain the beaches. Bertoni *et al.* (2012, 2016) documented an impressive volume loss of pebbles in an artificial beach in Marina di Pisa in a short timespan due to sediment abrasion which might exceed 50% of the original fill volume just after one year in the most dynamic portion of the beach.

12. Concluding remarks: River sediment supply, shoreline management, and future environmental change

Shorelines retreat where sediment supply is insufficient to fill the accommodation space created by sea-level rise. There have been numerous case studies of coastal erosion purportedly attributed in part or in whole to climate change, and a useful synthesis of the potential impact of climate change on coastal sediment budgets has been discussed by Ranasinghe & Stive (2009) from a process point of view for low coasts composed of clastic sediments. These authors examined, in particular, the potential for longshore and cross-shore redistributions of coastal sediment that will differentially impact shores in the future. From a coastal management point of view, the vulnerability of the Mediterranean's coasts has been highlighted, among others, by recent compendia such as those of Cooper & Pilkey (2012), and Pranzini & Williams (2013). The rise in sea level will become an important future constraint on the survival of the densely developed beach and barrier shorelines and deltas of the Mediterranean.

It is now clear that the dwindling of fluvial sediment supplies related to river catchment modifications, and the emphasis on coastal stabilization, at whatever cost, that has underpinned coastal management practice in the Mediterranean need to be thoroughly reconsidered. Stabilization will become costlier in the future, as pressures from coastal development increase, as sea level rises and as sediment stocks continue to diminish. The situation calls for change, with openings coming from larger environmental awareness, the need for a 'source-to-sink' approach in fluvial sediment supply to the coast (Anthony & Julian, 1999), recognition of the failure or poor performance of many coastal stabilization projects, and the diversification of the actors involved in coastal management and planning (Anthony, 2014). These developments are progressively generating a new logic of wider concert, on the basis of a more prospective, upfront and long-term approach to coastal management, instead of the logic of a 'stabilization-only' and a commonly one-shot immediate response to storm erosion problems that had tended to prevail in the past.

This will require both goodwill and enhanced investment in research and in innovative research approaches to coastal management. Regarding this last point, a joint research team (COSTE Team) involving the Universities of Pisa, Siena and Florence is pointing the way forward by proposing a multidisciplinary data acquisition and visualization platform integrating heterogeneous data acquired from remote sensing systems and in-situ sensing systems (Bartolini *et al*., 2018; Pozzebon *et al.*, 2018). The data are stored, integrated and fused in a single platform that also enables data visualization and analysis on the basis of the paradigm of *Augmented Virtuality*. This concept forecasts the evolution of a virtually reconstructed environment using data collected in the real world, and represents a novel holistic approach that brings together various disciplines with different data acquisition techniques but with the common objective of a broad definition of coastal dynamics aimed at better tackling coastal erosion.

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