IMPACTED FLUVIAL AND COASTAL SEDIMENT CONNECTIVITY IN THE MEDITERRANEAN: A BRIEF REVIEW AND IMPLICATIONS IN THE CONTEXT OF GLOBAL ENVIRONMENTAL CHANGE

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Abstract – Sediment connectivity refers to the continuity of the flux of sediment along transport pathways that may be fluvial as well as coastal. Clastic coasts built essentially from sediments supplied by rivers are abundant in the Mediterranean. This supply has been modulated by river catchment characteristics and human influence. Many pocket beaches in small bays in the Mediterranean directly trap bedload supplied by small streams or eroded from nearby bounding headlands, whereas fluvial bedload supply to more or less long open shores has been conditioned by longshore current redistribution from river-mouth bar deposits, many associated with deltas that have built up from fine-grained and organic sedimentation behind coarse-grained barriers. Sediment has also been derived from nearby abandoned delta lobes, older relict or actively formed nearshore carbonate deposits, and from shoreline reworking, but connectivity between shore and lower shoreface has always been limited in the Mediterranean because of the steep continental shelf. Significant sediment deficits along many of the Mediterranean's coasts have resulted from anthropogenic fragmentation of rivers that has generated loss of sediment connectivity. The most important human interventions are flow regulation by dams, sediment trapping by reservoirs, fluvial channel engineering and bank engineering, and sand and gravel extractions. These activities were largely preceded in many river catchments by multi-millennial climate and land-use changes. Because of the strong wave influence and low tidal ranges, longshore sediment transport from river mouths operates within the framework of one or several sediment cells. Many such cells are now characterized by artificial boundaries that block bedload transport and impair alongshore sediment connectivity. These include harbours and terminal groynes, products of coastal urbanization and economic development, especially over the last two centuries. Climate change and sea-level rise spell further increasing vulnerability of the Mediterranean's fragmented rivers and coasts and call for the urgent need to foster efforts aimed at re-establishing sediment connectivity.

Introduction

Sediment connectivity refers to the continuity of the flux of sediment along transport pathways, a concept pertinent to river water and sediment cascades down to the sea, but also to coasts, given the overarching importance of fluvial sediment supply to the formation of coastal deposits such as deltas, beaches and dunes. The concept of connectivity is increasingly permeating all spheres of environmental science as the impacts of breakdowns in nexuses among spheres are felt as a result of human activities and their effects on climate.

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This situation is especially pertinent in the Mediterranean coastal zone, largely bordered by steep mountain slopes, and where population and development pressures (Figure 1), notably associated with the exponential growth of tourism over the last 80 years, are among the highest on Earth, bringing enormous pressure to bear on the 46 % of clastic shorelines that make up the 46 000 km of the Mediterranean coast (Anthony et al., 2014). The Mediterranean captures up to 30 % of the world's tourists and although the developed areas are dominantly coastal, a long history of human occupation and exploitation of river resources in a zone of climatic stress has also meant that pressures have been high on the fluvial systems debouching into the Mediterranean (UNEP/MAP/Plan Bleu, 2020). The impacts of anthropogenic pressures and the need for an integrated management approach have drawn attention, as illustrated by UNEP/MAP/Plan Bleu (2020) and by thousands of scientific publications, reports and symposia dedicated to marine and coastal pollution, ecological fragmentation, and stress on biodiversity. These impacts have had, in turn, dramatic effects on economic activities and livelihoods around the Mediterranean. Although there has been awareness of the problems generated by the harnessing of river resources, the problem of sediment flow has received less attention than that of impacts related to pollution, fish resources, and biodiversity. Figure 2 shows an example of sediment connectivity from the fluvial through delta-plain transition onto the river mouth and adjacent coast in the Mediterranean. Invariably, any breakdown in sediment connectivity through the fluvial corridor, and alongshore, has serious repercussions on the stability of coastal deposits. The Mediterranean is iconic of this fundamental nexus, but also shows perhaps the best examples, at the world-scale, of how this nexus has been severely impaired over various timescales by human activities. Anthropogenic pressures through the ages and up to the current Anthropocene epoch have shaped the present status of Mediterranean coasts, especially through impacts on fluvial-to-coast sediment connectivity, generating further knock-on effects on perturbed shorelines through engineering efforts to maintain stability. This impaired connectivity is briefly reviewed in this paper.

Mediterranean rivers and coasts: the nexus

More than 160 rivers with a catchment size >200 km^2 discharge into the Mediterranean Sea, but only six have catchments larger than 50 000 km^2, thus highlighting the importance of small rivers. Mediterranean rivers have high sediment yields, comparable to those of catchments in tectonically active areas (Milliman and Farnsworth, 2011), but discharge can be variable, with impacts on sediment supply to the coast (e.g., Bini et al., 2021). River sediment supply is particularly important in the Mediterranean basin where shorelines, infilling lagoons and delta plains are mainly sourced by rivers. Although fluvially-supplied sediment has been the main source of sediment for the Mediterranean's coasts, the shoreface can be productive regarding carbonate sand and shells (Anthony and Aagaard, 2020). The Mediterranean seaboard faces a Heterozoan carbonate factory, a type that is generally quite productive and beaten by waves (Laugié et al., 2019), and that is also commonly associated with organic plant production, notably through seagrass meadows offshore, especially *Posidonia oceanica*. The importance of carbonate sediment for Mediterranean coasts, is, however, not known, and the overarching prevalence of terrigenous sediment, dominated by quartz, for the sand and gravel fractions, with subsidiary contributions from black, volcanic sands in certain areas (Corsica, Sicily), needs to be emphasized. Since the coastal hydrodynamic context is largely conditioned by waves in a low tide-range context, the alongshore supply of fluvial bedload by wave-generated longshore transport 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. Shoreline development in these cases has generally been sourced by rivers with discharge strong enough to flush bedload to the nearshore zone, where this sediment forms a reservoir for wave-induced alongshore supply to adjacent shorelines. Suspension loads and organic sedimentation are typical of the delta plains and lagoons. High river discharge can lead to significant offshore transport of fine-grained sediments.

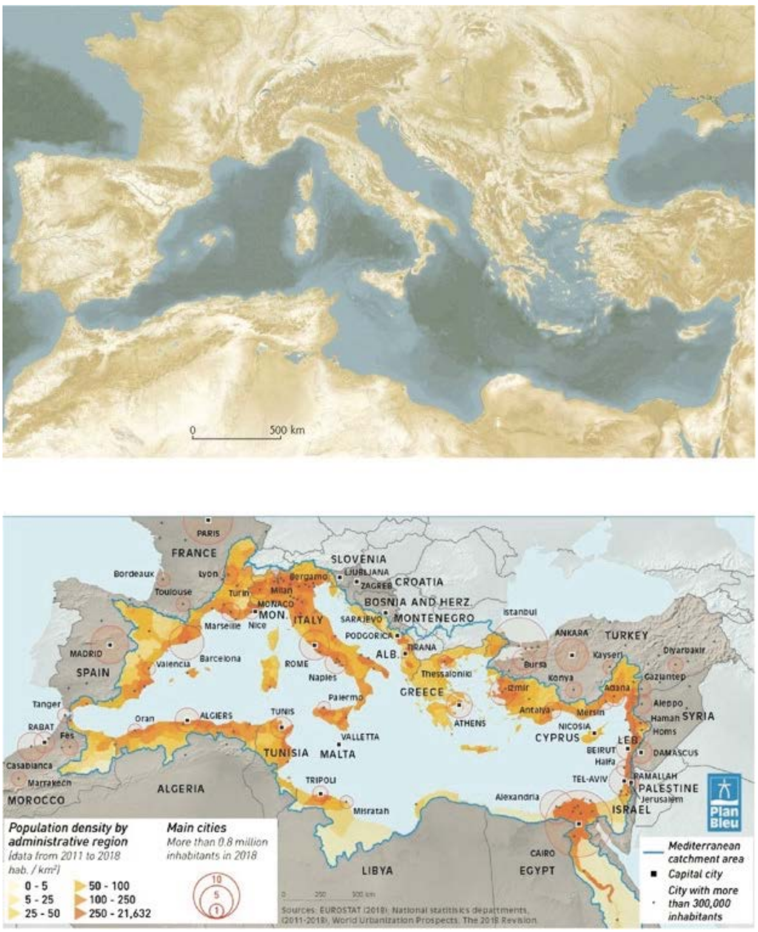

Figure 1 – Relief map of the Mediterranean (top), and population density (bottom, from UNEP/MAP/Plan Bleu, 2020).

River-mouth bar deposits are fundamental to the connectivity between fluvial bedload supply and longshore transport (Figure 2). They are the building blocks of most wave-exposed deltaic and adjacent barrier shorelines in the Mediterranean, as elsewhere (Anthony, 2015). The critical river-mouth area from where bedload is transported to feed the longshore transport system is also a complex hydrodynamic environment because of the diversity and space- and time-varying intensity of fluvial water discharge, tides, and wind and wave activity. Fluvial supply of bedload to the coast is particularly important in the course of strong river flood events. The river-mouth bar can, thus, be reworked by high river discharge and storms, but can also temporarily disappear when river outflow does not balance wave action, leading to smoothing of the shoreline and redistribution of bar sediments alongshore by wave-induced longshore transport. Where fluvial bedload supply is high relative to wave reworking, rapid river-mouth silting can ensue. Prolonged sediment accumulation of this type without correlative redistribution can lead to delta channel abandonment over timescales as short as secular, as Provansal et al. (2015) have shown for the Rhône in France. Sediment accumulation can also lead to navigation problems and recourse to dredging where yachting and fishing harbours are housed in river mouths, a common situation in the Mediterranean.

The mouth-bar deposits generally exhibit two morpho-sedimentary functions: (1) they mainly 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); (2) they can also be built up directly by waves to form longshore barriers that provide shelter for fine-grained and organic sedimentation in delta plains, back-barrier plains and lagoons. 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 multitude of more or less deeply embayed shores of all lengths (< 10 m to >100 km) locked between the numerous bedrock headlands (Anthony et al., 2014). The smaller bays commonly have limited space for sediments to accumulate and are sediment supply-limited, with little or no progradation, but some are sourced by episodic inputs from ephemeral streams. Other bays developed as rias since sea level stabilized in the mid-Holocene (Vacchi et al., 2020). High fluvial bedload supplies and locally impeded longshore transport between 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. Short coarse-grained streams debouching from steep mountainous hinterlands are common, as in parts of Italy and the French Riviera. Along the steep Alpine margins, the shelf is dissected in many areas by deep fossil canyons inherited from the Messinian Salinity Crisis and some of which practically impinge on the coast, as in Nice, where the beach can lose artificially recharged gravel as a result of downslope transport in the small canyons during storms (Anthony et al., 2011).

The coastal sediment cell concept is commonly used in a sediment budget framework and to delineate eroding, stable and accreting sectors alongshore (Figure 2). The emphasis is, thus, on identification of each coastal cell, its segments and net sediment gains and losses (e.g., Pranzini et al., 2020; Bertoni et al., 2021). 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. In the Mediterranean, the numerous pocket beaches are likely to be swash-aligned.

Figure 2 – River-to-coast sediment connectivity in the lower Rhône river and delta in France. Top image shows engineered sediment flux diversion to the advantage of the main Rhône distributary. Arrows show sediment (essentially fine-grained) spill-over onto the deltaic plain, and divergent (erosional sectors) and convergent (depositional sectors) bedload-transport sediment cells along the coast, including reworking of an abandoned delta lobe (from Sabatier and Anthony, 2015). Red box represents area of the river-mouth bar with bathymetry shown in bottom image. Photo insert on the left shows the small sandy river-mouth bar on the Argens delta, about 120 southeast of the Rhône delta.

Mediterranean river fragmentation and loss of connectivity

Mediterranean rivers show relatively high levels of fragmentation and loss of connectivity as a result of dams and river channel regulation (Grill et al., 2019). These rivers provide eloquent examples of the reductions in sediment supply caused by the plethoric construction of dams and reservoirs (Figure 3), although environmental and other concerns saw dam construction tailing off in the 1990s, only to regain favour since the mid-2000s in the drive for 'clean' energy (Flaminio et al., 2021).

The importance of river management practices in the Mediterranean is an outgrowth of the climatic conditions which can be characterized by very dry and hot summers and variably humid winters, a clear imbalance in water availability, particularly, for agricultural needs. However, the climate is also characterized by short high-river discharge spates that can be threatening to life and damaging to the environment, as shown by the dramatic effects of Storm Alex in the Maritime Alps of France and Liguria, Italy, in October 2020. The steep hinterlands bounding parts of the Mediterranean coast and its islands are commonly a source of massive sediment release, associated with deforestation in the past, and hence the recourse to erosion check dams in many areas that have further contributed to loss of sediment connectivity, with impacts on the coast (e.g., Anthony and Julian, 1999; Bombino et al., 2022). Dams are, however, relatively recent in the history of rivers. 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 (Anthony et al., 2014). The deleterious effects of river modification on Mediterranean coasts are directly linked to the diminution of sediment supply resulting from flow regulation through attenuation of the peak bedload-mobilizing flows caused by dams, but also to sediment trapping and the effects of channel and bank engineering. The regulation effect can dominate over trapping by reservoirs (e.g., Martin-Vide et al., 2020). Flaminio et al. (2021) have suggested a need for a stronger dialogue between the scientific and public domains on the impacts of dams, indicating that such knowledge transfer and exchange would be particularly beneficial regarding perceptions of 'renewable energy' and 'green energy,' and in a consideration of alternative modes of governance regarding dams.

Coastal erosion and delta subsidence

Massive engineering interventions with far-reaching consequences on coastal sediment transport and coastal stability are products of both deficits in fluvial sediment supply and rampant coastal urbanization and economic development over the last two centuries (Anthony, 2014). The expansion of coastal urban fronts, leisure ports and tourism in the course of the 20th century has, in this parallel context of sediment deficit, been the main driver of large-scale modification of the coast in various parts of the Mediterranean (e.g., Molina et al., 2018; Pranzini et al., 2018; Capucci et al., 2021; Kasmi et al., 2020; Hzami et al., 2021). Large-scale planned and unplanned development involving joint state and private capital ventures has, in many cases, exacerbated coastal instability, by leading to breakdown in alongshore sediment connectivity, while endangering coastal ecosystems. The growth of urban fronts has commonly led to drastic reductions in beach widths and to dune degradation. The construction of marinas, leisure harbours and artificial beaches has resulted in the emergence of veritable artificial shorelines that are sometimes built at the expense of the natural beaches, degraded by sediment deficits. These artificial shores generally blend with urban fronts.

Several deltas and distant coasts dependent on the rivers have become more or less severely eroded as a result of negative sediment budgets (Besset et al., 2017). By reducing river liquid discharge and sediment supply, human activities upstream have favoured accelerated subsidence of deltas (Figure 4), whereas extractive activities can exacerbate this problem in the delta environment itself (Anthony et al., 2021), invariably enhancing the potential influence of waves in washover processes and in dispersing deltaic bedload and fine-grained sediment, but also in exacerbating coastal erosion.

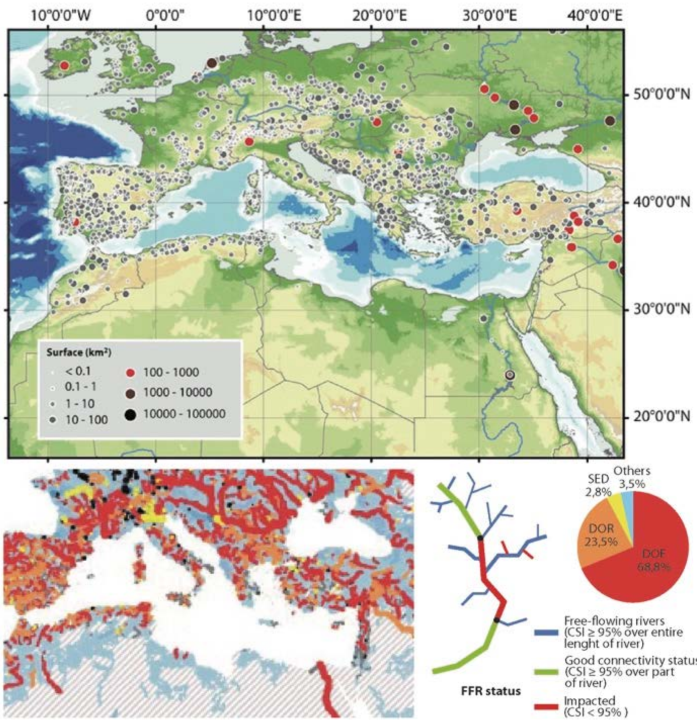

Figure 3 – Mediterranean dams and reservoirs, and river fragmentation and loss of connectivity. (a) Upper plot shows surface area of reservoirs rimming the Mediterranean and Europe (in square kilometres - adapted from the Global Reservoir and Dam Database (Lehner et al., 2011). Lower figures, all adapted from Grill et al. (2019), show highly impacted connectivity (CSI – connectivity status index <95 % and loss of free-flowing status (FFR)) in Mediterranean rivers (red). The degree of fragmentation (DOF), degree of regulation (DOR), and sediment trapping (SED) represent mean global values that are probably less than those in Mediterranean catchments.

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 (e.g., Pranzini et al., 2018). The construction of groynes, breakwaters and sea walls in response to development pressures, and notably to cater for tourism, has perturbed the longshore transport of already dwindling sediment supply 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 engineering structures, in addition to generally costly beach nourishment schemes. On many other beaches in the Mediterranean, 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, thus further fragmenting longshore transport cells, creating artificial cell boundaries, and exacerbating the loss of alongshore sediment connectivity.

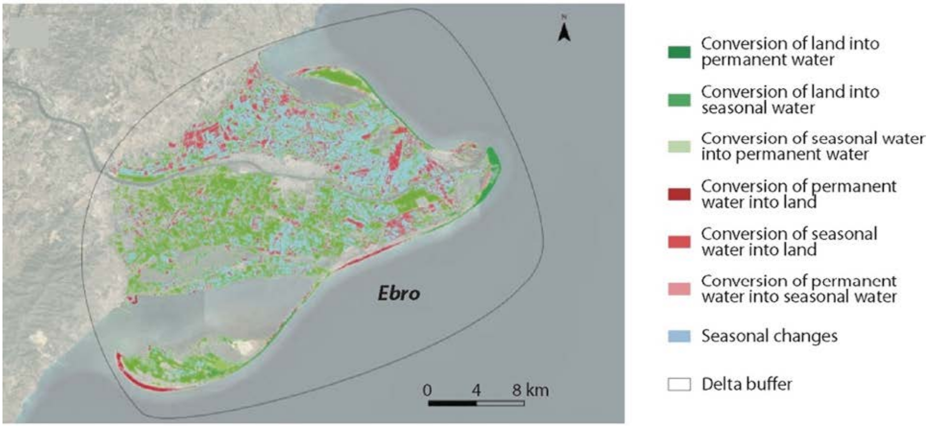

Figure 4 – Map of land→water and water→land conversions (1984-2019) for the Ebro delta culled by Anthony et al. (2021) from the Global Surface Water (GSW) database of Peket et al. (2016). The net preponderance of conversion of areas of land to water suggests prevalence of exacerbated subsidence as mapped by Rodriguez-Lloveras et al. (2020), highlighting a delta particularly vulnerable to sea-level rise.

Concluding remarks: challenges ahead

From a coastal management point of view, the vulnerability of the Mediterranean's coasts has been highlighted in thousands of publications over the last two decades. Sea-level rise will become an important future constraint on 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 and channel modifications, and the emphasis on coastal stabilization, at whatever cost, that has been the cornerstone of 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 fluvial sediment stocks continue to diminish, with further uncertainties regarding the impacts of climate change on river discharge variability. The situation calls for change, with openings coming from larger environmental awareness, the need for a connectivity approach in fluvial sediment supply to the coast, involving a balanced approach regarding the advantages and deleterious effects of river dams, recognition of the failure or poor performance of many coastal stabilization projects, and the diversification of the actors involved in coastal management and planning. These developments must necessarily debouch on a more prospective, upfront and long-term approach to coastal management.

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