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Understanding morphological evolution and sediment dynamics at multi-time scales helps balance human activities and protect coastal ecosystems: An example with the Gironde and Pertuis Marine Park

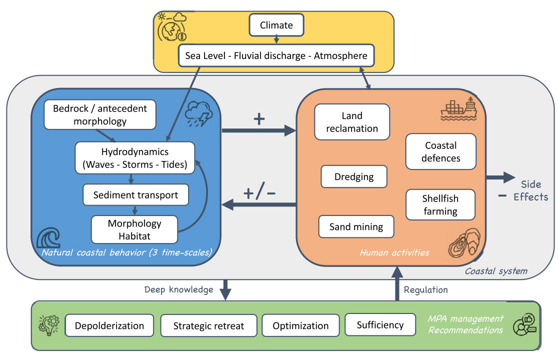
A. Schmitt *, E. Chaumillon

UMR 7266 LIENSs CNRS La Rochelle University, France

HIGHLIGHTS

- Complex interactions occur between sedimentary coastal ecosystems and human activities.
- Deep knowledge of sediment dynamic is needed to manage human activities and sedimentary coastal ecosystems preservation.
- Our main recommendation is to reduce instabilities (positive feed-back) and negative side effects.
- Ecosystem-based solutions are strongly recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

Finding a balance between the preservation of habitat, species and the sustainable development of human activities in Marine Protected Areas (MPAs) is made even more challenging in coastal areas where sediment dynamics entails naturally changing habitats. To achieve this goal, a solid knowledge base is needed, and reviews are essential. Starting from an extensive review of sediment dynamics and coastal evolution at three-time scales (from millenaries to events), in the Gironde and Pertuis Marine Park (GPMP, French Atlantic coast), we investigated the interactions between human activities, sediment dynamics and morphological evolution in the GPMP. Five activities were identified as having a maximum interaction with coastal dynamics: Land reclamation, shellfish farming, coastal defences, dredging and sand mining. In sheltered areas, where natural sediment fill occurs, land reclamation and shellfish farming increase sedimentation through a positive feedback mechanism, leading to instability. Natural coastal erosion and sediment fill in harbours and tidal channels are fought by coastal defences and dredging, respectively, creating negative feedback and stability. However, these activities also generate negative side effects such as upper beach erosion, pollution, and increased turbidity. Sand mining, mainly developed in submarine incised valleys, results in a deepening of the sea floor, which is naturally filled by sediments from surrounding areas, tending towards shoreface profile restoration. However, sand extraction exceeds natural renewal rates, and may impact the stability of coastal ecosystems in the long term. These activities are at the heart of environmental management and preservation issues. This review and a discussion of the interactions between human activities and coastal behaviour enabled us to make recommendations that could counteract instabilities and negative side effects. They mainly include depolderization, strategic retreat, optimization and sufficiency. Given the diversity of the coastal environments and human activities found in the GPMP, this work is transferable to many MPAs and coastal areas whose objective is to foster sustainable human activities compatible with habitat preservation.

* Corresponding author.
E-mail address: anais.schmitt@univ-lr.fr (A. Schmitt).

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Contents

1. Introduction

Today's erosion in biodiversity is mainly related to habitat loss (Ceballos et al., 2015) and there is indeed a need for protecting coastal marine habitats that support some of the most productive and valuable ecosystems of the world (Costanza et al., 1997; Pörtner et al., 2019). In this context, Marine Protected Areas (MPAs) have been created worldwide and their number is increasing exponentially (Edgar et al., 2007; Mazaris et al., 2019). The OSPAR Commission (1998) designated an MPA as "an area situated in the maritime area for which protection, conservation, restoration or precautionary measures, in accordance with international law, have been instituted for the purpose of protecting and conserving species, habitats, ecosystems or ecological processes of the marine environment". These areas are increasingly being promoted as an ocean-based tool for climate change mitigation and adaptation (Jacquemont et al., 2022). MPAs are generally designated and created on the individual initiative of states; they comprise several legal categories with varying scope and effectiveness under both international and domestic laws. Under French Law, there are 9 legal categories of MPAs in metropolitan France that are designated on the basis of their type of management (Article L 334–1 of the French environmental code). The legal category of Marine Natural Parks was created in 2006. The aim of this category is: (1) to preserve the marine environment; (2) improve knowledge; and (3) contribute to the sustainable development of maritime activities (Article L 334–3 of the French environmental code). Thus, a Marine Natural Park is multi-use and includes commercial areas such as fishing, mining and drilling, managed so as to achieve specific sustainable use and conservation objectives (Art. 1, CBD, 1992). Today there are eight Marine Natural Parks in France.

This review focuses on the Marine Natural Park named "*Parc Naturel Marin de l'Estuaire de la Gironde et de la Mer des Pertuis*" (Fig. 1; ID: 555589788 in the World Database on Protected Areas), referred to here as the "Gironde and Pertuis Marine Park" (GPMP) (Lafon, 2017). It is the largest park in metropolitan France, considering temperate estuarine settings, and it includes a wide diversity of coastal habitats and human activities. As such, it constitutes a reference site for the management of coastal environment protection and human activities. Coastal marine sedimentary habitat stability depends on the balance between sediment input and output. Due to the estuarine context of the GPMP, sediment diversity (Poirier et al., 2010) and shoreline changes are very important (Castelle et al., 2018). Together with variations in salinity and water depth, sediment dynamics set strong constraints on coastal ecosystems. Sedimentation directly impacts nearshore ecosystems where increasing sediment loads lead to the burial of benthic communities and increasing water turbidity, reducing light penetration and leading to numerous associated negative effects (Thrush et al., 2004). Increasing sedimentation is also a major problem for many coastal ecosystems like rocky reefs (Airoldi, 2003), sea-grass systems (Orth et al., 2006) and soft sediment communities (Thrush et al., 2004). Erosion mainly impacts coastal ecosystems developing along sandy barriers (Martínez and Psuty, 2008; Castelle et al., 2019; Gao et al., 2020). Sediment dynamics is under the control of both natural processes and increasing human activities. Moreover, estuarine environments are highly vulnerable to climate change (Yang et al., 2015). Indeed, sea level rise could lead to an increase in salinity levels and cause tidal amplification, stronger tidal currents and enhanced suspended sediment concentration levels (Van Maanen and Sottolichio, 2018). Another serious impact related to climate change is the increase or decrease in fluvial freshwater input (Boé et al., 2009; Le Treut, 2013).

Thus, a general key question for MPA management is "How do we reconcile environmental protection and the development of human activities in a context of climate change and biodiversity erosion?". This question becomes critical in coastal areas dominated by sedimentary coasts that are strongly impacted by human activities and likely to be significantly transformed by sea level rise and climate change. In the context of a highly dynamic coastal zone, the first step that needs to be taken in order to answer this general question is to produce a synthetic and shared report, accessible to all the stakeholders involved. Thus, the aim of this review is to

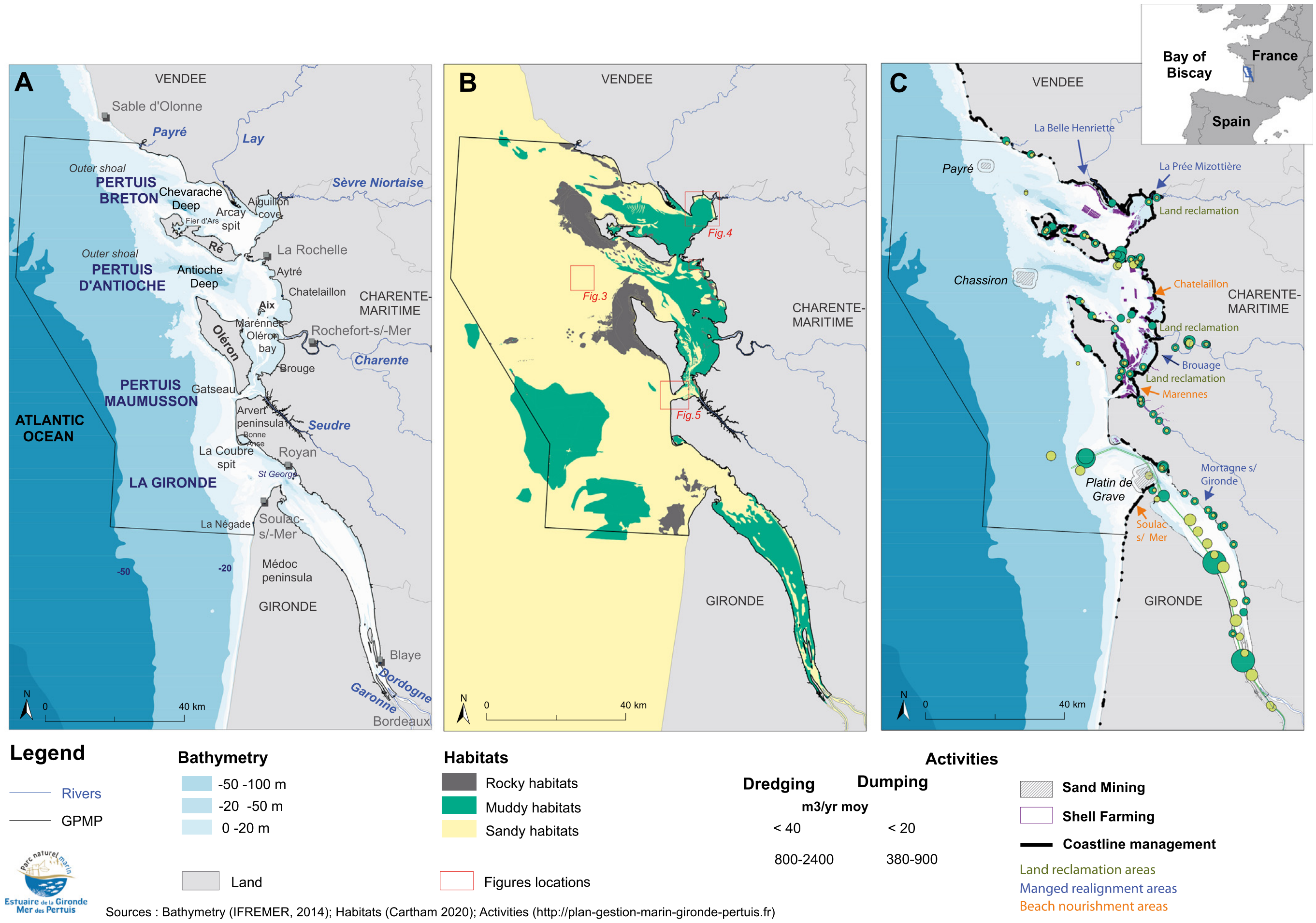

Fig. 1. General setting maps showing: A) GPMP boundaries (corresponding to the −50 m isobath offshore and to the shoreline and inner limits of the estuaries), the bathymetry and the location names used in this review; B) Main submarine habitats (rocky, sandy, muddy) and figure locations; C) Main Human activities in the GPMP.

synthesize, for the first time, the available knowledge on the complex morphological evolution and sediment dynamics that occur in the mixed rocky and sedimentary estuaries of the GPMP. Based on this synthesis, we will show how natural processes and human activities interact in this complex coastal system with several feedback loops acting at different time scales. Given the diversity of ecosystems, natural processes and human activities interacting in this marine park, this study may serve as a reference for the management of ecosystem preservation and human activities in MPAs with significant sediment dynamics and morphological changes.

2. The study area setting

2.1. Geography and coastal environments

The GPMP faces the Atlantic continental margin (Bay of Biscay), a sediment-starved margin where modern sediment input is mainly delivered by two large rivers, the Loire and the Gironde, with about 0.6 to $1.5.10^6$ t/yr of suspended load respectively (Jouanneau et al., 1999). Covering an area of 6500 km^2, it is located on the French Atlantic coast between the mouth of the Payré Estuary, to the north, and the Négade point, to the south (Fig. 1.A). The Park is limited to the east by a complex 1100 km-long shoreline including 6 estuaries, from north to south: Payré, Lay, Sèvre-Niortaise, Charente, Seudre and Gironde. The offshore GPMP boundary corresponds to the - 50 m isobath, and thus includes the inner shelf and the shoreface domain. There are 3 islands in the GPMP (Ré, Aix and Oléron, Fig. 1.A) with an alternation of exposed and sheltered areas. Between these islands and the continent lie elongated embayments and large inlets, locally named “Pertuis” (Pertuis Breton, Pertuis d'Antioche and Pertuis de Maumusson, Fig. 1.A). Thus, this coastal area displays a huge diversity of sediment environments, including wave-dominated coasts (barriers attached to the continent and sandspits), tide-dominated coasts (tidal bays, wide tidal flats and salt marshes, tidal channels and sandbars) and mixed tide and wave dominated coasts (tidal inlets and estuary mouths). Such a complex coastal environment, with intermingled rocky, sandy and muddy substrates, where there are fast sediment dynamics, is a place of wide diversity in coastal habitats and ecosystems (Fig. 1.B).

2.2. Hydrodynamics

2.2.1. Tides

Tides in the GPMP are semi-diurnal with small diurnal asymmetries. The tidal range at the coast varies from 1 m during neap tides to >6.5 m during spring tides, with an annual mean of around 3.75 m in La Rochelle Harbour; a large part of the GPMP can therefore be considered as macrotidal (Dodet et al., 2019a). Tidal currents are locally strong, with velocities exceeding 2 m/s in tidal inlets (Bertin et al., 2005) and near capes. The two largest estuaries in the park, the Gironde and the Charente, are hypersynchronous, meaning an increasing tidal range within the estuary (Allen et al., 1980; Allen, 1991; Toublanc et al., 2015).

2.2.2. Waves

The Bay of Biscay is exposed to the large waves generated in the North Atlantic Ocean (annual mean wave height of 1 to 2 m; peak period of 6 to 12 s; mean direction from WSW to WNW). The wave climate is characterized by a strong seasonal variability, with higher waves during winter and storm waves exceeding 10 m by 50 m water depths (Bertin et al., 2015; Dodet et al., 2019b). Wave heights of 6 m have been measured at the breaker along the coast (Guérin et al., 2018; Pezerat et al., 2022). A general southward net littoral drift occurs along north-south coasts owing to the N280 dominant wave direction. Nevertheless, due to the complex shoreline morphology, the local net littoral drift displays significant direction variability. Storms regularly hit the study area, with about 60 storms since 1924 (Breilh et al., 2014). They are more frequent and intense in autumn-winter (Breilh et al., 2014; Castelle et al., 2015). They can generate massive erosion (Chaumillon et al., 2019b) and coastal flooding (Bertin et al., 2014; Baumann et al., 2017a; Chaumillon et al., 2017).

2.2.3. Rivers

Seven rivers contribute to freshwater input into the GPMP (Fig. 1.A, Table 1) with variable seasonal flows (high river flow in winter and low river flow in summer).

2.3. Human activities

Over the centuries, the estuarine environments of the GPMP were ideal places for many human activities. Starting in the Middle Ages, episodes of deforestation occurred between 1300 and 1950 (Lesueur et al., 1996; Dinis et al., 2006; Poirier et al., 2011) and land reclamation between 1600 and 1965 shaped the coastline (Pawlowski, 1998; Pontee et al., 1998). Massive exploitation of salt marshes was initiated with salt production and continues today with oyster, mussel and shrimp farms. The complex coastline morphology of the GPMP being advantageous for military and commercial development, there are four international harbours (Bordeaux, Rochefort sur Mer, La Rochelle, Les Sables d'Olonne). The increase in frequentation and boat size led to an intensification of navigation and a need to maintain accessibility conditions through dredging (1930-currently) (Fig. 1.C). Along the coast, demography increased during the 19th and 20th centuries. In Charente Maritime, for example, the number of permanent residents increased from 438,042 in 1791 to 651,358 in 2019, with a concentration in cities and along the coast (INSEE). In addition, the population triples during the tourist season (July–August). The attractiveness of this coastal zone is associated with numerous infrastructures that in the main began to appear in the 1960's. >20 % of the GPMP coastline is currently artificial and more than half of this artificial coastline corresponds to coastline defences. The progression of urbanization is associated with the intensification of resource exploitation including fishing, shellfish farming and marine sand mining in 3 areas, and an intensification of recreational activities (fishing and yachting) (Fig. 1.A).

3. Methods

3.1. Synthesis methodology

We conducted a comprehensive search of the peer-reviewed scientific literature and grey literature to compile a database documenting the morphological evolution and sediment dynamics in the GPMP. In total 300 scientific papers, 20 theses, 50 study reports and 4 books were used to create a synthesis for the park (*https://plan-gestion.parc-marin-gironde-pertuis.fr/drupal/sites/default/files/2023-01/CELHYSE_synthese_LRUniversite_PNMEGMP_Jan2023.pdf*).

In addition, we used unpublished data to better restrict the specific coastal sedimentary evolution. Given that morphological evolution and sediment dynamics are controlled by various forcing parameters (sea level change, climate, hydrodynamics, human activities) acting at different time scales, we organized the synthesis along 3 time scales: (1) the geological or long time scale (millenaries to centuries); (2) the engineering or medium time scale (centuries to decades); (3) a short time scale (years to days including short-time events). Based on available data, the transition between the long-term and medium-term time scales corresponds to the year 1850 and the transition between the medium-term and short-term time scales corresponds to the year 1999.

3.2. Unpublished data

Bathymetric data were collected within three key-areas for sediment dynamics and human activities: the Chassiron sand mining area, the Maumusson Inlet and Aiguillon Cove (Fig. 1.B).

3.2.1. Bathymetry

The bathymetry in the Chassiron area (Fig. 3) was collected in 2016 and 2019 (CREOCEAN, 2020). Bathymetric measurements were recorded with a R2Sonic 2022 multi-beam bathymetric echosounder coupled with an RTK GPS positioning system (Proflex800) and a motion unit (Coda Octopus F185R+). The bathymetric data were collected at a 200 KHz frequency and a maximum swath of 140°. Hypack software was used for data acquisition, calibration (roll, pitch and yaw) and processing (cleaning, positioning using RTK data and motion sensor, sound velocity correction and triangulation). Digital Terrain Modeling (DTM) with 2 m grid-node was conducted for each dataset.

The bathymetry in the Maumusson Inlet (Fig. 5) was collected during the EMEMO-17 (2017) and EMEMO-18 (2018) cruises on board R/V Haliotis. Bathymetric measurements were recorded with an interferometric sonar coupled with a GPS HDS800. Processing included removing of reflections in the water, tide and vertical reference correction. The data were validated with adjacent profiles and intertidal topographic measurements. Repetitive bathymetric profiles were recorded in the same position to evidence seafloor evolution during time periods of 7 days and 1 year. On the basis of these data, two 1 m mesh DTM (Digital Terrain Model) were generated for years 2017 and 2018.

3.2.2. Lidar

The bathymetry of the Aiguillon Cove (Fig. 4) was collected by IFREMER in 2000 (Populus et al., 2001) and OPSIA in 2021. For the new 2021 Lidar survey, a RIEGL VQ-780 II airborne laser scanner coupled to a GPS was used, at flight heights of between 750 and 1650 m, for the acquisition of the 3D point cloud. After processing, including classification and interpolation, a DTM (Digital Terrain Model) was generated at the centimetre resolution.

4. Results: synthesis of morphological evolution and sediment dynamics within the GPMP at three time scales

We will first present a bibliography-based synthesis of the morphological evolution and sediment dynamics within the GPMP at long, medium and short time scales (Fig. 2.A.B.C.). From this synthesis, we will highlight the natural forcing parameters controlling GPMP evolution.

4.1. Long time scale evolution (millenary)

Extensive seismic exploration of the inner shelf and estuaries of the GPMP have revealed a series of four main incised valleys (IV) connected to major embayment, tidal inlets and estuaries (contour map of incised valleys on Fig. 2.A, Chaumillon et al., 2008b; Chaumillon and Weber, 2006; Weber et al., 2004a, 2004b; Lericolais et al., 2001). The complex

Table 1
Rivers flowing into the GPMP. Data of the draining area, lengths and freshwater rivers flows in 2016 (Banque hydro 2018).

Rivers		Drainage area (km^2)	Length (km)	High – Mean – Low River flow (m^3/s)
Gironde estuary	Garonne	56,000	647	5400–650–110
	Dordogne	23,900	483	1700–340–49
Charente		9526	381	370–30–1.70
Sèvre Niortaise		4130	160	160–11.6–1.3
Lay		1970	142	200–9–0.09
Seudre		775	68	8.4–0.9–0.02
Payré		154	21	9–0.49–0.01

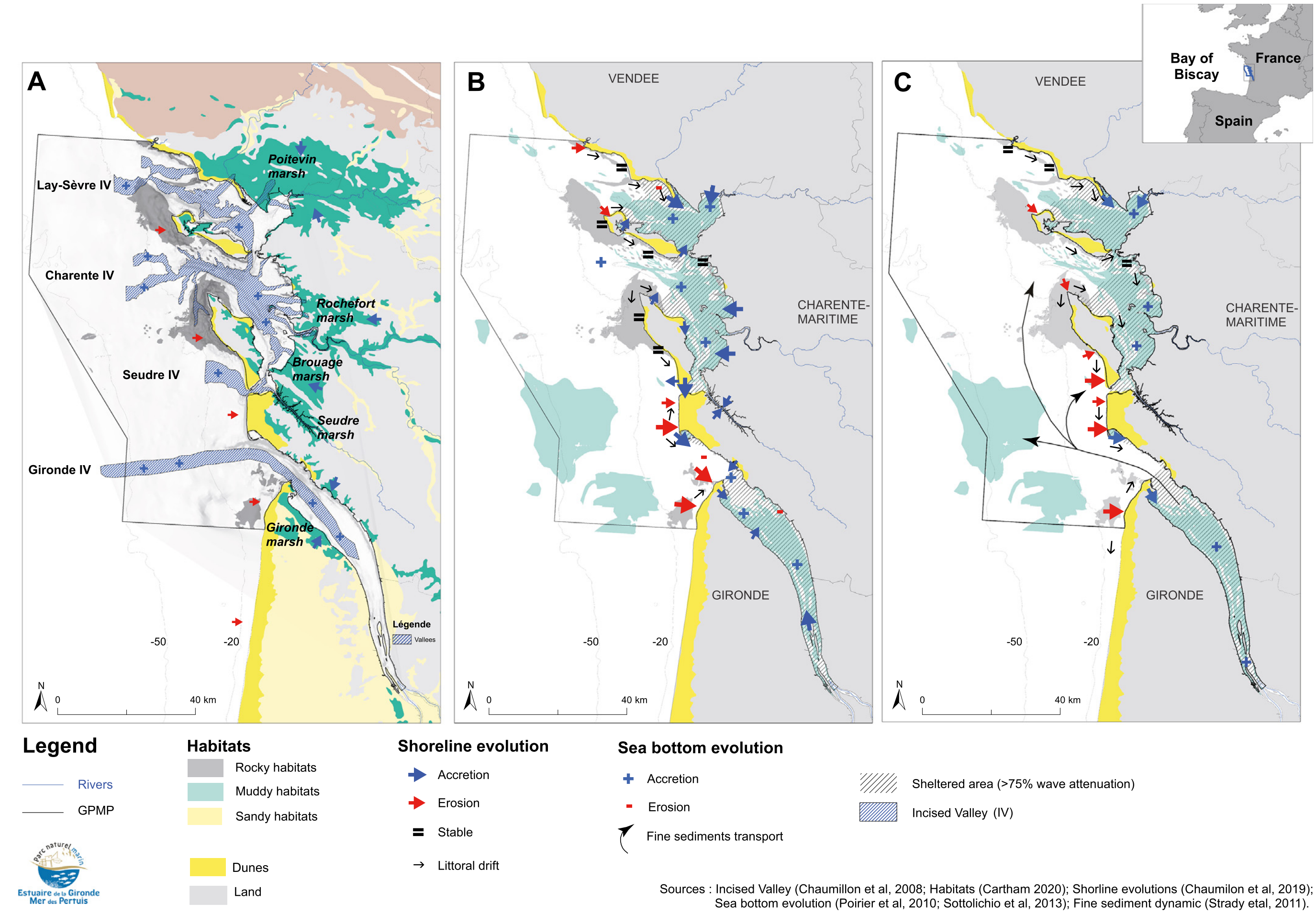

Fig. 2. Synthesis maps of submarine and shoreline morphological evolution within the GPMP at 3 times-scales: A) Long time-scale evolution and the contours of the main incised valleys; B) Medium time-scale evolution; C) Short time-scale evolution and main sediment pathways including littoral drift and suspended sediment transport.

geomorphology of the present-day shoreline of the GPMP, with a succession of islands, headlands and estuaries, is inherited from these wide (a few kilometers) and deep (a few meters) incisions. Onshore, these valleys extend beneath the coastal marshes (Poitevin Marsh, Rochefort Marsh Seudre Marsh and the Gironde Marsh, Fig. 2.A) where present-day rivers flow. Other marshes are located on secondary incised valleys. Most of these marshes are currently below the highest astronomical sea level and correspond to approximately 50 % of the GPMP coastline. These valley incisions taper approximatively 50 km offshore, below 40 to 70 m present-day sea-level (Lericolais et al., 2001; Chaumillon and Weber, 2006). This incision decrease is located where the shelf gradient decreases (Cirac et al., 2000), indicating that the seaward termination of the incision is mostly related to the shelf morphology (Chaumillon et al., 2008b).

Overall, the incised valley sediment fills consist of two main depocenters, with one offshore, located in the present-day inner shelf, and a second, located in the inner part of the bays and estuaries and extending below the coastal marshes (Chaumillon and Weber, 2006; Chaumillon et al., 2008a). Those two main depocenters are separated by valley segments where sediment fill is reduced or absent. The onshore depocenters, corresponding to the coastal sedimentary prism, include the marshes, barriers and estuary sediment fills (Fig. 2.A). Sand-dominated bodies include barriers located in wave-dominated environments. They also include tidal deltas and tidal sandbanks within tidal inlets and estuary mouths (mixed tide-and-wave environments). They are also in the form of tidal sandridges found in tidal channels and bay head delta (tide-dominated settings, Billy et al., 2012; Chaumillon et al., 2013). Mud-dominated sediment bodies are located within estuaries and tidal bay-fill (Allen and Posamentier, 1994; Allard et al., 2010; Poirier et al., 2011) and below present-day marshes (Baumann et al., 2017a). Fine-grained sediment supply increase is mainly recorded by a muddy drape, emplaced since the late 18th century (Poirier et al., 2011; Allard et al., 2010).

4.2. Medium time scale evolution (secular)

In the studied area, exposed coasts were arbitrarily defined as coasts where offshore wave height decrease is lower than 75 %. These coastlines and their seaward prolongation in the shoreface and inner continental shelf are considered to be exposed environments. Sheltered coasts were arbitrarily defined as coasts where offshore wave height decrease is higher than 75 % (Chaumillon et al., 2019b). These coastlines and their seaward prolongation are considered as being sheltered environments (Fig. 2.B). Areas belonging to both exposed and sheltered environments correspond to tidal inlets and estuary mouths connected to the Atlantic Ocean.

Most of the sandy shorelines located along exposed coasts and facing sandy shorefaces (Arvert and Médoc Peninsulas, Fig. 1.A) have narrowed during the last two centuries (Chaumillon et al., 2019b, Fig. 2.B). Maximum erosion rates have been observed on both sides of the Gironde estuary mouth. Erosion rates of − 14 m/yr (period 1840–2016) and − 35 m/yr (period 1785–1824) were observed in the southern Arvert Peninsula (Bertin and Chaumillon, 2005; Chaumillon et al., 2019b) and in the Médoc Peninsula (Négade Point, Levêque, 1936), respectively. In contrast, sandy barriers lying on intertidal or close to subtidal rocky outcrops (South Vendée Coast, Ré and northern Oléron Islands, Fig. 1.A) display moderate morphological changes. Most of the seafloor changes in the shoreface area at the medium time scale cannot be documented as historical bathymetric profiles are sparse. Locally, recent bathymetric profiles recorded along historical profiles have shown shoreward migration of sand bodies in the western part of the Antioche Deep (Weber et al., 2004a, 2004b).

Sandy shorelines located on sheltered coasts include barriers attached to the shoreline and sandspits. Barriers attached to the shoreline are mostly stable in a cross-shore direction. Sandspits locally display high elongation rates over the last two centuries (Fig. 2.B). The Arçay Sandspit (Fig. 1.A) elongates at a mean rate of 28 m/yr (period 1811–1945, Allard et al., 2008, Fig. 2.B). Muddy shorelines located on sheltered coasts display significant changes. The Aiguillon Cove (Fig. 1.A) displays a fast shoreline modification (maximum seaward migration rate of 20 m/yr; Godet et al., 2015) and a significant mudflat vertical accretion (a few meters for the period 1824–1959 to 1983; Poirier et al., 2010). A seaward shoreline migration of up to 2 km was observed within the Marennes-Oléron Bay (Fig. 1.A) between 1824 and 1997 (about 11 m/yr, Bertin et al., 2005). Brouage (Fig. 1.A), the main trading harbour for salt during the 11th century, is actually 1 km farther from the shoreline, attesting to a significant seaward shoreline migration (Papy, 1935). These seaward coastline migrations are associated with high sedimentation rates within the intertidal flats and subtidal channels. A mean sedimentation rate of 46 mm/yr was calculated for the whole Marennes-Oléron Bay (period 1824–2003, Bertin et al., 2005). High sedimentation rates have also been observed in large parts of the Pertuis Breton and Pertuis d'Antioche (Poirier et al., 2010) and at the mouth of the Charente River (Bertin et al., 2005). Within the Gironde Estuary, areas of mud-dominated accretion and erosion have been evidenced (Sottolichio et al., 2013). The area of maximum volume of sediment accretion migrated upstream within the estuary (period 1962–1994).

The biggest morphological change was observed in the vicinity of the tidal inlets (South of Oléron Island, Bertin et al., 2004, 2005; Chaumillon et al., 2002, 2008b, 2019a, 2019b) and on both sides of the Gironde Estuary (Castelle et al., 2017) (Fig. 2.B). The elongated sandbanks located in the wide estuary mouths (Gironde Estuary mouth and northern Marennes-Oléron Bay) are also areas where rapid morphological changes have been observed. For example, the St Georges Bank displayed a sediment accretion of 90.10^6 m^3 between 1824 and 1994 (average sediment supply of 500,000 m^3/yr; Bertin and Chaumillon, 2005).

4.3. Short time scale (decennial)

Most of the sandy shorelines located along exposed coasts and facing sandy shorefaces have retreated during the last two decades. Maximum erosion rates reaching 8 to 19 m/yr were observed in the south of Oléron Island (Baumann et al., 2017b; Chaumillon et al., 2019b) and at the west of the Médoc Peninsula (average of 4 m/yr; ARTELIA, 2012; Fig. 2.C). In contrast, exposed sandy barriers lying on intertidal or subtidal rocky outcrops (Ré and Oléron Islands and south Vendée, Fig. 1.A.B) display moderate erosion (< 4 m/yr) or are stable (< 2 m/yr). Longshore transport ranged from 50,000 to 140,000 m^3/yr in SW Oléron Island (Bertin et al., 2008).

Successive bathymetric data show shoreface changes westward of the Oléron Island (Chassiron sand mining area, Figs. 1.B.C; 3). This area, located in the marine segment of the Charente incised-valley (Fig. 2.A), has a water depth ranging from −19 to −20 m below the lowest astronomical tides. The shoreface consists of a very gentle seaward slope and sand mining areas are revealed by 4 elongated deeps or pits (orientation *E*-W to WSW/ENE), about 1 to 2.5 km long and 0.2 to 0.8 km wide. Their depth relative to the adjacent shoreface varies from 1 to 8 m, with a mean slope < 5 % (3°). Unlike the surrounding shoreface, the pits display large to very large subaqueous dunes (80 to 150 m wavelength, 0.5 to 1 m amplitude), their crest being mostly sub-perpendicular to the deep elongation. These dunes consist of fine sand (0.4 to 0.08 mm), also found in the shoreface, and lie on coarse and older units of the valley-fill (2 to 0.4 mm, Fig. 3; CREOCEAN, 2020; Weber et al., 2004b). These subaqueous dunes are asymmetric with the stoss face oriented to the east. Many furrows, approximatively 30 to 2500 m long and 0.1 m deep, are observed in pits and are related to sand mining (Fig. 3.D, Profil 1). The difference in bathymetric maps between 2016 and 2019 shows a deepening and widening of the extraction areas, more particularly the Chassiron B concession (Fig. 3.C). A shoreward migration of subaqueous dunes was evidenced by alternation of erosion and accretion areas (Fig. 3.C; CREOCEAN, 2020). Focusing on the same dunes, observed in both the 2016 and 2019 data (Fig. 3.D Profil 2), their shoreward migration can be estimated at about 13 m/yr. Assuming that this sand migration is limited to the sand dune thickness (about 1 m), the dune migration rate can be converted into a minimum volume of local shoreward bedload sand transport corresponding to 4.10^{-4} kg/m/s. It should be noted that the total flow of transported sediment is considerably higher given the suspended load transport, which is dominant in this area (Pezerat, 2022). Hydrodynamic measurements conducted in November 2002 close to this area (Idier et al., 2006) showed strong residual currents generated by waves, tides and winds (> 1 m/s) near the seabed, by 23 m of water depth. The shoreward sediment transport flux was estimated to be 0.15 kg/m/s (Idier et al., 2006).

Sandy attached barriers and sandspits located on sheltered coasts are mostly stable or show a local sediment accretion (Chaumillon et al., 2019b; Fig. 2.C). Arçay sandspit elongation reached a mean rate of 22 m/yr between 1945 and 2005 (Allard et al., 2008), which can be explained by an annual longshore transport ranging from 80,000 to 131,000 m^3 (Bertin et al., 2007; Allard et al., 2008). Very large subaqueous dunes (150 to 400 m wavelength, 2 to 8 m Amplitude) observed in the eastern Antioche Deep are asymmetric and show sand transport convergence driven by ebb and flood tidal currents (Weber and Chaumillon, 2004).

Most shorelines bordering muddy sheltered coasts correspond to hard defences, and are therefore stable. Sheltered mud flats are areas of high siltation on a short time scale. An example is given by the Aiguillon Cove where Lidar measurements in 2000 and 2021 evidenced a mean sediment gain of 262,000 m^3/yr in mudflats, corresponding to a vertical accretion rate of 1.32 cm/yr (Fig. 3). Similarly, the mudflats of the Marennes-Oléron Bay display a positive sediment budget (Bertin et al., 2005; Bertin and Chaumillon, 2006). Fine sedimentation within this bay originates from both the Gironde Estuary (Fig. 2.C, Froidefond et al., 1998; Dabrin, 2009) and from the nearby Charente River, with a suspended matter supply reaching 100,000 t in 3 months (Le Hir et al., 2010).

Within the Gironde estuary, suspended matter input has been estimated at 3.10^6 t/yr (Lesueur and Tastet, 1994; Schäfer et al., 2002; Dabrin et al., 2014). The Gironde sediment fill is prevented by extensive dredging to maintain the navigation channel. The zone of maximum turbidity (concentration > 3000 g/m^3) migrates shoreward in summer and seaward in winter, as a function of the change in the river flow. During flooding periods, this turbid zone is expulsed towards the continental shelf ($1.6.10^6$ t/yr) (Froidefond et al., 1998; Doxaran et al., 2009). The riverine sediment supply from the Gironde Estuary to the continent shelf is estimated to contribute 60 % of fine sediment input into the Bay of Biscay and to settle in the so-called Gironde mudflat (Lesueur et al., 2002). The potential supply of sediment from the Gironde estuary towards the Marennes-Oleron bay ranges from 800 to 2000 t/day.

As for the medium time scale, the largest morphological change in both shorelines and seafloor was observed in the vicinity of the tidal inlets and exposed estuary mouths (Castelle et al., 2018). In recent decades the highest erosion rates along exposed coasts were observed in south Oléron Island, updrift of the Maumusson Inlet (Chaumillon et al., 2019b). High resolution bathymetry data captured the intense sediment dynamics within this large tidal inlet (Fig. 5). Subaqueous dunes, with wavelengths ranging from <10 m to >100 m, were evidenced in the main inlet channel and on the flood delta (Fig. 5). Repetitive bathymetric surveys conducted in 2017 showed that some of these dunes migrate at a rate ranging from <1 m to 1.5 m/day (Fig. 5.D). The different bathymetric maps produced between 2017 and 2018 show a tidal channel migration of about 300 m to the south and an alternation of the erosion and accretion areas within the tidal inlet indicating the displacement of subaqueous dunes (Fig. 5.C).

4.4. Forcing parameters of sediment and shoreline dynamics

Studies of the sedimentary and morphological evolution in the GPMP on long, medium and short time scales evidenced the main controlling parameters of this evolution.

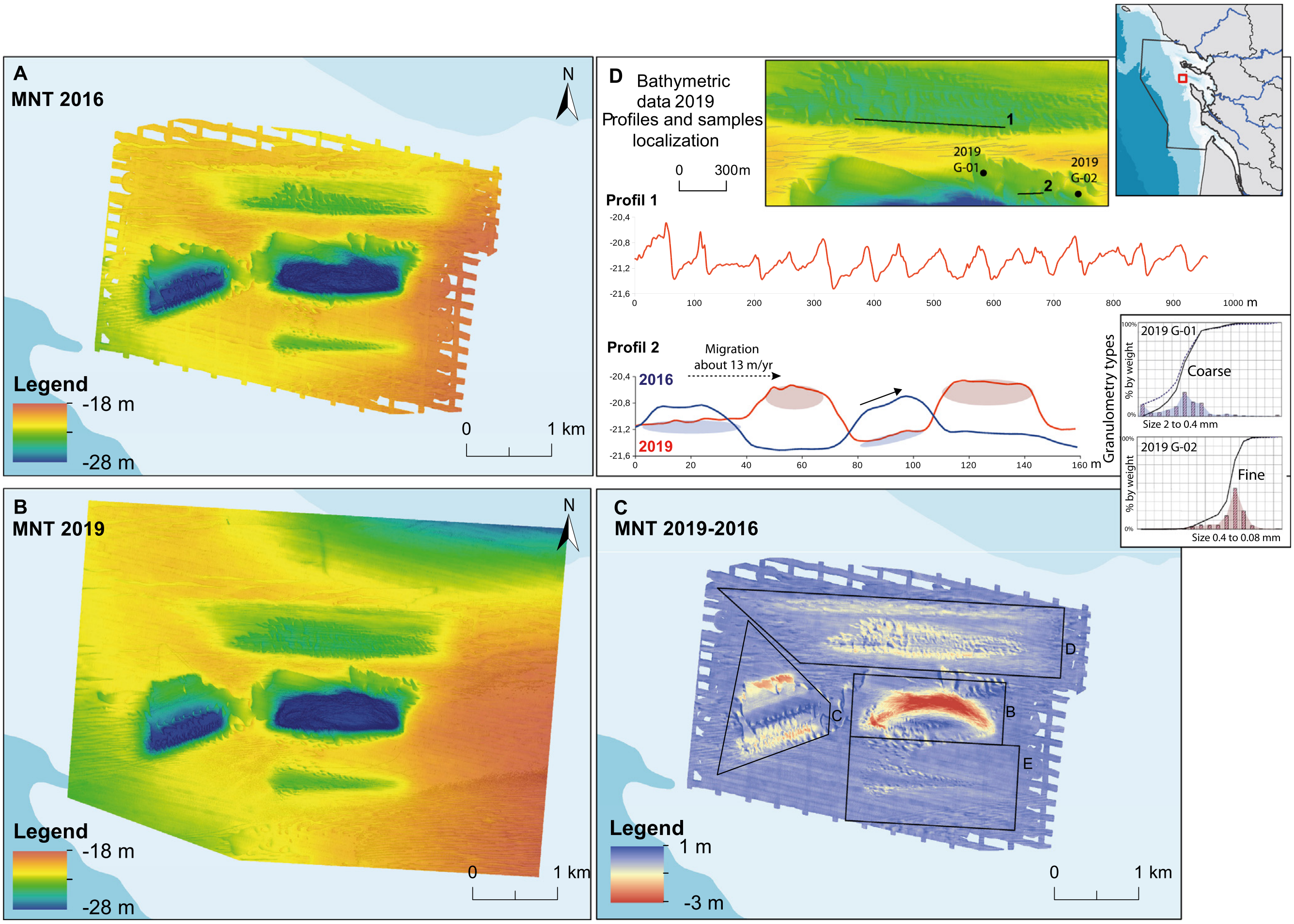

Fig. 3. Bathymetric data collected in the Chassiron sand mining area. A) Bathymetric map of 2016; B) Bathymetric map of 2019; C) Difference between the bathymetric maps of 2016 and 2019; D) Bathymetric profiles showing the residual sand transport direction (profile 1) and the subaqueous dunes migration between 2016 and 2019 (profile 2). Grain size curves of sand sampled at the top of a subaqueous dune and in the trough between two subaqueous dunes (G-01 and G-02). The location of the bathymetric profiles and grain size samples is shown on the bathymetric map of 2019.

The first order controlling parameter of the long-term evolution is global sea level changes (Chaumillon et al., 2010). Large sea level changes during the glacial/interglacial cycles led to the erosion and flooding of the valleys, imposing a rugged morphology of the substratum (Fig. 2.A). This bedrock morphology is the second order controlling parameter which explains the strong variations in hydrodynamics, which in turn accounts for the diversity in coastal environments (Chaumillon et al., 2008b, 2010). The NW-SE oriented bedrock highs and lows control the juxtaposition of western coasts exposed to the waves, displaying sandy barriers and/or rocky coasts, and mud-dominated sheltered coasts, where wave influence is weaker and where sandy barriers are reduced or absent. This bedrock morphology explains the occurrence of strong tidal currents in entrenched areas within the incised valleys and near headlands. The substratum morphology also controls tidal inlet and estuary mouth locations (Bertin et al., 2004; Feniès et al., 2010). Climate changes through wave climate and precipitations are important controlling parameters of the long-term coastal evolution. This climate control was evidenced in very contrasted sedimentary environments, from mud-dominated (Poirier et al., 2011), to sand-dominated sediment bodies (Poirier et al., 2017a, b).

Medium and short-term changes (Fig. 2.B·C) are also strongly controlled by bedrock antecedent morphology. The most significant change was observed close to exposed estuary mouths and tidal inlets and along sandy exposed beaches where bedrock outcrops are absent (Chaumillon et al., 2019b). In contrast, moderate to slow changes are observed in areas where rocks outcrop in the foreshore, even if they are exposed to large waves. Indeed, stable shallow bedrock outcrops within the upper shoreface or foreshore increase the bottom friction and strongly dissipate wave energy (Poate et al., 2018). The other main controlling parameter is the hydrodynamics. The biggest morphological changes, observed in estuary mouths and tidal inlets (Castelle et al., 2018), are due to strong currents induced by both waves and tides. Fast shoreline changes occur along exposed coasts where large waves combined with tidal variations may produce extreme water levels and serious erosion or overwashes (Baumann et al., 2017b). Medium and short-term changes in many sediment bodies (e.g. sandspits, sandbanks, beach profiles) are also controlled by climate change (Poirier et al., 2017a, b). Storms and clusters of storms cause the biggest morphological changes along both exposed coasts (Chaumillon et al., 2010; Castelle et al., 2015; Baumann et al., 2017) and sheltered coasts (Breilh et al., 2013). Changes in river flows are an important controlling parameter for fine sediment dynamics (Toublanc et al., 2016; Diaz et al., 2020) and sedimentation on estuarine tidal sandbars (Chaumillon et al., 2013).

At all time scales, human activities are forcing parameters of sediment dynamics and coastal geomorphology and conversely are influenced by them. These interactions are discussed in the following section.

5. Discussion: human activities and habitat preservation within the GPMP in the light of morphological evolution and sediment dynamics at different time scales

In this section, we will analyse the interactions between human activities, sediment dynamics and coastal geomorphology in order to identify instabilities and unsustainable activities with the aim of helping to manage human activities and ecosystem protection. For this purpose, we will first describe the relationships between sediment dynamics, morphological change and the eight main human activities that exist in the GPMP today (Fig. 6).

Three human activities, namely deforestation, commercial fishing and leisure activity related to tourism, have a relatively moderate impact on sediment dynamics and morphological chnage. Deforestation occurred during the last two centuries and resulted in an increase in soil erosion and fine sediment supply recorded as a mud drape in estuaries and sheltered areas (Poirier et al., 2011, 2016). Commercial fishing strongly depends on the complex sediment spatial distribution in the GPMP (Fig. 1.B), which controls the species richness, abundance and biomass of benthic communities and many fish (Hily, 1977). Fishing resources are also controlled by mud suspension dynamics, particularly in estuaries and bays (Dara and Douglas, 2001). Fishing activities, in particular bottom trawling, strongly influence sediment dynamics (Oberle et al., 2015). Many activities related to leisure activities (e.g. fishing, yachting, surfing, swimming) are influenced by sediment distribution and exposure to waves. Rapid coastal change impacts these activities by causing beach erosion (Fig. 2), beach access disturbance and sand fill in harbour entrances and/or tidal channels.

In contrast, five human activities, namely land reclamation, shoreline management, harbour development and dredging, shellfish farming and sand mining, interact significantly with sediment dynamics and morphological change, indicating that they depend strongly on this change and, in turn, impact it through a feedback mechanism. These activities have a significant impact on sediment dynamics and morphological change and require careful management to ensure ecosystem protection (Figs. 6, 7). Diagrams displaying these interactions are shown in Fig. 7. The details of the interactions between these five human activities, sediment dynamics and morphological change are analysed below.

5.1. Management of land-reclaimed areas

Land reclamation occurred in sheltered areas of incised valleys (tidal bays and estuaries, Fig. 2.A) naturally prone to sediment fill and siltation. Land reclamation of salt marshes started early during the 10th century in Europe. Since the seventies, this practice has become globalized (OSPAR commission, 2008). Famous examples of coastal land reclamation include Hong Kong, Singapore and the Netherlands (Stauber et al., 2016). Within the GPMP, the first land reclaimed areas were used for salt production during the Middle Ages (Gedan et al., 2009) and later on they were used for agriculture (Sauzeau and Péret, 2014). Today, as land-reclaimed areas are fertile, they are mostly used for agriculture (Kuenzer and Renaud, 2012). Locally, reclaimed areas are also used for housing or tourism accommodation. To prevent marine flooding of reclaimed areas, dikes and locks were built over the last two centuries. A major side-effect of dikes and levees is the interruption of the sediment supply in reclaimed areas. This abrupt break in marine sedimentation, together with soil subsidence related to both natural mud compaction and agricultural practices, leads to extensive low-lying areas: today, 45 to 50 % of the coastal land of Charente-Maritime (Figs. 1.A; 2.A) lies below the highest astronomical tides (Breilh et al., 2013). In the Poitevin Marsh (Fig. 2.A), some agricultural fields are located 2 to 3 m below the highest astronomical tides. Thus, land reclamation has considerably increased the vulnerability of these coastal zones to flooding. These low and vulnerable coastal areas are not exclusive to the GPMP: 10 % of the world's population live in low elevated coastal zones, which cumulatively cover 2 % of the global land area (IPCC, 2014). In the GPMP, the Xynthia Storm in 2010 induced a marine flooding that extended as much as 10 km inland and was an eye-opener concerning this vulnerability (Breilh et al., 2013; Chadenas et al., 2014). A tide gauge located in Rochefort-sur-Mer showed that the sea level rise in Rochefort, during Xynthia, had been limited to an elevation corresponding to the height of the dike bordering the marshes located between Rochefort and the sea. Consequently, the flooding of these marshes (Fig. 2.A) prevented a water level rise in Rochefort (Breilh, 2014). This result was confirmed by hindcast of the marine flood associated with Xynthia showing a maximum water level limitation locally that reached 1.0 m when flooding was permitted (Bertin et al., 2014). Other studies have shown the impact of marsh flooding in terms of extreme water level limitation (Townend and Pethick, 2002; Huguet et al., 2018). Therefore, flooding of low-lying areas minimizes the risk on stakes, while protective structures lead to the loss of excess water storage space and no longer allow the coastline to adapt to extreme sea levels. These results support the idea that managed realignment could be an important defence option as the probability of extreme sea levels and the risk of flood disaster will increase with global sea level rise (Goeldner-Gianella et al., 2015; Bhunia et al., 2021).

Beyond increasing water storage capacity there are many other advantages with managed realignment or depolderization. First, a huge increase in sedimentation rate is observed in depolderized areas after they are opened to coastal waters. The sedimentation rate reached >2 cm/yr within the Mortagne-sur-Gironde marsh (Fig. 1.C) when it was reconnected to the Gironde Estuary, after the Martin Storm in 1999 (Allou, 2016). Second, salt marsh areas are particularly effective ecosystems for carbon sequestration (Ouyang and Lee, 2020). The largest carbon pool in salt marsh ecosystems is the soil, with a sequestration rate of 210 g $CO^2/m^2/yr$ (Chmura and Anisfeld, 2003; Howard et al., 2014; Amann et al., 2022). The development of salt marshes related to depolderization could be helpful for trapping the CO^2 produced by human activities, and this gives marsh areas an exceptional ecological function in the context of decarbonization (IPCC, 2022). Third, depolderization leads to an increase in shoreline length and shallow coastal zone surface, resulting in an increase in areas suitable for feeding and nursery. Thus, depolderization can increase biodiversity (Kneib, 1997; Cattrijsse and Hampel, 2006). Fourth, the highly productive coastal marsh ecosystems help filter polluted land water. Pollutant mitigation by salt marshes (reduction of nutrient enrichment) results in improved ocean water quality (Nelson and Zavaleta, 2012). Fifth, marshes are attractive landscapes owing to their rich biodiversity (observation and leisure in natural reserve areas) and constitute a natural heritage (patrimonial value) that should be preserved (Godet et al., 2015). Thus, coastal marsh restauration and depolderization could play a key-role in coastal defences, notably though excess water storage during storms and a very high sedimentation rate and related marsh elevation (Gedan et al., 2009). In addition, depolderization provides a whole series of services: carbon sequestration, safeguarding biodiversity, improving water quality, maintaining attractiveness and landscapes, heritage value (Barbier, 2007). Despite these advantages, in Europe there are only a few (around 15) depolderized areas, in the United Kingdom, Germany, Belgium, Italy and Spain (Goeldner-Gianella-Gianella, 2007). Moreover, it is estimated that since the 18th century 50 % of saltmarshes have been lost or degraded worldwide due to human activities (Gedan et al., 2009; Barbier et al., 2011). Several barriers have been listed to explain such a low number of depolderized areas: (1) lack of knowledge on the marsh environment and on the impacts of depolderization; (2) a general lack of fear of the sea and coastal risk; (3) attachment to local polders and their uses; and (4) a lack of cost-benefit analysis (Goeldner-Gianella et al., 2015). Economic arguments could increase acceptance by local habitants, such as the estimated cost of polder management (e.g. restoration), land purchase etc. (De la Vega-Leinert et al., 2012). A better knowledge of marsh ecosystems and sharing this knowledge with the general public could help achieve a higher acceptance of this ecosystem-based solution in order to adapt to climate change (Goeldner-Gianella, 2010). In this regard, we have developed a series of humorous scientific shows associated with books for the general public (Chaumillon et al., 2019a, 2021; https://vimeo.com/404551187).

Land reclamation has developed in areas naturally prone to sediment fill (Fig. 4) and regression, and conversely increased natural regression tendency, by virtue of a positive feedback mechanism (Fig. 7.A). In addition, land reclamation generates negative side effects: (1) an increase in vulnerability related to the development of low-lying coastal zones; and (2) a reduction in intertidal areas that are a key habitat for many species. Due to the key-importance of the GPMP for migrating birds, land reclamation projects in the seventies were abandoned to maintain wide intertidal areas

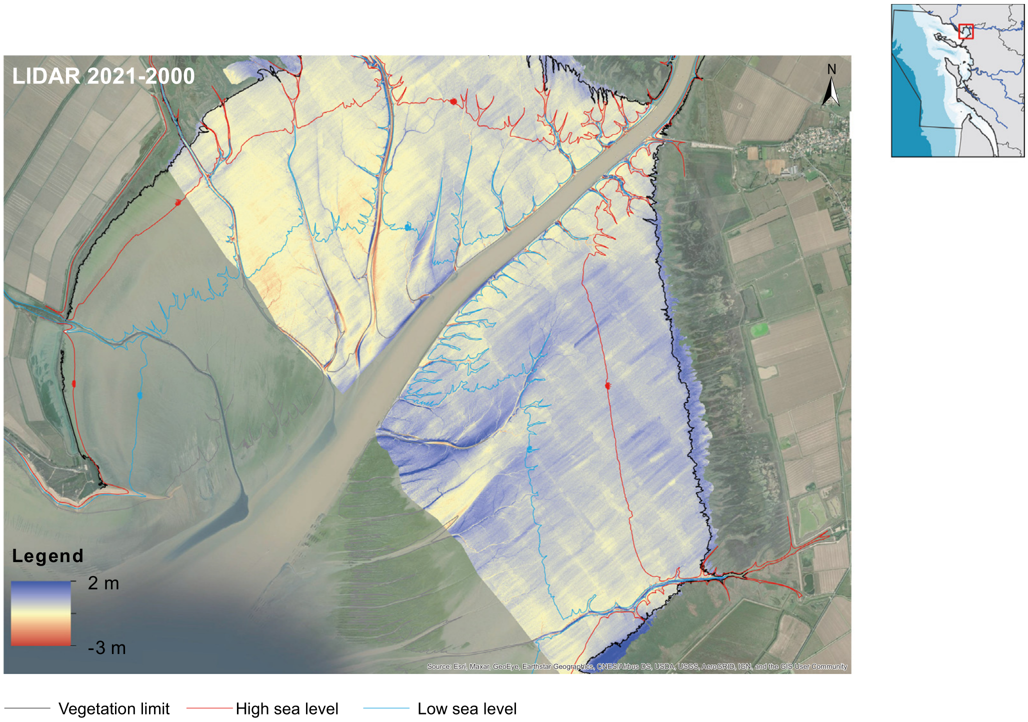

Fig. 4. Difference between the Lidar topographic maps in the Aiguillon Cove between 2000 and 2021.

(Verger, 2005). This turning point can be considered as a regulation process regarding the positive feedback induced by land reclamation (Fig. 7.A). Since 1999, regulation processes are ongoing, with the depolderization and restauration of intertidal habitats and wetlands. In the GPMP, three marshes have been reconnected to the sea: Mortagne sur Gironde, La Prée Mizottière and Tasdon (Fig. 1). The Tasdon depolderized area in La Rochelle was created with the aim of increasing biodiversity, carbon sequestration and attractivity for inhabitants (Dupuy et al., 2022). Beyond these pioneering sites, in a context of accelerating sea level rise, our recommendation is to implement a more extensive experimentation of depolderization with the aim of: (1) better quantifying the added value of ecosystem restoration, and (2) studying acceptability among the local population.

5.2. Management of coasts vulnerable to erosion

Hard defences are proliferating around the world (Firth et al., 2013a, b). The aim is to control shoreline position and navigation channels and reduce erosion and flooding (Komar, 1976; Brampton, 2002). Given the fast shoreline dynamics and extensive low-lying zones in the GPMP (Fig. 2), this park is exposed to major coastal risks, including marine flooding and coastal erosion. As a consequence, 26 % of this 1100 km-long shoreline is protected by hard defences (Fig. 1.C). Many of these defences have been developed in relation to land reclamation and are located along sheltered coasts (see previous section). Some exposed coasts of the GPMP are also protected by hard defences. They are mainly located near towns, harbours, roads and tourist infrastructures. In 2014, the evacuation of a building (named “Le signal”), built in the 1970s only 200 m away from the sea, made the French news because, for the first time, a large building had to be abandoned due to coastal erosion. The destruction of this building began in February 2023. It has become a symbol of coastal erosion and the strategic retreat from the French Atlantic coast. Although hard defences are efficient in stabilizing the shoreline, they have several negative impacts (Cooper and McKenna, 2008). Hard defences can alter the natural sediment budget (McLachlan et al., 2013; Brown et al., 2011). One example is the dike located downdrift of the Bonne Anse Inlet (Fig. 1.A) which caused severe erosion in the seventies (Dussier, 2016). Moreover, hard defences can cause steepening of the foreshore and beach erosion due to wave reflection on dikes (Williams et al., 2018). This resulted in coastal squeeze and decreased intertidal habitats that impact many organisms. Examples are the various species of birds (e.g. *Charadrius alexandrinus*, *Calidris alba, Arenaria interpres*) that use the foreshore as a resting or nesting place. Finally, hard defence support lowers biodiversity more than natural habitats due to the absence of environmental heterogeneity on artificial structures (Firth et al., 2013a, b).

Regarding coastal ecosystems and habitat protection, there is an increasing interest in soft coast defences. Soft coast defences are time-limited and reversible. They include revegetation (*Ammophila arenaria* is frequently used for this purpose in the GPMP, Favennec, 2001), plant debris covers, wind breaks and beach nourishment. Like hard defences, beach nourishment is costly and needs periodic maintenance (Williams et al., 2018). It has been extensively used in the GPMP (Châtelaillon, Marennes and Soulac-sur-Mer; Fig. 1.C). At the scale of the Charente-Maritime, approximately 1.7 Mm^3 of sand was used for beach nourishment between 1989 and 2009. One third of this volume came from sand dredged close to harbour entrances filled by sand supplied by the littoral drift along the northern coast of Oléron Island (Fig. 2; Pupiez-Dauchez, 2008). Beach nourishment in the Medoc peninsula (Soulac-sur-Mer) is supplied by sand dredged from the main channel at the mouth of the Gironde estuary so as to maintain the navigation channel (ARTELIA, 2018). Along this exposed coast it is not as effective as on sheltered coasts (Châtelaillon, Marennes). Indeed, the sediment supply limits the erosion of the frontal dune but does not maintain the beach and must be combined with hard defences to prevent shoreline recession. Beach nourishment is not without effects, including changes in the morphology and habitats in offshore borrow placement areas or potential changes in sediment size and mineralogy (Nordstrom, 2021).

Coastal defences result in shoreline stabilization along transgressive exposed shorelines (negative feedback), but favour sediment fill in sheltered environments (positive feedback, see previous section). Hard defences along beaches generate negative side effects, particularly a decrease in beach width, and consequently a decrease in coastal habitats and attractivity (Fig. 7.B). The disappearance of intertidal habitats in connection with anthropogenic pressure is called “coastal squeeze” (Pontee, 2013). Beach nourishment has less negative side effects but is costly and

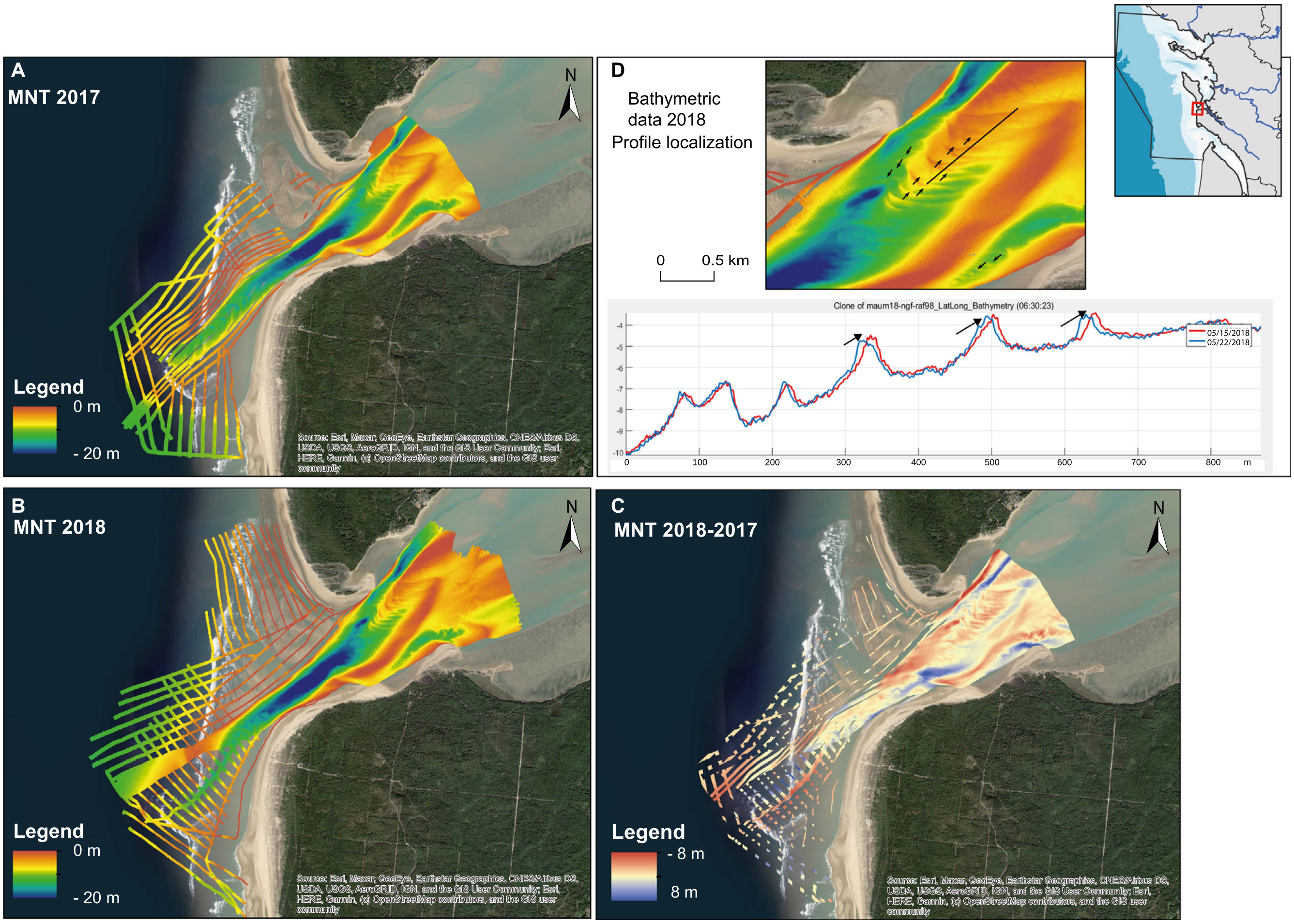

Fig. 5. Bathymetric data collected in the Maumusson Inlet. A) Bathymetric map of 2017; B) Bathymetric map of 2018; C) Difference in the bathymetric maps between 2018 and 2017. D) Bathymetric profiles showing the residual sand transport direction and the subaqueous dune migration between the 15th and 22th of May 2018. The location of the bathymetric profiles is shown on the bathymetric map of 2018.

cannot be considered extensively at the scale of the 1100 km long GPMP shoreline.

In this context of coastal erosion, the aim of the French "Littoral law" is to regulate coastal development with the implementation in 1975 of a public establishment: the "Coastal Conservatory". The purpose of this "Coastal Conservatory" is to buy coastal lands to protect and/or restore them (Law No. 86-2 of January 3, 1986 relating to the development, protection and enhancement of the coast). Beyond these protected areas (13 % of the metropolitan French coasts), our recommendation is to give broader consideration to strategic retreat and the development of natural coastal ecosystems as an adaptation to climate change. Focusing on eroding beach barrier ecosystems, maintaining a non-urbanised back barrier area provides space for barrier roll-over (Arens et al., 2013).

5.3. Harbour development and dredging

The complex and indented shoreline of the GPMP, with its flooded incised valleys (Fig. 2), has provided an optimal geomorphological setting for the development of many harbours. Today, 60 harbours are localized in the GPMP. They are currently of various sizes and are devoted to trade, fishing, shellfish farming and yachting. La Rochelle and Bordeaux are the 6th and 7th largest French commercial harbours, respectively. The yachting harbour of La Rochelle (Les Minimes) is one of the largest yachting harbours in Europe. Harbours developed early during antiquity in the GPMP (*Portus Santonum*, Mathé et al., 2020). During the 15th century, the GPMP domain was very busy (Acerra and Sauzeau, 2012). For example, Brouage Harbour was established during the 15th century and became active and famous in Europe for the trade of salt, wine and later on (18th century), for mussels (Papy, 1935; Camus et al., 2014). The Brouage Channel was dredged to maintain access for navigation, but progressive siltation led to channel sediment fill and the abandonment of Brouage Harbour (Papy, 1935).

Dredging to enlarge and deepen access levels for large vessels has increased drastically since the early 20th century. Annually, the dredged sediment volume reaches approximately 600.10^6 m^3 worldwide (Kasmi et al., 2017). In the GPMP, dredging volumes reach approximately 1 and 10.10^6 m^3/yr for the Charente and Gironde estuaries, respectively (Fig. 1.A.C), corresponding to about 34 % of the total dredged volume in France. The dredged material is dumped by immersion or used locally for beach nourishment (see previous section). Dumping sites are chosen based on knowledge of the hydrodynamics and sediment transport pathways. Immersion sites are chosen downstream of the dredging areas in dispersive areas so as to avoid rapid refilling of channels and harbours and to promote a cost/efficiency compromise. For example, between 2002 and 2018 5.10^6 m^3 of fine sediment was dumped offshore from La Rochelle Harbour (Fig. 1.C), close to an incised-valley segment where tidal currents are powerful (Volume from an impact study report carried out by the Atlantic port in 2018 (grey literature), in accordance with the declaration made to the Departmental Directorate of Territories and the Sea - DDTM). Within the GPMP, dredging and dumping can remobilize elements trapped in fine sediments, such as cadmium originating from the Garonne and Charente Rivers (Fig. 2; Dabrin et al., 2014). Cadmium can have a severe impact on shellfish farming, leading to inedible shellfish when the concentration is too high (Strady et al., 2011). Indeed, the European community has set

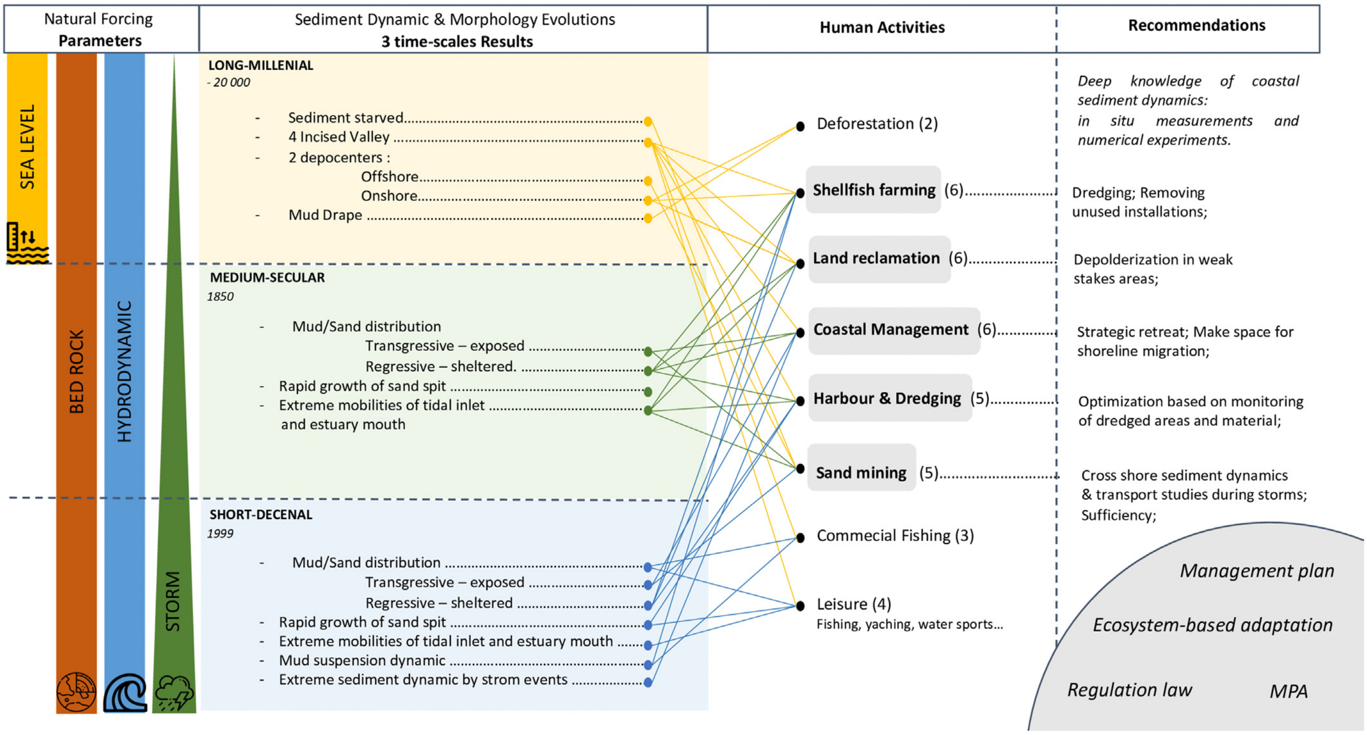

Fig. 6. Diagram of the relationships at 3 time scales between sediment dynamics, morphological change and human activities within the GPMP.

up a classification based on the concentration of Cadmium above a consumption standard (1 $\mu g.g^{-1}$ fresh weight), making the production and consumption of shellfish prohibited (Ministerial order of July 2, 1996 setting the health criteria that must be met by live shellfish intended for immediate human consumption).

Dredging and dumping operations are therefore governed by regulatory thresholds with regard to potential contamination. Channel deepening also impacts tidal propagation and can increase tidal range (Dam et al., 2013; Winterwerp et al., 2013). Within the Gironde Estuary, the tide increased by 12–15 % upstream between 1953 and 2014 due to morphological changes (Jalón-Rojas et al., 2018). However, the consequences of deepening operations alone have not been documented in the Gironde estuary and should be investigated.

Most of the harbours within the GPMP have been placed in sheltered environments prone to siltation and sediment fill. Dredging activities counteract this tendency and can be considered as a negative feedback effect on

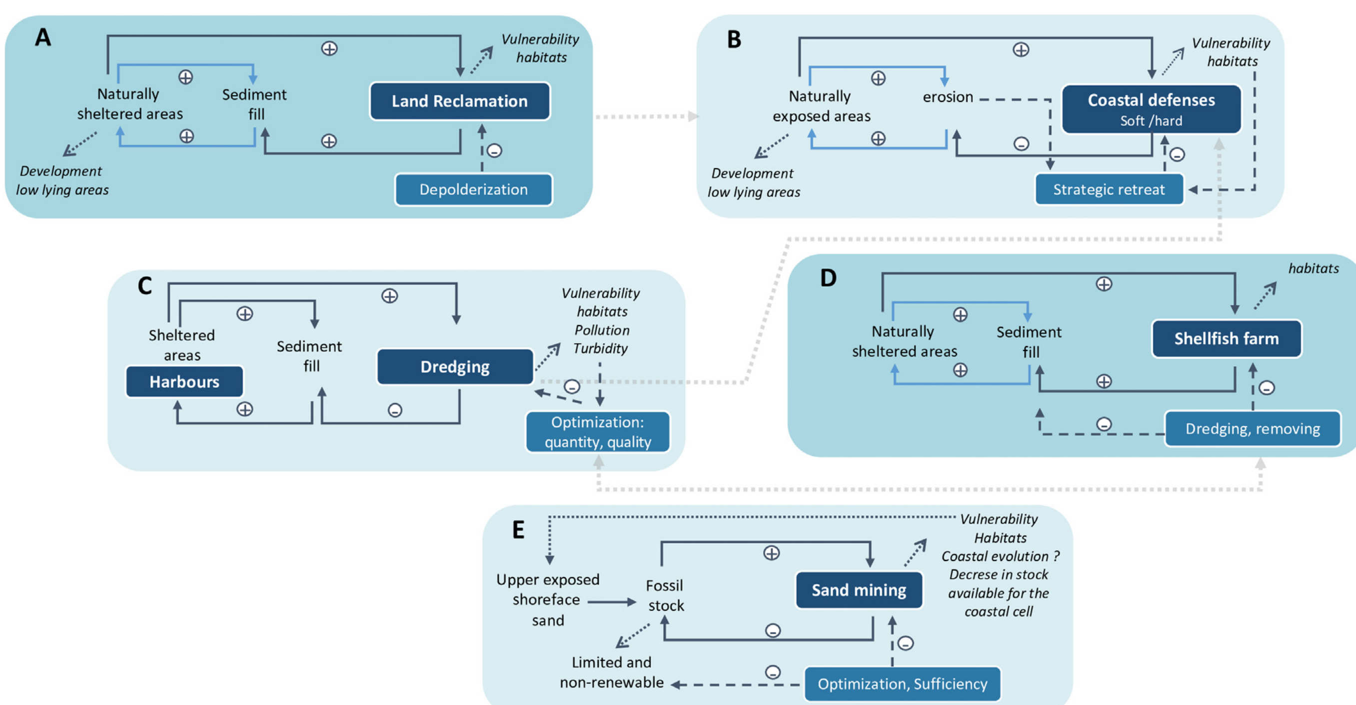

Fig. 7. Diagrams of the relationship and feedback loops between morphological change and five human activities heavily dependent on sediment dynamics: A) Land Reclamation; B) Coastal defences; C) Harbour development and dredging; D) Shellfish farming; E) Sand mining.

natural sediment fill. Nevertheless, dredging activities generate several side effects, in particular an increase in turbidity which impacts habitats and remobilizes the pollutants contained in the mud (Cooper et al., 2011). In order to reduce these negative side effects, our recommendation is to optimize dredging operations based on detailed knowledge of: (1) sediment dynamics based on both in situ measurements and numerical modeling; and (2) the nature and level of contamination of the sediments to be extracted (Fig. 7.C). In this regard, the Charente-Maritime Departmental Council, the marina of La Rochelle and the "Grand Port Maritime" of La Rochelle have implemented a management plan for dredging.

5.4. Management of Shellfish farms

Coastal aquaculture is now an important economic activity, with 82 million tons of aquatic organisms farmed around the world in 2018 (FAO, 2012, 2020). Extensive shallow and intertidal muddy environments in the GPMP are areas of strong bioproductivity and are particularly favourable for shellfish farming (Healy et al., 2002; Savelli et al., 2019). Oyster farms are mainly distributed in the estuaries and tidal bays of the GPMP (Fig. 1.C). Historically, oysters and mussels have been present in the GPMP at least since prehistoric times (Gutiérrez-Zugasti et al., 2011). In France, the culture of this shellfish resource started during the 13th century and was industrialized around 1860 (Bonnet and Troadec, 1985). Today, the Marennes-Oléron Bay is the leading oyster farming area in Europe, with an annual production of 40,000 tons in 2014 (AGRESTE, 2015). Intensive mussel farming is a major industry in the Pertuis Breton, Pertuis d'Antioche and Aiguillon Cove (Fig. 1). This industry has played a critical role in shaping the environment as well as the social and economic organization of the local populations (Goulletquer and Le Moine, 2002). Shellfish farms, whether they are permanent or temporary, have an impact on sedimentation by modifying the bathymetry, increasing bottom roughness and reducing currents by bottom friction. The intensive production of filter-feeding organisms in sheltered marine waters promotes the accumulation of mud rich in organic matter (Sornin, 1981). Concentrations of shells favours the strong sedimentation of fine particles by trapping bio-aggregates, which are difficult to remobilize (Sauriau et al., 1998; Bergström et al., 2020). Shellfish farms act as a hydrodynamic obstacle (Wang and Shen, 1999; Birben et al., 2007) and can reduce the speed of tidal currents by 50 % and wave height by 30 to 50 % (Sornin, 1981), thus reducing the resuspension potential of sediments by currents (Kervella, 2009). In the Marennes-Oléron Bay, where shellfish farming covers 20 % of its total area, the volume of sediments built up by oyster farming since 1824 is estimated at 35.10^6 m^3, i.e. 30 % of the volume of sediments deposited in the bay (Bertin et al., 2005; Bertin and Chaumillon, 2006). Sedimentation is a threat to sustainable shellfish farming. Thus, to prevent rapid sediment fill, oyster farm management actions include: (1) dredging between shellfish farms (Mercaldo-Allen and Goldberg, 2011); (2) removing unused shellfish farms; (3) removing shellfish farms during winter, a period of strong sediment remobilization; (4) removing wild oyster reefs which grow on mudflats; and (5) developing tidal leasing grounds and offshore production in order to decrease the biomass stocked in intertidal zones (Goulletquer and Le Moine, 2002).

Extensive shallow intertidal areas and bays in the GPMP favoured the development of shellfish farming in these naturally regressive areas. In turn, this activity increased sedimentation following a positive feedback loop (Fig. 7.D). This positive feedback induces an instability and threatens the sustainable development of shellfish farming. Faced with this instability, several management actions are designed to prevent fast sedimentation in shellfish farms and can be considered as self-regulation.

5.5. Management of sand mining areas

Sand mining is increasing worldwide (Peduzzi, 2014) in relation to the growing population in coastal areas. The GPMP is no exception to this rule, with three main sand mining areas. Although offshore sand mining in France only represents 2 % of French sand production, 18.10^6 t/yr of marine sediment were extracted between 2000 and 2019, with $1.8.10^6$ t/yr in the GPMP (https://www.unpg.fr/wp-content/uploads/unpg-chiffres-2019-web.pdf). Sand mining areas in the GPMP are located in marine segments of incised valleys where fossil sand accumulation constitutes an ideal resource (Weber et al., 2004a; Chaumillon and Weber, 2006). The largest volumes of sand are extracted in the outer Charente incised-valley, with $1.4.10^6$ m^3/yr maximum allowed (Chassiron Concession, Fig. 3). In the example of the mining area "B" (Fig. 3), the sand volume calculated from differences between the bathymetric maps of 2016 and 2019 is 15 % lower than the extracted sand volume. This difference can be explained mainly by sand trapping within this pit, estimated at about 40,000 m^3/yr. Nevertheless, the presence of subaqueous sand dunes with morphologies recording a residual shoreward sand transport (Fig. 3), both in the western and eastern part of the pit, indicate that beyond sand trapping, a certain quantity of sand moves shoreward, out from the pit. This example also shows that substantial morphological change can take place below the depth of closure (Hallermeier, 1980), which is estimated at −14 m for the French Atlantic coast (Pezerat, 2022). Similar observations have been reported in other studies (Anthony and Aagaard, 2020). Although, the depth of closure is used as a recommended limit for sand mining, (Hallermeier, 1980) it would seem more appropriate to consider the wave base definition as cross boundary. Wave changes due to pits in Chassiron were modelled (ARTELIA, 2021) and the results showed that changes in wave conditions are restricted to 3 km shoreward of the pits. For storm conditions, bathymetric deepening also induces a local increase in wave height (ARTELIA, 2021). Moreover, the increase in turbidity related to dredging in the Chassiron mining area seems to be localized and reduced in time and space due to a low proportion of fine sediments. Given the moderate impacts of pits on sediment dynamics shoreward of the Chassiron area, sand mining was authorized in 2022 (*https://parc-marin-gironde-pertuis.fr/actualites/le-conseil-de-gestion-emet-2-avis-conformes-favorables*). In contrast, another sand mining project, within the mouth of the Gironde Estuary (Matelier) and at a similar water depth (−20 m bsl), was refused an authorization in 2018 (*https://parc-marin-gironde-pertuis.fr/actualite/avis-conforme-defavorable-au-projet-dextraction-de-granulats-marins-sur-le-gisement-du*) because it was considered to be too close to the shoreline and contrary to the objectives of preserving marine habitats. The complexity of sediment dynamics in this wide estuary mouth (Mallet et al., 2000) together with the huge erosion rates along the adjacent coastlines (Chaumillon et al., 2019b) were also cited as arguments against sand mining in this area.

Pits related to sand extraction are naturally filled by sand eroded from the surrounding seafloor, showing a tendency to restore the bathymetry as it was before extraction (Van Rijn et al., 2005; Garel et al., 2009). This behaviour can be considered as a negative feedback mechanism leading to the restauration of the shoreface balance profile. Nevertheless, over the long term, sand filling of pits may also induce sand loss for natural beach nourishment (Hamon-Kerivel et al., 2020) and a lack of balance for the sediment budget of the coastal system. Accelerating sand mining clearly exceeds natural renewal rates and may impact the coastal sediment budget. In this way, sand mining has negative effects on coastal ecosystems (Fig. 7.E). An assessment of the impact of sand mining on coastal areas is still limited by our incomplete knowledge of cross-shore sediment transport, particularly during storms, due to the lack of in situ measurements. Indeed, there is a need to continue the study of sediment dynamics and morphological change in the shoreface domain. Present-day impact studies made by technical consultants compare the impacts of future sand mining with the current state, namely an already dredged shoreface with deep pits. The initial state (shoreface without pits) is not considered, which limits the assessment of the impact of sand mining. Our recommendation is to consider the initial state in order to avoid the "shifting baseline syndrome" (Soga and Gaston, 2018). Given the non-renewable nature of shoreface sands and the increasing demand for housing and construction along the coastline, sand mining should be limited, the use of sand restricted to essential construction (sufficiency) and the use of recycled material must be increased.

6. Conclusion

This review provides for the first time an overview of the morphological change and sediment dynamics of the GPMP, a marine park located along the southwest French Atlantic coastline. The aim of this overview is to provide a scientific basis to help manage ecosystem protection together with the development of human activities. With 6 estuaries, a 1100 km-long indented shoreline and many human activities, the GPMP may provide a reference site for a large variety of coastal MPAs.

The first key-message from this synthesis is that, although long-term change covers much longer periods than those typically considered for coastal management and human activities, it must be carefully investigated because it exerts a strong control on change over shorter time scales and on many human activities. As a result, incised valleys and their sediment fill control the large-scale morphology of the coastline and inner shelf, which themselves control many human activities such as the location of harbours, land reclaimed areas and shellfish farms in sheltered areas, and sand mining in the shoreface domain of valley-fills. Thus, antecedent bedrock morphology is a key controlling parameter at every time scale. In view of the extensive development of mixed rocky and sedimentary coasts around the world, such a result is critically important and transferable to many MPAs. Despite its importance, this controlling parameter is neglected in numerical experiments, which usually focus on short time scales. In our review, we emphasize the importance of considering the control exercised by the antecedent morphology and geology of a bay on coastal behaviour and human activities.

This synthesis also provides a basis for exploring some relationships and feedback mechanisms between natural coastal processes and human activities, as evidenced in the GPMP. Beyond their application to local management issues, these relationships are transferable to other MPAs. Sheltered areas (estuaries and bays), where natural sedimentation induces regression, favour the development of land reclamation and shellfish farming. Many examples can be found worldwide with extensive land reclaimed areas and a huge development of shellfish farms in estuaries, bays, rias and fjords. These activities result in positive feedbacks because they favour sedimentation, but they are leading to a loss of balance. Depolderization, dredging within shellfish farms and removing unused shellfish farms are examples of management issues that can help to counteract these positive feedbacks. Coastal defences and dredging in harbours and navigation channels are common worldwide. They both involve negative feedback as they tend to stabilize geomorphology by fighting against erosion or sediment deposition, respectively. However, they have several side effects on habitats. Protecting all world coastlines against erosion is unrealistic. Thus, a strategic retreat should be considered. Increasing shipping activity and harbour development is associated with huge dredging volumes leading to pollution and increased turbidity. Monitoring and regulation plans are needed to limit these side effects. Sand mining is increasing exponentially worldwide. Sea floor deepening after sand mining tends to be filled by sediments eroded in surrounding areas, leading to the restoration of a balanced shoreface profile following a self-regulation mechanism. Nevertheless, sand mining exceeds natural renewal rates and has a negative impact on the long-term stability of coastal ecosystems. There is an urgent need for a regulation of this activity at a global scale.

Because of their impact on coastal ecosystems (positive feedback mechanisms and instabilities, pollution, habitat destruction, and a decrease in non-renewable resources), these activities are at the heart of conflicts of use. This implies a regulatory framework and decisions by MPA management committees. These decisions must be based on shared knowledge of relationships between human activities and coastal ecosystem behaviour at different time scales. In this regard, knowledge syntheses, like this review, are essential. They should be implemented in all MPAs. Stabilization is not always possible in MPAs where strong sedimentary and shoreline dynamics occur. Then the question of "laissez-faire" and nature-based solutions, which require space, community involvement, land rights and economic incentives, arises. In this regard, coastal defence realignment and the restauration of ecosystems, particularly sedimentary barriers and coastal wetlands, should be increasingly considered as solutions for balancing habitat protection and human activities. From this overview, it appears that faced with the increasing costs of coastal defences against sea level rise, and the growing population along the shoreline, ecosystem-based adaptation brings multiple co-benefits, such as: shoreline stabilization, coastal resilience, protection from floods, improved water quality, carbon storage, increased biodiversity, and the preservation of natural heritage and human health. One of the key aspects of ecosystem-based adaptation is the role of sediments in shaping and maintaining coastal ecosystems. Sediments are essential building blocks of beaches, dunes and wetlands, and they play a critical role in coastal processes such as erosion, accretion and sedimentation. The availability and quality of sediment resources may significantly affect the success of ecosystem-based adaptation measures, and understanding sediment dynamics and budgets is crucial for effective planning and implementation of ecosystem-based adaptation projects.

To sum up, a comprehensive understanding of sediment dynamics is a key component of successful coastal ecosystem-based adaptation strategies as it can help to ensure the long-term resilience and sustainability of coastal ecosystems, while also providing a range of co-benefits for both nature and people.

CRediT authorship contribution statement

A. Schmitt: Conceptualization, Writing – original draft, Investigation, Writing – review & editing. **E. Chaumillon:** Conceptualization, Writing – original draft, Investigation, Validation, Resources, Supervision.

Data availability

Data will be made available on request.

Declaration of competing interest

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