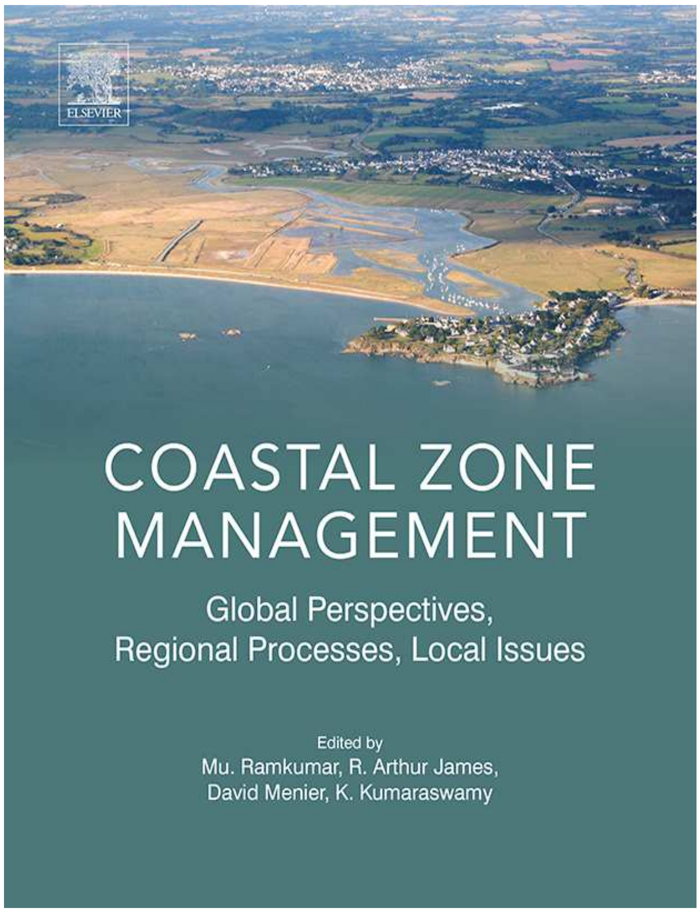

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CHAPTER 8

Influences of Inherited Structures, and Longshore Hydrodynamics Over the Spatio-Temporal Coastal Dynamics Along the Gâvres-Penthièvre, South Brittany, France

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1 Introduction

Coastal systems function over a variety of temporal and spatial scales, owing to the diversified interactions between topography, sedimentary, and hydrodynamic processes that lead to changes in coastal landforms, ranging from the instantaneous to the geological scale (Cowell and Thom, 1994). Documentation of these temporal and spatial scales enhances our understanding of sediment transport trends and the evolution of coastal landscapes (Schwarzer et al., 2003). Numerous studies have been carried out to assess the shorter time scales' morphodynamic behavior of beaches and their topographic responses to changing sedimentation, and wave and tidal current conditions (Levoy et al., 1998; Ramkumar, 2000, 2003; Wijnberg and Kroon, 2002; Masselink et al., 2006; Ramkumar, 2015; Ramkumar et al., 2015). Over longer periods of time and larger spatial scales, coastal changes are assessed within the scope of the sediment cell concept (Stapor and May, 1983; Bray et al., 1995). A coastal segment is an area where sediment are moved updrift to downdrift by alongshore currents, leading to beach erosion and accretion (Carter, 1999). These studies also include analysis of coastline variations measured using remote sensing and aerial photography data (Ruggiero et al., 2003; Ferreira et al., 2006). Factors driving coastal changes over a regional scale refer to a wide range of data, which can be addressed through the use of GIS (Robin and Gourmelon, 2005). Although various authors have discussed the benefits of such a tool for improving the

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understanding of coastal system behavior (Robin and Gourmelon, 2005), only a few studies have taken advantage of its new analytical applications. For example, Anfuso et al. (2007) used both GIS facilities and field data to assess the medium- and short-term coastal morphological evolution of Moroccan beaches located between Ceuta and Cabo, and Backstrom et al. (2009) and Dawson and Smithers (2010) used GIS to assess topographic evolution. In most cases, however, the use of GIS in coastal studies is restricted to coastal management and risk analyses (Brown, 2006; Rodriguez et al., 2009). The study described in this chapter focuses on evolution of the Gâvres-Penthièvre beach-dune system, located in South Brittany; Northwestern France (Fig. 1). Over a regional scale, the South Brittany coast displays specific morphological characteristics, including the roughness of the coast and the presence of nearshore and offshore bedrocks (Pian, 2010; Menier et al., 2010; Dubois et al., 2011). The Gâvres-Penthièvre sand dune extends over >50 km between the Gâvres and Penthièvre headlands. It represents the only sandy coastline at South Brittany mainly composed of beaches backed by sand dunes and orientated oblique to the prevailing wind and wave directions. In spite of these peculiar regional morphological features, except the works of Pinot (1974) and Vanney (1977), no systematic studies have ever been made. Using both field data and a set of spatial data supporting spatial analyses, the study aims at identifying the main direction of sediment transport schemes driving coastal changes at different time and space scales with an objective to evaluate the beach evolution, for which suitable management programs can be planned.

2 Regional Setting

The study area is located in South Brittany and extends for about 50 km SW between the Gâvres headland in the north and the Penthièvre isthmus toward the south. It consists of sandy beaches backed by sand dunes. The coastline is interrupted by the Etel Ria (Menier et al., 2006; Estournès et al., 2012) (Fig. 2). On the Gâvres headland (Fig. 2), there are cliffs that are approximately 3 M high that consist of weathered periglacial deposits (Horrenberger, 1972). On the western part of this headland, a climbing dune has developed covering the top of the cliffs. The foot of the cliff is fronted by pocket beaches, partly fed by the material eroded from the cliffs. At Gâvres, the beach is backed by a sea wall. Over the entire beach-dune system, sediment grain size is heterogeneous, ranging from fine to coarse sand and pebble (Estournès et al., 2012). The beach faces are wave-dominated, with coarser material deposited on the upper part of the beaches.

Offshore outcrops and a rocky barrier running parallel to the coastline act as a buffer and reduce the energy of the waves (Vanney, 1977) reaching the coast. Based on previous analyses of bathymetric data, Pinot (1974) identified a slope-break at around 17 m water depth. More recent grain-size and bathymetric analyses confirmed the prevalence of closure depth at about 15–20 m off the Gavres Peninsula and the Penthièvre Isthmus (Estournès et al., 2012). Migniot (1989) analyzed sediment movements near the shore and proposed that around 6000 m^3/yr of

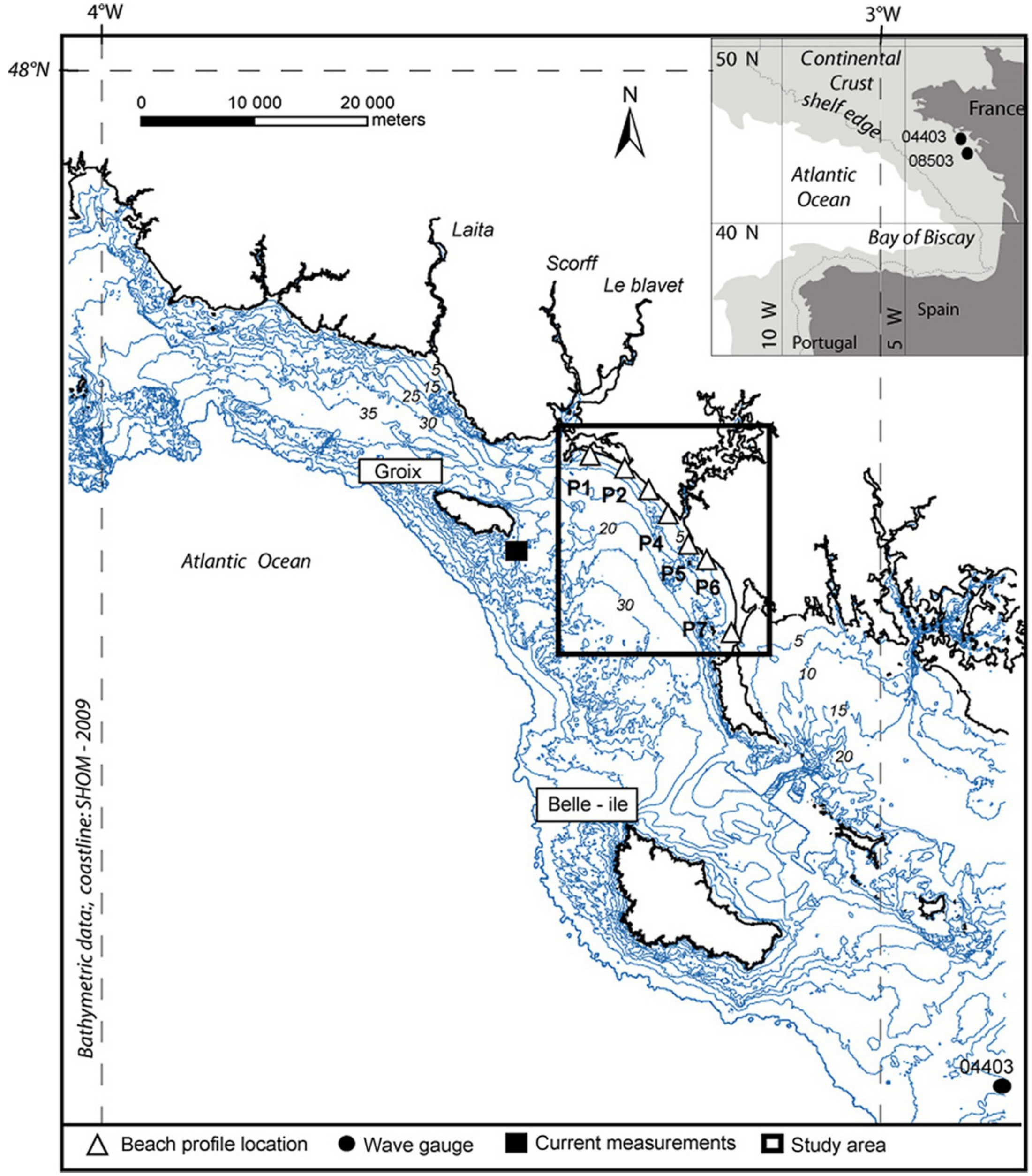


Fig. 1
Location map of the study area.

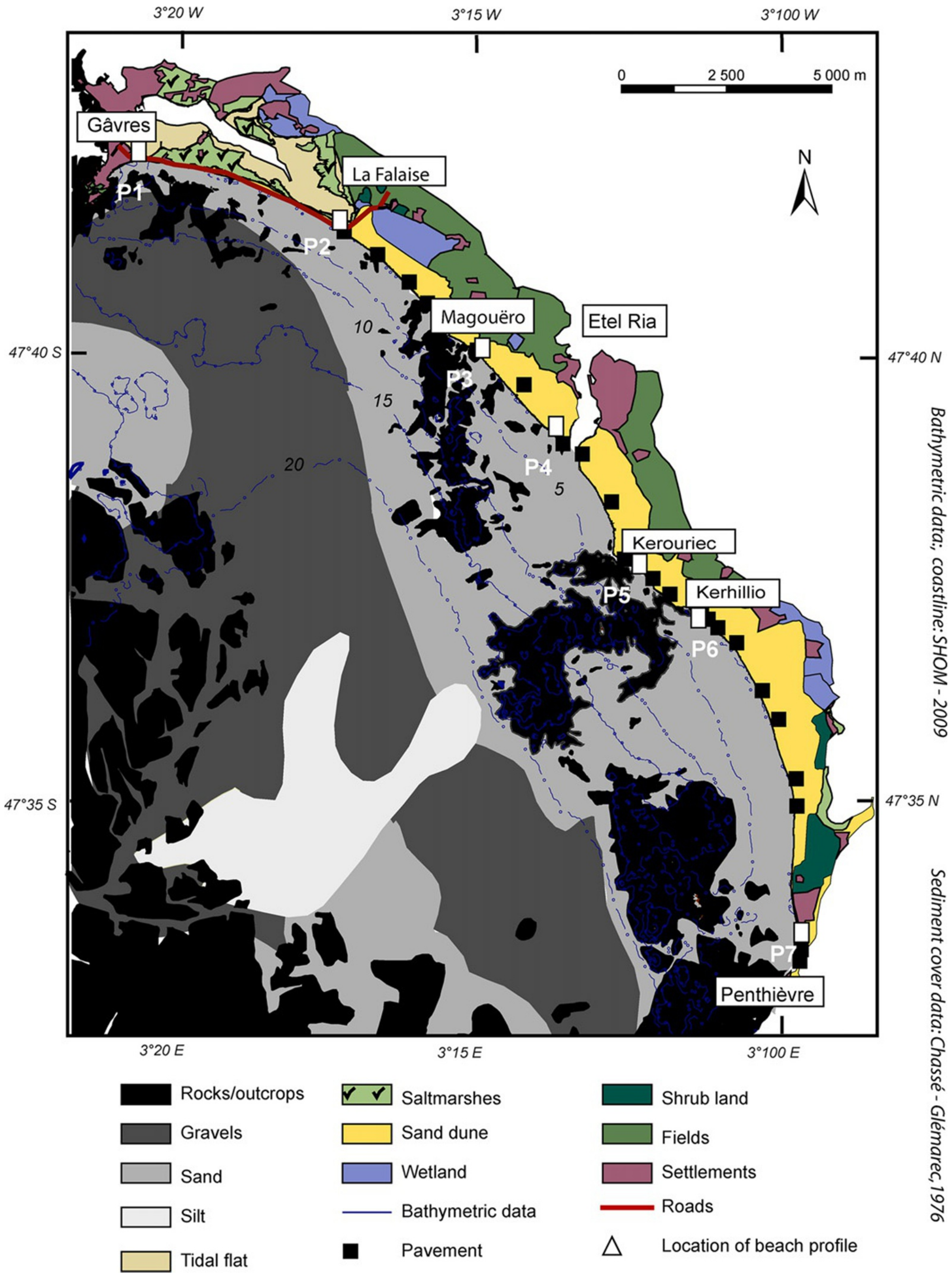


Fig. 2
Geomorphological setting of the Gâvres Penthièvre beach-dune system.

sediments are transported from Gâvres to the Etel Ria by a south-easterly longshore drift confirming the results of previous studies (Pinot, 1974; Bos and Quélennec, 1988).

Typical of the southern coast of Brittany, the studied area is subjected to westerly and southerly winds (Fig. 1). Wind records at Belle-Ile, about 30 km offshore from the studied sites, indicate that the strongest winds blow from the south and the west (Pirazzoli et al., 2004). These winds are generated by a high-pressure center, located south of Morocco and Spain, combined with a low-pressure area close to the English Channel and British Isles. Prevailing waves are characterized by a height ranging from 0.5 to 2.5 m with a period of 5–9 s. They mainly propagate from the northwest and west (Fig. 1). The most energetic waves, with a significant height of >9 m, show an annual periodicity and generally reach the coast from the west and southwest (Tessier, 2006).

3 Material and Methods

Currents, aerial photographs, and spatial data were used to assess coastal changes on a wider spatial scale and longer time scales using GIS spatial analysis. Beach profiles, and wind and wave records were used to analyze coastal changes over a shorter time scale.

3.1 Waves and Currents

Wave data were obtained from two offshore buoys, named l'Iled'Yeu Nord (8503) and Le plateau du Four (04403), which are owned by CETMEF (Centre d'Etudes Techniques Maritimes Et Fluviales), the French national office for shipping and river studies. Wave data are incorporated within the CANDHIS (Centre d'Archivage National de Données de Houle In-Situ) database managed by the CETMEF. The wave characteristics used here include significant wave height (H_s) and its associated period (T_s) recorded from March 2008 to March 2009, except for February 2009, due to a temporary interruption in buoy records. Wind data were provided by the METEO France database and cover the whole period (March 2008–March 2009) of beach surveying. The data were recorded at Le Talut station, located on the south coast of Belle Isle.

Current data were derived from the Mars S4 hydro-numerical model, set up by the design office SAFEGE (2008) (multidisciplinary engineering subsidiary of SUEZ Environment), which aims at modeling the main direction of coastal currents according to tide, wave, and wind data. The model was built over a grid of 100 m cell size, extending between the coordinates: 47°49′13 N, 47°19′22 N, 3°7′17 W, and 3°29'31 W, including offshore, shallow, and coastal waters. Tidal current direction and intensity were modeled using a 2-D depth approach and assessed with current data obtained from an ADCP (Acoustic Doppler Current Profiler) deployed at a water depth of 12.5 m. Based on the current data, sediment transport simulations were carried out using the Inglis and Lacey method. Correlations between modeled and measured data were tested for three different periods characterized by different tidal stages and wind conditions. Results show that current intensity is correctly described by the model, but current directions vary according to the wind direction. Hence, many simulations were undertaken using the 3-D depth approach for different wave and wind directions and intensities. They suggested that refraction of prevailing waves induced the coastal waves and currents, and orientated the longshore with wave convergence around the Gâvres and Magouëro headlands. Residual current direction in shallow waters is strongly controlled by wind direction. The South Brittany Coast is exposed to prevailing winds blowing from the west, and the coastline forms a vast curb that is southwest orientated, suggesting that coastal currents in shallow waters are frequently orientated toward the southeast. Such assertion agrees with previous empirical observations made along the coastline over a regional scale (Bos and Quélennec, 1988; Migniot, 1989).

3.2 Analyses of Beach Changes Over a Short Time Scale

To analyze seasonal beach changes, a beach monitoring program was carried out from March 2008 to May 2009. Seven beaches were surveyed at intervals of 2 months. Twenty-seven beach profiles were leveled from the toe of the dune to the water level line using a TRIMBLE electronic theodolite. For each site, the theodolite was placed on a fixed feature, and the location was carefully recorded using D-GPS data, marked with visual indicators, and referenced to a benchmark of the French National Geodetic Service (I.G.N. 69). The location of each beach profile was defined according to coastline orientation and nearshore morphology in order to monitor foreshores likely to record significant changes in regard to sediment transport schemes.

The coastline orientation, distribution of nearshore bedrocks, and beach access were considered for the distribution of beach profile sampling along the coastline. After Dail et al. (2000), Masselink and Pattiaratchi (2001), Sedrati and Anthony (2008), or Frihy et al. (2008) the temporal variations of offshore significant wave height (H_s) and period (T_s) (Fig. 3) were used to characterize hydrodynamic conditions prevalent during each survey period and interpret the morphodynamic changes. The dates of each beach survey are reported on the graphs describing the wave and wind regimes (Figs. 3 and 4), and categorized into six survey periods (SP1-SP6).

The first survey period (SP1), which ended in March 2008, was characterized by extremely rough weather conditions associated with the most severe storm of the period under study (Cariolet et al., 2010), with significant wave height (H_s) higher than 2.5 m (Fig. 3) and strong southwesterly winds (Fig. 3) exceeding speeds of 12 m s^{-1}. This storm occurred during spring high tide, leading to a storm surge of >3.80 m according to PREVIMER (FRENCH PRE-OPERATIONAL COASTAL OCEAN FORECASTING) wave modeling data (2008). No similar storm surge was recorded during the period of beach survey. The second survey period (SP2) extended from March 27, 2008, to June 23, 2008. It was characterized by two important subperiods of about a month and a half each. The first subperiod ended in May 2008, and was

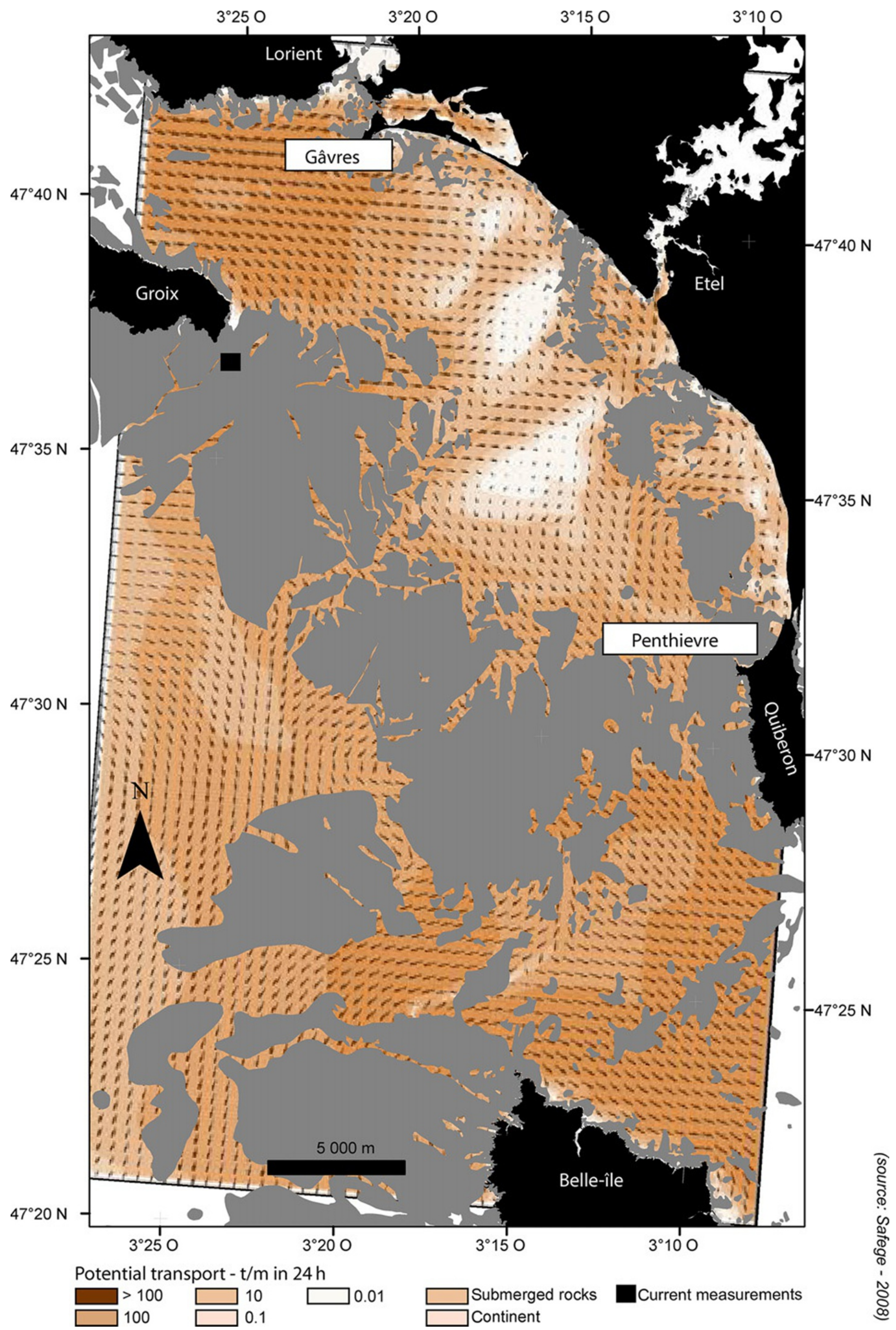


Fig. 3
Variations in wave characteristics between February 2008 and May 2009.

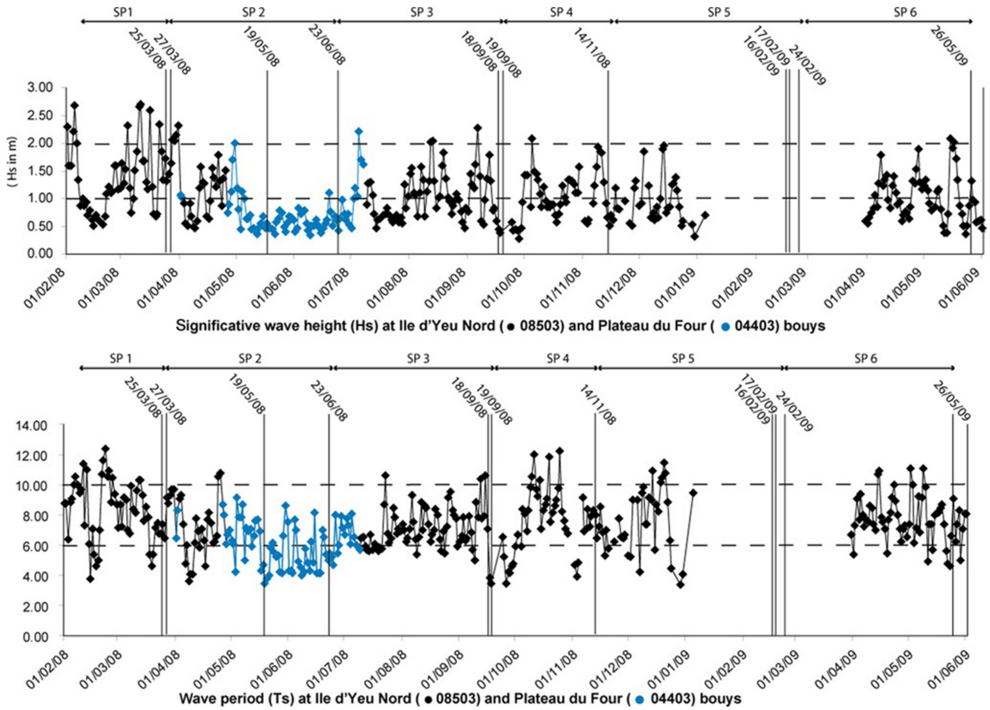


Fig. 4

Variations in wind characteristics between February 2008 and May 2009.

associated with rough weather conditions: H_s was comprised between 1 and 2 m, wind speed between 10 and 15 m s^{-1}, with winds flowing mainly from the southwest. The second subperiod ended in July 2008, and was characterized by fair weather conditions with easterly winds with speeds that did not exceed 10 m s^{-1}, and modal wave conditions with a mean H_s of 0.50 m. The third period (SP3) started in June 2008 and ended on September 19, 2008. It was characterized by agitated conditions with H_s between 1 and 2 m during most of the survey period. Three storms with H_s exceeding 2 m occurred in July, August, and September 2008. During the storm events, winds flew from the northwest and the southwest. At the end of July, a period of more modal wave conditions occurred with H_s <1 m, and accompanied easterly and northeasterly winds. The fourth survey period (SP4) extended from the September 19, 2008 to the November 14, 2008. It is characterized by two storms (H_s > 2 m and T_s > 10 s) occurring at the beginning of October 2008 and at the end of November 2008. These storms were associated with strong northwesterly and southwesterly winds, respectively. Agitated wave conditions occurred a few days after and before these storms. Between these two agitated subperiods, fair weather wave conditions prevailed. The fifth survey period (SP5) extended from November 14, 2008 to

February 24, 2009. For this survey period, wave data are not available. In early December, the wave conditions were characterized by the occurrence of two storms ($H_s > 2$ m and T_s comprised between 8 and 11 s) during 1 and 2 days, respectively, dominated by strong southeasterly winds. These storms were followed by several days of fair weather conditions. Then, the last 2 weeks of December 2008 were characterized by fair weather conditions, with easterly winds with a mean speed of $<10\,\mathrm{m\,s^{-1}}$. The end of the period, in January 2009 and early February 2009, was characterized by more severe wind conditions. Wind speeds exceeded $20\,\mathrm{m\,s^{-1}}$ several times during this period. On the February 9, southwesterly winds exceeded a speed of $25\,\mathrm{m\,s^{-1}}$. These meteorological data suggest a prevalence of rough sea-surface conditions, associated with strong waves coming from the west. The sixth and last period of survey (SP6) ended on May 26, 2009, and only concerns the Penthièvre West Beach. In April 2009 and in May 2009, two storms occurred with $H_s > 2$ m and $T_s = 10$ s. The later storm continued for 3 days. The days following these storms were characterized by rough conditions. Winds were northwesterly and southwesterly. Between each of these severe episodes, a few days of fair weather conditions occurred.

3.3 Analysis of Coastline Variation

Coastal changes occurring on the spatial scale of the sediment cell were assessed through the use of spatial and aerial photographic data. Aerial photographs were used to estimate coastline variations over different time intervals, from 1952 to 2004, at a regional scale (Fletcher et al., 2003).

Spatial data were digitized both from existing maps and from the 2004 orthophotograph produced by the IGN (French National Geographic Institute). The orthophotographs were projected in the Lambert II extended geographic coordinate system, and then integrated within a GIS database (Pian and Menier, 2011). Offshore and nearshore bathymetric data were digitized from the bathymetric map sheets 7139L to 7144L published by the SHOM (Service Hydrographique and Océanographique de la Marine) and projected in the Lambert II extended geographic coordinate system. The scale of these maps ranges from 1:15,000 to 1:2000. Offshore and nearshore sediment cover was digitalized from published maps (Pinot, 1974; Chasse and Glémarec, 1976) and from the SHOM maps. Included within this layer is the information on the presence of submarine outcrops that, in turn, are likely to influence the wave refraction process in terms of wave convergence or divergence. Coastal morphology and orientation were digitized from the 2004 orthophotograph on two different polygon layers. Four data attributes were created to describe coastline morphology: beach, sand-dune, cliff, and salt marsh. Coastline orientation was digitized at a scale of 1:2000. At this scale, five orientations were recognized along the coast: southeast, south, southwest, west, and northwest. One of these orientations was assigned to each polygon as an attribute.

As the spatial migration of the coastline is an indicator of coastal change in the long- and medium-term, positions of the coastline were plotted on aerial photographs dating from 1952 to 2004. First, aerial photographs were scanned with a spatial resolution of 1200 and 1000 dpi. Then, each photograph was geo-rectified, using ArcGis9.2 software. For each photograph, between 12 and 15 ground control points were plotted from the orthophotograph taken in 2004. Then a second-degree transformation was applied. For each geo-rectified photograph, the RMS error is around 4 and the cell sizes varied from 0.68 to 0.96 m (Table 1). After geo-rectification, all photographs covering each site for a given year were assembled into a mosaic using Envi3.0 software. The vegetation covering the toe of the dune and the cliff top line were plotted onto each document (Kroon et al., 2008) as a polyline by means of the ArcGis Editor tool.

Then, the polylines representing the shoreline position for each site at two different dates were merged into a new layer using the ArcGis toolbox function, and then converted into a polygon layer. An attribute describing the direction of shoreline migration (accretion vs. erosion) was assigned to each polygon. This polygon layer was intersected with the polygon layer describing coastline morphology (Fig. 5). Thus, a polygon layer describing the migration of coastline features was obtained for each site and time interval. By measuring the polygon areas, surface area eroded or accreted for each site and each time interval was thus estimated. Before measuring the polygon areas, the margins of error linked to geo-rectification and digitalization processes were extracted from the polygons (Table 1).

3.4 Identification of Sediment Cell Boundaries

To explain both coastline advances and retreats, the position of the coastline within the sediment cell was assessed using GIS and spatial analysis techniques. Fig. 5 summarizes the operations carried out using these GIS layers to relate coastline variations with position within the sediment cells (Pian and Menier, 2011).

Bathymetry, sediment cover, coastline morphology, and orientation data were used to identify discontinuities in these transport patterns that are likely to represent the boundaries of coastal subcells or cells (Carter, 1986; Battiau-Queney et al., 2003). The GIS layers were overlaid onto the 2004 orthophotograph in order to identify the boundaries of the sedimentary cells. Then, the coastline was segmented into three sites according to position of each straight with respect to

Table 1 Error margins associated with georectification and digitization

Air Photograph	RMS Error (m)	Cell Size (m)	Margin of Error (m)
1952	3.60	0.77	4.37
1985	4.42	0.96	5.38
1999		0.50	0.50
2004		0.50	0.50

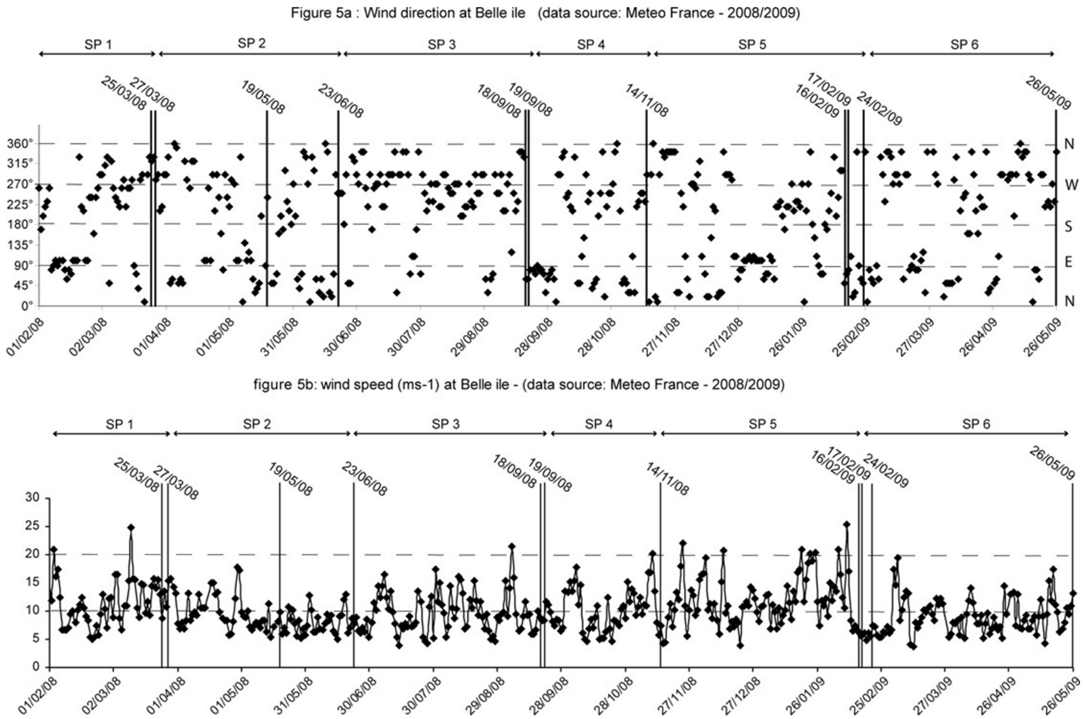


Fig. 5

Schematic diagram showing the relationships between GIS layers used to analyze coastline variations in relation to coastline position within sediment cells.

the boundaries of the sediment cells: (i) the source attribute refers to the sectors where the coastline evolution is mainly driven by coastal erosion processes, (ii) the sink attribute characterizes zones where sediments accumulate as a consequence of coastal currents, and (iii) transport areas are characterized by either temporal and spatial alternating sequences of erosion and accretion in time and space or minor coastal changes, both related to sediment input and output rhythms. Initially, based on current data, approximate coastal cell boundaries were defined: the northern part of the sand dune system is assimilated to a source area, the central part to a transport area, and the southern part to a sink area. This first delimitation was then refined by discontinuities likely to interfere with longshore sediment transport that allowed subdivision of the sediment cells into different units. These discontinuities include the Etel Ria, bathymetric variations controlling coastal currents convergence and divergence, and nearshore bedrocks and slight variations of the coastline at Kerhillio. Recognizing these sediment cell delimitations and discontinuities, each segment of the coastline was digitized either as source, transport, or sink site as a polygon layer. Using the identify function, this last polygon layer was intersected with each of the polygon layers describing the evolution of the coastline for a given time interval. The identity function allowed subdivision of a polygon layer according to the polygon boundaries stored in another polygon layer, and kept all the attribute values associated with both polygon layers. With this procedure, an attribute value was assigned to each polygon in relation to coastline variations, using it to describe the position of the coastline within the sediment cell. By the same method, attributes describing the orientation of the coastline were also associated with each polygon layer referring to coastline variations. These operations led to the construction of a spatial database describing the behavior of the coastline at different time intervals in relation to its morphology, orientation, and location within the sedimentary cell.

4 Results

4.1 Sediment Transport

In the most common fair weather conditions characterized by mean annual wave conditions and moderate westerly winds ($5\,\mathrm{m\,s^{-1}}$), sediment transport was found to be broadly oriented alongshore, in a southeasterly direction, except around Kerhillio Beach, where cross-shore sediment transport was locally dominant (Fig. 6). At Penthièvre, the longshore drift was northwesterly. Under storm conditions characterized by southwest waves with a period of 7 s and a height of 6 m, an alongshore coastal current orientated southeast was observed between the Gâvres headland and the Etel Ria. Between Etel Ria and Kerhillio Beach, offshore sediment transports occur. Under storm conditions characterized by westerly winds and waves, coastal currents in shallow waters were orientated southeast along the coastline.

4.2 Beach Profile Evolution

Beach profile variations were analyzed in relation to wave and wind regime changes (Figs. 3 and 4). Fig. 7 shows the observed variations in beach profiles (Pian et al., 2014). At Gâvres, the beach is backed by a sea wall. These profiles display the most pronounced vertical variations recorded along the beaches of the sand dune system. The vertical range of the profile envelope is about 2.5 m, and is located at the upper shoreface, between mean sea level (MSL) and the mean high water spring (MHWS) lying within the surf zone. Erosion prevailed between March 2008 and February 2009 (Fig. 7).

At La Falaise Beach, the profile is SW-NE oriented. The vertical range of the beach profile was about 1 m. The most marked beach profile variations were recorded on the lower shoreface, between the MSL and MLWS (mean low water spring). On the upper part of the profile, beach cusps and transverse bars were identified, especially during May 2008. Erosion prevailed between May 2008 and February 2009 (Fig. 7).

At Magouëro Beach, the profile was oriented SW-NE and embedded within a dense zone of emerged outcrops of bedrock (Fig. 2). The vertical range of the profile envelope was about 2 m. Except for the profile leveled in May 2008, beach profile variations were more pronounced

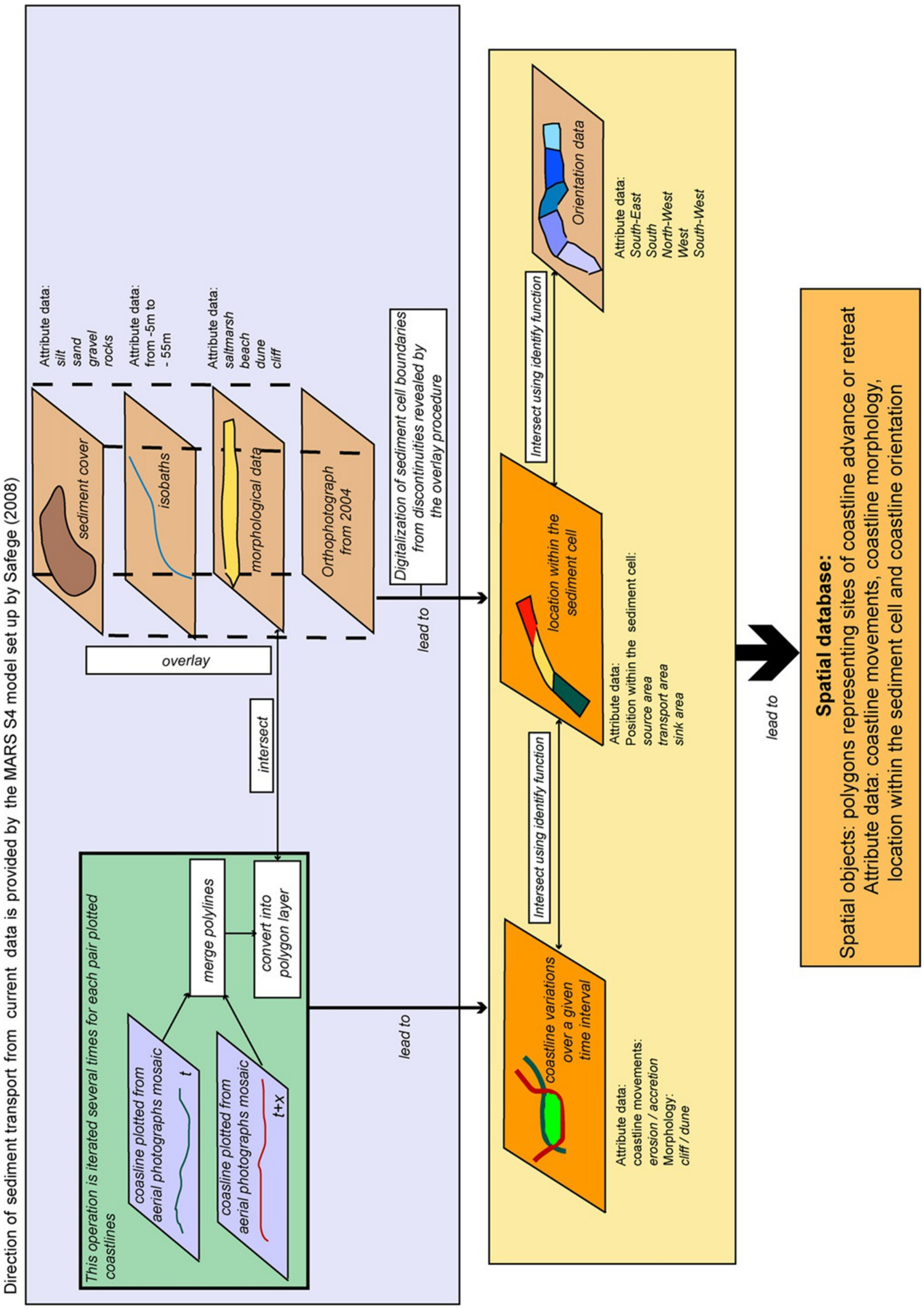
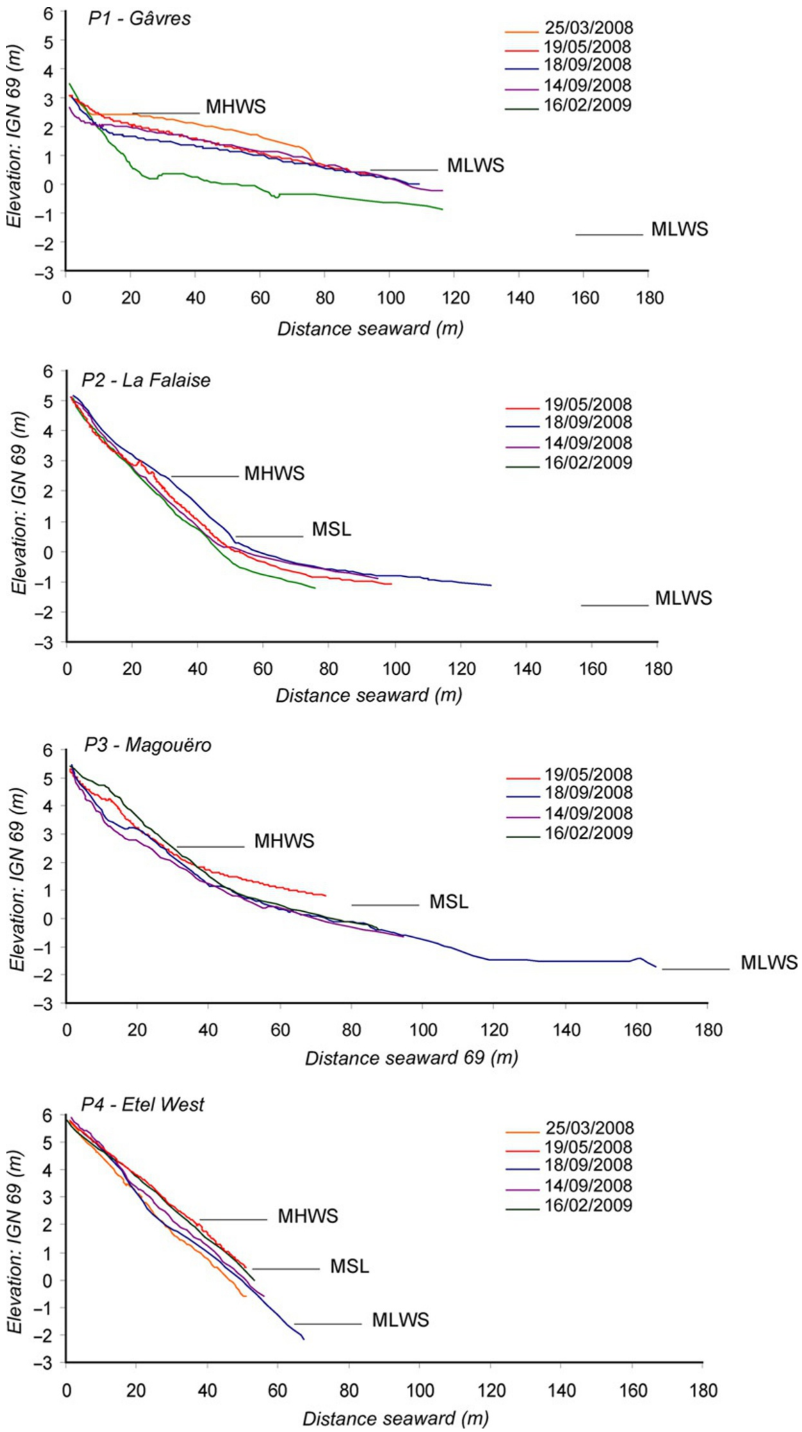


Fig. 6
Simulation of sediment transport by wave and tidal currents under both fair and storm weather conditions using the MARS S4 model.


P1 - Gâvres
25/03/2008
19/05/2008
18/09/2008
14/09/2008
16/02/2009
MHWS
MLWS
MLWS
Elevation: IGN 69 (m)
Distance seaward (m)
P2 - La Falaise
19/05/2008
18/09/2008
14/09/2008
16/02/2009
MHWS
MSL
MLWS
Elevation: IGN 69 (m)
Distance seaward (m)
P3 - Magouëro
19/05/2008
18/09/2008
14/09/2008
16/02/2009
MHWS
MSL
MLWS
Elevation: IGN 69 (m)
Distance seaward 69 (m)
P4 - Etel West
25/03/2008
19/05/2008
18/09/2008
14/09/2008
16/02/2009
MHWS
MSL
MLWS
Elevation: IGN 69 (m)
Distance seaward (m)

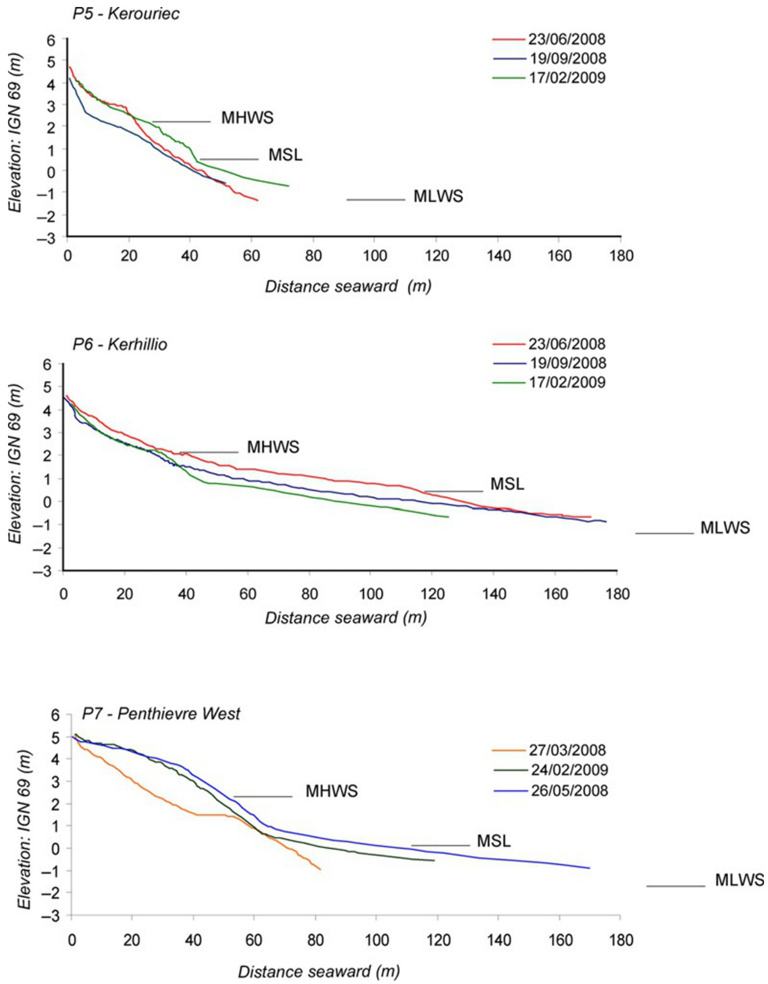


Fig. 7

Topographic profiles of the studied beaches and their variations between February 2008 and May 2009.

on the upper shoreface, partly within the surf zone. Accretion prevailed between May 2008 and February 2008 (Fig. 7). The Etel West profile was SE-NW oriented. Located west of the mouth of the Etel Ria, the profile displayed a much more reflective shape, with the surf zone at a lower elevation than other profiles. The vertical envelope of profile variation was about 1 m. Between March 2008 and February 2009, the profile variations displayed a probable cyclic evolution (Fig. 7). At Kerouriec, the profile was oriented SW-NE and located in front of a dense zone of offshore emerged rocks (Fig.7). The vertical range of the profile envelope was about 1 m. These variations were restricted within the surf zone, between the MHWS and the LHWL. Accretion prevailed between June 2008 and February 2009 (Fig. 7).

At Kerhillio, the profile was also oriented SW-NE, but outcrops of emerged rocks were less abundant. The maximum vertical range of variation was about 1 m, with erosion prevailing between June 2008 and February 2009 (Fig. 7). At Penthièvre West, the profile was E-W oriented. Bedrock and emerged rocks were found to be extending offshore. The beach is backed by a small sea wall, <1 m in height. The beach profile was located on the upper shoreface lying within the surf zone, and showed a vertical range of >2 m. Accretion prevailed between March 2008 and June 2009 (Fig. 7).

4.3 Temporal Coastline Variations

Between 1952 and 2004, the beach system experienced both coastline retreat and advance (Pian and Menier, 2011; Pian et al., 2014). In terms of surface area, 8% of the analyzed coastline experienced dune retreat, and 91.8% dune advance (Table 2). This evolution is highly variable, and the rate of shoreline migration was not linear. The beach-dune system was characterized by a severe erosion of frontal dune during 1952–84 and 1999–2004, when the total eroded area exceeded 51% and 89%, respectively (Table 2). On the contrary, during 1984–99, the beach-dune system underwent a period of dune recovery, with >92% of the area in accretion (Table 2). In addition, during the four periods under consideration, several areas, including the northern part of the sand dune system, around Gâvres, Etel Ria, and Kerhillio beaches (Fig. 8) underwent frontal dune retreat. On the contrary, throughout the time interval under study, the coastline advanced in the southern part of the sand dune system. The most variable evolution was related to the occurrences of pockets of erosion in the southern part of the beach-dune system, which were more numerous during 1952–84, and even more abundant during 1999–2004.

5 Discussion

5.1 Coastal Dynamics as Revealed by Profiling

The profiles were found to be leveled at the end of the SP1, 5–7 days after the storm occurred. At Gâvres, the profile was well fed, especially on the upper shoreface, and it can be interpreted as a consequence of onshore sediment transport feeding the upper beach.

Table 2 Migration of the coastline in m^2 between 1952 and 2004, for each time interval

	Erosion (m^2)	Accretion (m^2)	Balance (m^2)	% Erosion (m^2)	% Accretion (m^2)
1952–84	330,455	315,959	−14,496	51.21%	48.79%
1984–99	2606	1,159,705	1,157,099	0.28%	92.72%
1999–2004	184,833	20,888	−163,945	89.86%	10.14%
1952–2004	**80,384**	**933,688**	**853,484**	**8.04%**	**91.86%**

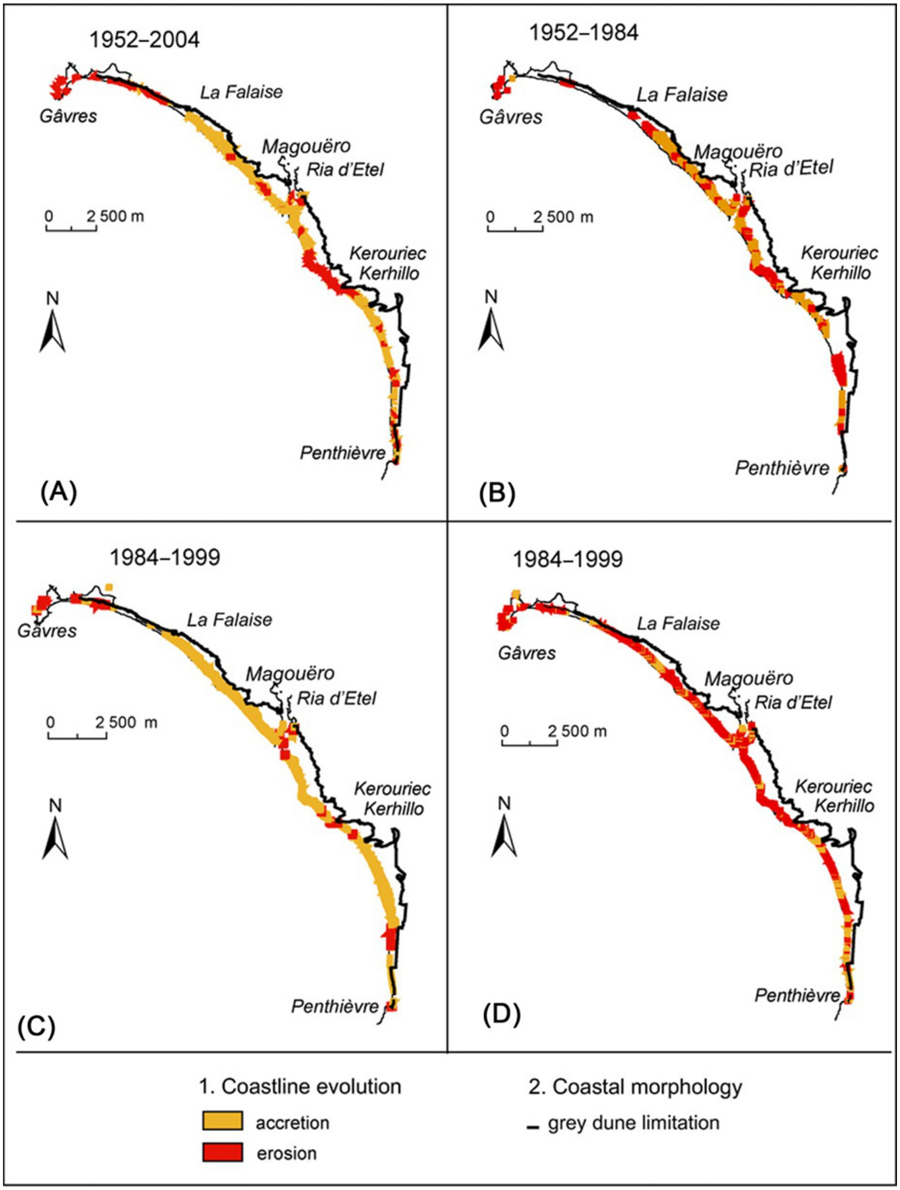


Fig. 8
Spatial distribution of coastline advance and retreat between 1952 and 2004, for each time interval.

This inference of onshore sediment transport is supported by evidence of overwash processes occurring during the storm, with sand accumulating behind the sea wall on the car parks. At the Etel Ria and Penthièvre West, the effect of the storm was likely to have eroded the beach because the profiles leveled during March were the lowest among all the profiles on both of these beaches. During the SP2, the beach profile was eroded at Gâvres, but it remained more nourished than the profiles leveled subsequently. This could have resulted from the redistribution along the profile of sand accumulated during the storm of the preceding survey period in March 2008. The profile leveled at La Falaise was located in the middle of the vertical range of profile envelopes, and was characterized by the presence of cusps on the upper shoreface. At Magouëro beach, the profile was fed and a berm formed on the upper shoreface as a consequence of sand accumulation under fair weather conditions with low-amplitude waves. At Etel West, the profile variations indicated accretion as the consequence of beach profile recovery. At Kerouriec, the profile was marked by the presence of a berm resulting from sand accumulation on the upper shoreface during fair weather conditions. At Kerhillio, the same phenomenon was recorded with lesser amplitude. During the SP3, the profile became lower at Gâvres, especially between the MHWS and MSL, owing to the upper shoreface erosion during rough wave conditions. On the contrary, at La Falaise Beach, the SW-NE-oriented beach profile experienced accretion in the surf zone, with beach cusps occurring between the MHWS and MSL. This suggested first a longshore transport direction toward the southwest between these beaches, and then differential responses of beach profiles according to their location, but under similar wave conditions within the sediment cell. At Magouëo, the lower shoreface was severely eroded over a vertical range of 1 m. The sub-aerial beach was also eroded, with a migration of the berm seaward. At Etel beach, the profile was also eroded, especially in the surf zone. Similar characteristics were observed also on Kerouriec and Kerhillio beaches. Such changes can be linked with the occurrence of rough wave conditions and the effects of both offshore and longshore transport.

The profiles leveled at La Falaise and Magouëo were lowered and displayed the effect of the last storm that occurred in November before the beach survey of SP4. At Gâvres, the upper part of the beach in front of the sea wall was eroded, but the rest of the profile recorded accretion associated with onshore transport similar to that recorded during the storms of March 10, 2008, but with lesser amplitude. At Etel West, the profile evolution during this period was almost stable, except around the MHWS, where slight accretion was recorded. The beach profile leveled in January 2009 displayed two types of responses during SP5. At Gâvres, La Falaise, and Kerhillio, morphological changes were dominated by erosion resulting from longshore sediment transport in the surf zone mainly driven by longshore drift currents toward the southeast. By contrast, at Magouëro, Etel West, Kerouriec, and Penthièvre West, morphological changes were dominated by accretion. Except at Etel West, these beaches were located in front of emerged rocks (Fig. 2) suggesting that these beaches trap sediment transported to the southeast under the action of longshore currents. Morphological changes recorded by the profile leveled at Penthièvre West indicated slight accretion during SP6.

5.2 Dynamics of Sediment Transport and Control of Beach Morphology

In a sandy coastal system, coastal cells provide a useful framework for analyzing the occurrence of erosion and accretion processes that control coastline variations at a regional scale (Komar, 1996). Relationships between onshore/shoreface sediment supply and frontal dune evolution have been well documented (Aagaard et al., 2004; Saye et al., 2005; Anthony et al., 2006). As a result, significant advance or retreat of the frontal dune can be interpreted in terms of predominant accretion or erosion processes favoring sand accumulation on the upper part of the beach and, in turn, the sand dune system. GIS analysis carried out to identify the sediment cell boundaries and the zones of active accretion and erosion within the cell revealed that, on a regional pattern, the coastline faces southwest coastal currents that moved sediments alongshore, from the north to the southeast. The Gâvres Beach, at the northern end of the beach-dune system, was recognized to be a source area, recording frontal dune retreat over the entire studied period (Fig. 8). Over intermediate studied time intervals, the evolution of the front dune is also characterized by retreat.

Dune foot vegetation smooths short-term events and provides indirect data about sand accumulation in the long or medium term (Anfuso et al., 2007). The retreat of frontal-dune vegetation, in association with a reduction of foredune surface area, reflects the occurrence of erosive processes and a negative sediment budget (Ojeda Zujar et al., 2003). The central part of the sand dune system is characterized by spatial and temporal alternations of coastline retreat and advance (Fig. 8) and behave as a transport area due to sediment input and output variability (Fig. 9). Beaches located in the south of the sand dune system are associated with frontal dune advance, although local retreats have occurred, especially since 1999 (Fig. 8). These dune advances principally occurring in sectors defined as a sink area (Fig. 9) were fed by the longshore drift. Thus, on a regional scale, the spatial distribution of areas of frontal dune retreat and advance matches with the sediment cell boundaries. On a finer scale, the sediment transport was disturbed by coastal features forming discontinuities, thus dividing the transport area into different sub-cells between which sediment passes. These discontinuities are mainly due to the variations in coastline orientation and/or the presence of submarine rocks and outcrops (Fig. 9), and include breaks in the coastline, such as the Etel Ria and Kerhillio Beach. The Kerhillio Beach was the source for the Penthièvre Beach between 1952 and 2004, and exhibited frontal dune retreat over the entire study period (Fig. 8). By contrast, the Magouëro and Kerouriec beaches received sufficient sediment supply over most of this period to favor frontal dune advance. In light of these observations, the transport area has been divided into three different sub-units extending from Gâvres to Magouëro, from Etel to Kerouriec, and from Kerhillio to Penthièvre West.

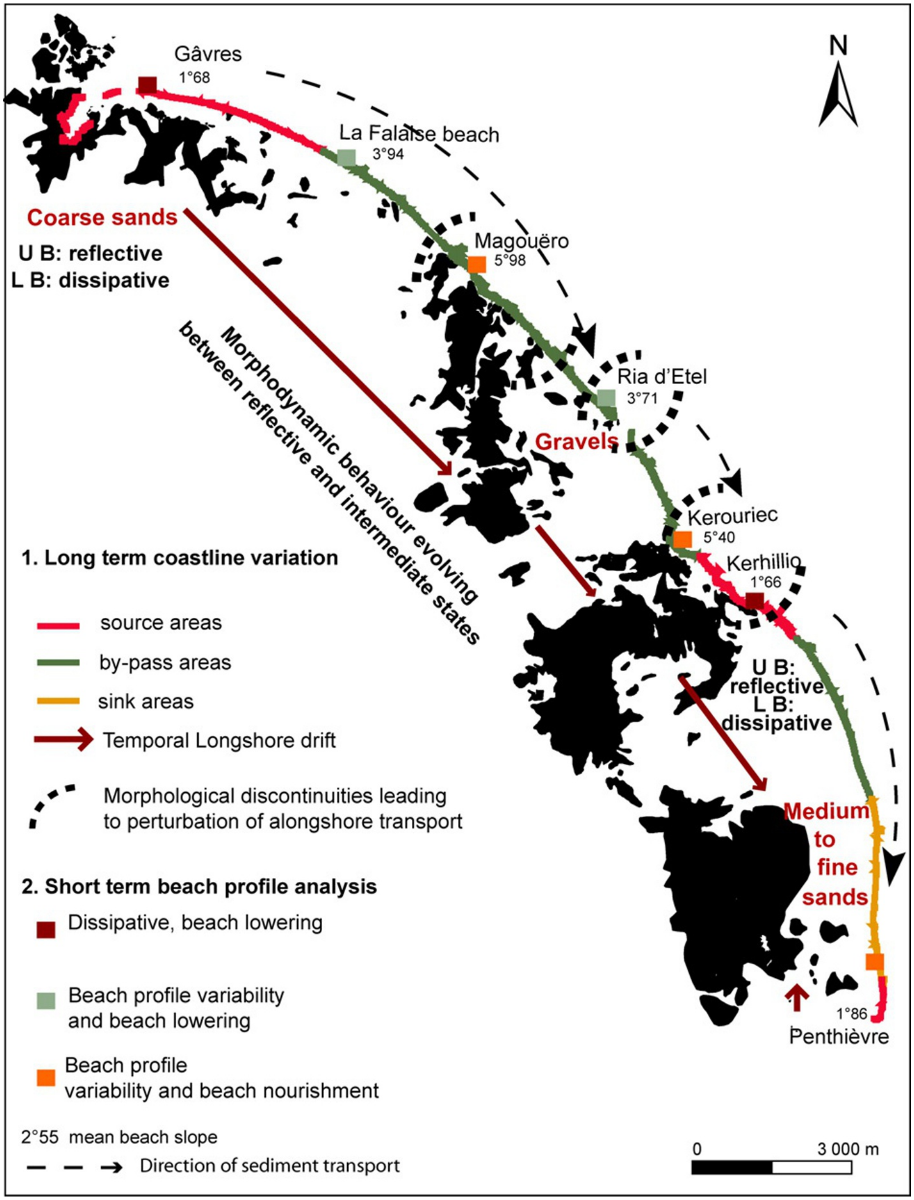


Fig. 9
Geomorphological behavior of the sand dune system over different temporal and spatial scales.

Over a long-term time and regional space scales, the front dune evolution along the Gâvres-Penthièvre beaches was driven by a southeast oriented longshore transport. The roughness of the coastline, as well as the location of nearshore bedrocks, interfere with this sediment transport and favor the relative stability of erosional or accretionary areas, which in turn matches with the sediment cell delimitations.

Beach profile variations over the short term also suggest the occurrence of longshore transport directed toward the southeast, both updrift and downdrift of the Etel Ria (Fig. 9). When onshore sediment transport dominates during storm surge conditions, sand accumulation occurs over the upper shoreface at Gâvres, but most of the time sediment is transported downdrift. According to the time interval between the two beach surveys, as well as the rate of sediment transport processes, sediments accumulate either on the beaches of La Falaise or Magouëo. Southeast of the Etel Ria, profiles leveled at Kerhillio and Penthièvre west result from erosion and accretion processes, respectively, which suggests sediment transportation toward the southeast. The morphological changes recorded were also controlled by seasonal variations of wave and wind conditions (Dubois, 1988; Hills et al., 2004). During survey period 2, when fair weather and modal wave conditions prevailed, accretion dominated in the upper shoreface as a consequence of onshore sediment transport processes. At La Falaise, Magouëro, and Kerouriec, onshore sediment transport led to the formation of a berm. Moreover, at Magouëro, Kerouriec, and Penthièvre west, beach accretion was favored by the presence of emerged outcrops of bedrock. The topographic relief of the emerged outcrops exercised control by acting as a sediment trap, and through reducing the bypass. Furthermore, the emerged outcrops can generate an atypical hydrodynamic circulation (gyre currents), which may interrupt the longshore transport and promote cross-shore transfer of sediments (Dubois et al., 2011). The dynamics of the Etel west beach were different, and were influenced by tidal currents associated with the river mouth. However, grain-size analyses carried out by Estournès et al. (2012) indicate sediment bypassing from the north to the southeast. Morphological changes recorded along the beaches of the sand dune system are thus partly explained by SE-directed longshore transport combined with seasonal wave and wind variations that alternately favor onshore and offshore transport. In addition, beach profile variations were prominent at Gâvres and Penthièvre west, which are both backed by sea walls. Thus, the higher amplitude of beach profile variations could be related to the presence of sea walls (Basco et al., 1997).

The morphological features of the coastline influenced the sediment transport over both the short and long term (Pian et al., 2014). They divide the sediment cell into different units and interrupt sediment transport over a short time scale, leading to temporary sediment accumulation, especially during storm events when higher amounts of sediments are transported. The responses of the beach to seasonal changes in wave regime are also coherent with their location within the sediment cell. In turn, sediment cell boundaries are controlled by the presence of emerged outcrops (Storlazzi and Field, 2000). Beach profiles located in source areas are eroded between February 2008 and June 2009. Inversely, beach profiles located in sinks experienced accretion. In transport areas, beach profiles experienced either erosion or accretion due to sediment output and input variability, suggesting a strong relationship between short-term profile behavior and long-term beach sediment budget evolution, and the important role played by the rocky barriers and outcrops on the wave regime attenuation, atypical current generation, and sediment transport regulation (Pian et al., 2014). The rocky outcrops limit offshore sand movement under moderate to lower high energy conditions, enhancing and concentrating the longshore sediment transport into a cross-shore corridor limited between the upper-shoreface and the rocky barrier. However, during high energy conditions, the offshore sediment can bypass this barrier within strong onshore-directed current, and may enrich the sedimentary stock in the sediment cell.

6 Conclusions

Analyses of spatial and temporal field and remotely sensed data and integration with oceanographic, geomorphologic, and sediment data through GIS has permitted the interpretation of prevalence of stable sediment transport direction on a long term and short term, and recognition of the impact of the coastline roughness on its evolution. Over a long period of time and at a large spatial scale, the coastline evolution is likely to evolve in relation to SE-directed longshore drift. The longshore redistribution of sediments from the north to the southeast leads to coastline retreat in the north, and sand accumulation downdrift to the southeast. Over the different time intervals studied, coastline retreat has occurred at least at two similar locations corresponding to downdrift areas. Coastline evolution displays no linear trend, and two of the survey periods were associated with severe frontal dune retreats. In addition, coastline retreat may have increased during the most recent survey period. Between 1952 and 2004, coastline evolution was also characterized by the occurrence of local pockets of erosion in downdrift areas. These pockets were more abundant between 1999 and 2004. On the short term and at a smaller scale, a dominant proportion of sediment transport was orientated southeast, although beach erosion was also related to seasonal variations in wind and wave conditions. This study shows that coastal morphodynamics recognized by aerial photographs on a long period do not necessarily reflect the short-term volumetric changes displayed by beach profile evolution.

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