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Assessing the Influence of Changes in Shoreface Morphology since the 19th Century on Nearshore Hydrodynamics and Shoreline Evolution in Northern France: A Modeling Approach

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The shoreface off the coast of northern France is characterized by the presence of numerous tidal sand banks, forming linear shore-parallel or slightly oblique massive sand bodies. Digitization of historic hydrographic field sheets from the French Hydrographic Service (Shom) archives enabled to produce Digital Elevation Models (DEMs) of the seabed morphology at different dates since the early 19th century. Our analyses of bathymetry changes based on differential DEMs showed significant morphological variations across the shoreface near Calais during the 19th and 20th centuries, which are largely due to changes in nearshore sand bank morphology and position. Sand bank mobility can be partially explained by tidal current asymmetry, inducing an elongation and an alongshore migration of this sand body in the direction of the net residual tidal current. Observed changes in shoreface and nearshore morphology attempt to be related with possible variations in hydrodynamics, this paper presenting the results obtained on tidal currents. TELEMAR-2D model was used to simulate 2D velocity field and water depth during a spring and neap tidal cycle over bathymetry grids based on historical bathymetric soundings. Depending on the bathymetric setting, modeling of tidal residual currents revealed notable increases or decreases in residual current velocity during distinct time periods, particularly in nearshore areas, which may lead to seabed erosion where current strengthening is observed through time or conversely to sediment accumulation in areas of decreasing current velocity. These results are consistent with the shoreline changes that occurred during the 20th century, with a correspondence between nearshore areas of decreasing (or increasing) residual current velocity and adjacent shorelines that were affected by seaward progradation (or erosion), suggesting strong links between changes in seabed morphology over the shoreface and shoreline evolution.

KEYWORDS: *Sand banks, northern France, hydrodynamic circulation, residual tidal currents, Calais.*

INTRODUCTION

Sand banks are large sedimentary features that occur in many coastal and shelf seas where there is a large amount of sediment and strong enough currents to transport it (Caston, 1972; Dyer and Huntley, 1999; Kenyon *et al.*, 1981; Pan *et al.*, 2007). The southern North Sea is characterized by multiple tidal sand banks that have been extensively studied (Berné *et al.*, 1994; Caston, 1972; Deleu *et al.*, 2004; Houbolt, 1968; Lanckneus *et al.*, 1994; Tessier *et al.*, 1999). Sand banks are particularly widespread off the coast of northern France where they form linear shore-parallel or slightly oblique sand bodies about 10–30 km long and 1–3 km wide (Figure 1, inset map). They belong to the Flemish Banks (Houbolt, 1968) and generally occur as groups of tens of meters from shallow coastal areas to depths of several tens of meters (Anthony, 2002; Vicaire, 1991). Near the coast, sand bank

mobility can be responsible for significant changes in bathymetry and seabed morphology (Aernouts and Héquette, 2006; De Moor, 2002; Héquette and Aernouts, 2010; Tessier *et al.*, 1999). Previous studies carried out in different coastal regions, including the coast of northern France, suggested strong relationships between shoreline evolution and nearshore sand bank mobility that would have induced changes in cross-shore and longshore sediment transfer (Carter *et al.*, 1982; Héquette *et al.*, 2013; Héquette and Aernouts, 2010; Shaw *et al.*, 2008; Thomas *et al.*, 2011). However, the modes of sediment transfer between nearshore sand banks and adjacent coastline are still unclear.

Historical bathymetries were used in several studies to modeling hydrodynamic circulation evolution to investigate interactions between coastal morphology and hydrodynamics (*e.g.*, Bertin and Chaumillon, 2005; Cooper and Navas, 2004; Héquette and Aernouts, 2010). For example, Horrillo-Caraballo and Reeve (2008) showed that the 150 year-long changes in

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sand bank morphology in the UK coastal zone can be mostly explained by variations in the pattern of tidal residual currents.

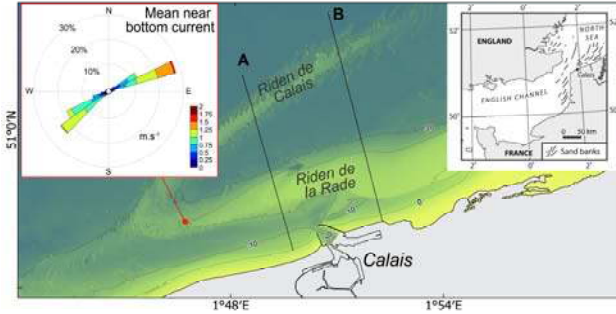


Figure 1. Location map of Calais with position of A and B bathymetry profiles presented in Fig. 2 and directional distribution of the mean currents recorded in 5 m water depths from 25/04/1975 to 13/05/1975

In northern France, topographic and hydrographic surveys of coastal and nearshore morphology were carried out by the French Hydrographic Service (Shom) since the beginning of the 19th century, enabling to describe the long-term characteristics of the seabed evolution. To assess changes in nearshore circulation, these historical bathymetries were used to simulate tidal currents at different dates. In this paper, we present the results obtained near Calais (Figure 1) where two prominent sand banks developed near the coast during historical time (Ruz *et al.*, 2017): the Riden de la Rade, which extends over 13 km alongshore, is connected to the Riden de Calais (11.5 km long) at its western end, forming a V-shaped sediment body with an angle of 20° (Figure 1). Strong tidal currents are channelized between the sand banks, with a flood-dominated asymmetry (Figure 1) that is responsible for a net sediment transport to the ENE (Héquette *et al.*, 2008) that can explain the longshore migration of the nearshore sand banks in the same direction (Latapy *et al.*, 2019).

METHODS

Bathymetry Changes

Hydrographic field sheets from the Shom, spanning from the mid-19th century to the beginning of the 21st century (Table 1) were used to study the morphological evolution of the sand banks and of the adjoining seafloor. These documents were scanned, digitized and then interpolated using the krigging method to produce Digital Elevation Models (DEMs). The

coordinate system is in WGS84 and elevations are in meters below chart datum. To quantify bathymetry changes, differential DEMs, alongshore and cross-shore transects and sediment volume calculation were made (more details on interpolation and computing methods can be found in Latapy *et al.* (2019)).

Numerical Model

To investigate the influence of seabed morphological changes on coastal hydrodynamics, a numerical approach was developed using TELEMAC-2D. Model domains extend from the Dover Strait to the Belgium border and integrate historical bathymetry (Table 1 in bold). The offshore open boundary is forced with specified elevations for 143 tidal harmonics from the tidal model cstFRANCE developed and used by the Shom (Le Roy and Simon, 2003).

Table 1. Bathymetric surveys used in this study (source: Shom, except for 2009, made by the port of Calais). MHE: Mean horizontal error; MVE: Maximum vertical error calculated using the method developed by Wheaton *et al.* (2010). In bold, bathymetry survey used in the numerical model.

Year	MHE (m)	MVE (m)
1861	15.5	1.9
1879	15.5	1.9
1910-1911	15.5	1.9
1929	15.5	1.9
1930-1932	15.5	1.9
1974-76	10.0	1.1
1983	5.0	0.8
1994	5.0	0.8
2009	3.0	0.5

Tidal prediction, water elevation observations and tidal current records were used to adjust and validate each model. The time step was set to 10 seconds and the model was run for a period of 30 days during the highest astronomical tides of 2015 (03/01/2015 to 03/30/2015) with sea-level elevations over the whole domain at 10 min intervals. Astronomical spring tides enabled to simulate the strongest and most intense currents in each mesh in order to identify high energy areas and those that have potentially undergone the most significant changes. Residual tidal current were computed over the complete simulated period and the generated maps were used to identify possible transport pathways. Tidal friction velocities were also computed to assess the variations in bed shear stress that could led to shoreface morphology change.

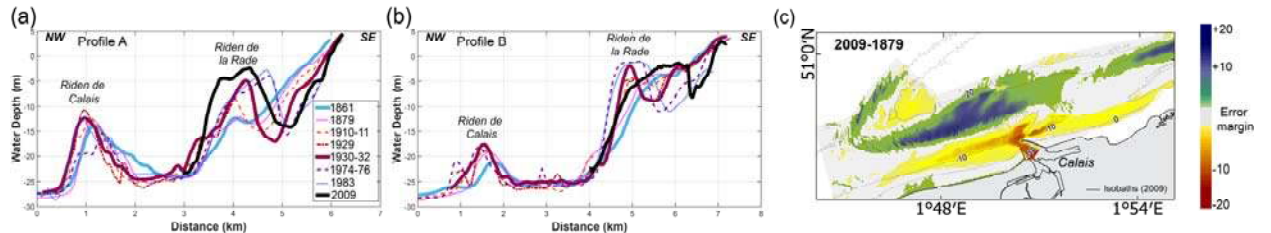


Figure 2. (a) - (b) Bathymetry profiles evolution from 1861 to 2009; A and B are cross-shore profiles (location on Figure 1), (c) bathymetric differential map between 1879 and 2009, red-orange patterns indicate a seabed lowering, conversely blue-green areas correspond to vertical accretion, areas in grey correspond to the error margin and are considered as stable over the study period.

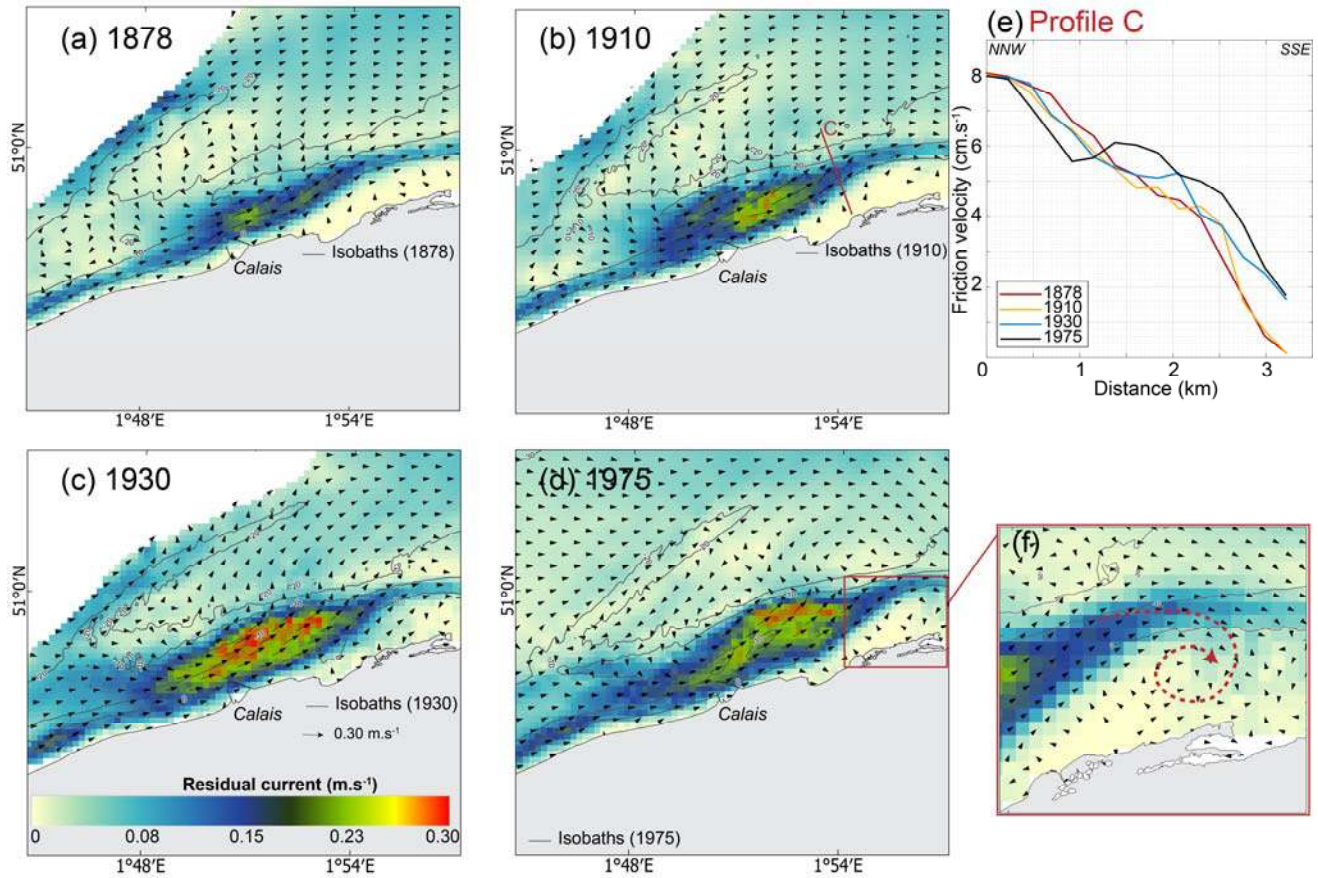


Figure 3. Simulations of changes in tidal residual currents over (a) 1878, (b) 1910, (c) 1930 and (d) 1975 bathymetries; (e) profiles of the friction velocity obtained along the transect C during the high water springs of March 2015 (location on (b)) for each simulation; (f) represents a zoom of the 1975 map showing clockwise gyre flows.

RESULTS

Calais Nearshore Evolution since the 19th Century

The Calais seabed morphology changed considerably since 1861 (Figure 2c), mainly due to significant variations in the morphology and position of one particular nearshore sand bank: the Riden de la Rade. Since 1861, a longshore growth of this sediment body was clearly visible on bathymetric maps (not shown). The lengthening of the bank was accompanied by an elevation of the crest of about 10 m (Figure 2c). This sand bank has evolved in 3 distinct phases:

- From 1861 to 1911, the Riden de la Rade was barely developed (Figure 2a-b). The increase of both width and height at the end of the 19th century, visible on cross-shore profiles, reveals a recent development.
- Between 1911 and 1983, the western part of the Riden de la Rade rose (+ 5 m) and gradually migrated onshore, with a maximum displacement of up to 800 m (Profile A) while the easternmost part experienced exclusively a vertical growth (Profile B). In the western part of the Calais harbor, the strong lowering of the foreshore (Figure 2c) can be attributed to the shoreward movement of the bank which induced the onshore

displacement of the channel between the coast and the bank (Profile A).

- From 1983 to 2009, the landward migration of the Riden de la Rade led to a deepening of the channel and its migration towards the coast (Profile B). The profile A reveals a widening of the Riden de la Rade as well as a shift from a seaward asymmetry to a symmetrical profile.

Evolution of Tidal Circulation

Figure 3 shows the computed tidally induced residual currents in the Calais nearshore zone for each bathymetry configuration between 1878 and 1975. Residual currents are essentially directed to the NE which corresponds to the flood direction. In the interbank area (between the Riden de la Rade and the Riden de Calais) currents are weaker ($< 0.04 \text{ m.s}^{-1}$) and mainly directed towards NE, except in the 1975 configuration where the flow is towards WSW.

Our results suggest significant changes in the hydrodynamic circulation with an overall increase in velocities of residual currents related to the formation and growth of the Riden de la Rade. In 1878, the strongest currents were close to the shore and

did not exceed 0.20 m.s^{-1} (Figure 3a). In 1910, the zone of highest current velocities expanded alongshore, accompanied by an increase in current velocities in some areas (Figure 3b). In 1930, while the channel continued to deepen, current speeds continued to increase, reaching 0.30 m.s^{-1} particularly in the central part of the channel (Figure 3c). Finally in 1975, residual currents above 0.15 m.s^{-1} in the channel and in the junction between the shoreface and the Riden de la Rade represent an area 3 times greater than that obtained in 1878 and 4 times greater for residual currents higher than 0.2 m.s^{-1} (Figure 3d).

On the foreshore, east of the Calais port, residual currents are gradually decreasing through time. Currents directions are mostly directed to the ENE in the 1878 and 1910 configurations. However, with the 1930 and 1975 set-ups, clockwise gyre flows are detected (Figure 3f). Figure 3e highlights a decrease and an increase of the friction velocity on the top of the Riden de la Rade and in the foreshore respectively. These changes could have favored sediment accumulation by reducing shear stress on the sand bank. On the foreshore, clockwise gyre flows combined with an increase in friction velocity may have enhanced sediment redistribution. West of Calais, there is an increase in velocities between 1878 and 1975, not only on the foreshore but also in the nearshore (up to the -10m isobaths).

DISCUSSION

Using historical bathymetry surveys, this study revealed significant morphological changes since the middle of the 19th century. The Riden de la Rade experienced sediment accumulation, with a maximum gain of $+17.9 \times 10^6 \text{ m}^3$ between 1930 and 1975 (Latapy *et al.*, 2019).

Channelization appears to be an important process within the study area. Since the early 1910s, the coastal channel increased in both width and depth (Figure 2a-c). This process, induced by the growth and the landward migration of the Riden de la Rade, resulted in higher flow velocities in the channel, potentially leading to erosion in the western part of the nearshore zone of Calais. The ebb-dominated current in the interbank, well-identified in the 1975 model, is consistent with observations made in this area (Augris *et al.*, 1990) and may be a result of the Riden de la Rade formation. Likewise, gyres at the eastern end of the bank in the 1930 and 1975 models may be a direct consequence of tidal current deflection by the welding of the Riden de la Rade with the shoreface, similarly to what was observed by Horrillo-Caraballo and Reeve (2008) in the eastern UK coastal zone. Shoreline changes since the 1950s revealed that the western area has been rather stable even if some erosion was locally detected (Chaverot *et al.*, 2008). However, shoreline progradation occurred eastward reaching about 60 m from 1949 to 2000 (Crapoulet, 2015; Héquette and Aernouts, 2010).

Simulation of wave propagation using historical bathymetry from 1910 onwards made by Héquette and Aernouts (2010) suggested that the onshore movement of the Riden de la Rade resulted in a decrease of wave energy in the nearshore, leading to more dissipative conditions that could enhance sediment supply. The present investigation proposes additional hydrodynamic processes. The increasing flows since 1878 on the foreshore and in the coastal channel, east of Calais, likely enhanced sediment remobilization and transport. Potentially, the coastal erosion observed in the mid-20th century may have also

been favored by these strongest currents. On the other hand, the velocity decrease of clockwise gyres currents in the eastern section could have led to sediment deposition which potentially contributed to shoreline progradation.

Even if tidal-induced sediment transport processes are not the only mechanisms that drive sand bank dynamic, the combination of numerical model output and historical measurements suggests that tidal residual currents have a significant role in governing the maintenance and evolution of this sandbank. However, because waves may intensify or diminish tidal currents and play an important role in coastal sediment transport (notably through longshore drift), a tidal-wave coupling model would bring new insights in the coastal hydrodynamic evolution and thus in the sandbanks dynamics in this area.

CONCLUSIONS

Morphological changes on the Calais shoreface and associated sand banks have been investigated from comparison of historical charts as well as with results from a tidal model applied to different bathymetries (1878, 1910, 1930 and 1975) to calculate residual currents.

The Riden de la Rade underwent major movements in almost 150 years with vertical accretion, landward migration and alongshore displacements. This led to the deepening of the coastal channel between the shore and the sand bank and the welding of the Riden de la Rade with the foreshore east of Calais.

These significant morphological changes induced variations in nearshore hydrodynamics with a strengthening of residual tidal currents in the channel. Since residual currents can be indicative of sediment transport patterns, the increasing longshore flow velocities in the channel could have favored longshore sediment dispersal rather than cross-shore transport, which may have limited onshore sediment transport to the beach. In the same way, the sediments transported in the nearshore were probably more easily deposited in the eastern part of the study area when numerical modelling reveals a decrease in the longshore current speeds. Gyres flows may have also favored sediment deposition leading to the shoreline progradation observed in the eastern part of the study area.

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