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The Variability of Ridge and Runnel Beach Morphology: Examples from Northern France

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ABSTRACT

The morphology of three macrotidal ridge and runnel beaches in northern France was analysed from over 200 profiles in order to identify intertidal spatial and short-term (weeks) profile variability, at both the inter-site and intra-site levels. The beaches, essentially composed of medium to fine sand, are exposed to fetch-limited waves variably dissipated by nearshore sand banks. They have spring tidal ranges of 5.6 to 7.2 m, and sediment budgets ranging from equilibrium to deficient or surplus. The results show that spatial and temporal morphological variability is controlled by: (1) variations in exposure to wave action that depend on the proximity of nearshore sand banks, as well as on protection offered by artificial structures; and (2) by the state of the beach sediment budget. Where equilibrium sediment budget conditions prevail, as in the Dunkerque-Est sector, the beach exhibits a regular alternation of ridges and runnels that represent a cross-shore alternation of fluid-bed interaction domains involving surf/swash activity and channel flow conditions. Energy dissipation at the bed is spent in the construction and destruction of wave and tidal micro- and meso-scale bedforms, leaving little scope for macro-scale ridge migration or change in form, except under exceptionally high wave energy conditions. Chronic sediment losses, as in Wissant Bay, or gains, as in Calais-Hoverport, are recycled respectively alongshore and to embryo dunes and are not necessarily translated in terms of significant meso-scale (years) beach volumetric changes. The short-term beach sediment budget changes however favour active bed readjustments that explain distortion of the regular ridge and runnel form and marked profile mobility, even under low to moderate wave energy conditions.

ADDITIONALINDEXWORDS: *beach profiles, macrotidal beaches, intertidal bars and troughs.*

INTRODUCTION

Although the term ridge and runnel beach has been applied to a variety of beach types in various hydrodynamic settings, true ridge and runnel beaches such as those discussed here are a particular type of beach found in sandy environments exposed to fetch-limited waves and tidal ranges larger than about 3 m (ORFORD and WRIGHT, 1978). These beaches are characterised, as their name implies, by intertidal ridges or bars, alternating with runnels or troughs whose number may range from two to six. First described scientifically by KING and WILLIAMS (1949) over fifty years ago, and considered as enigmatic features by ORME and ORME (1988) over a decade ago, ridge and runnel beaches are still enigmatic in many ways, despite a spate of recent studies on the hydrodynamic conditions associated with them and on the mechanisms involved in the formation and the intertidal location of the ridges (LEVOY *et al*., 1998; VOULGARIS *et al*., 1998; SIPKA and ANTHONY, 1999; MASSELINK and ANTHONY, 2001). One aspect of ridge and runnel beaches that has received little attention is their morphological diversity. This embodies not just the more commonly addressed problem of ridge mobility, but more especially inter-site and intra-site profile variability. MULRENNAN (1992) found marked spatial variations in ridge morphology along a 3.5 km long beach bounding Portmanock barrier in Ireland but did not critically examine the reasons for such spatial variability. She asserted that the range of conditions under which ridge and runnel profiles undergo change may be quite varied, depending on factors such as wave energy, tidal range and sediment availability. It may be deduced from this that ridge and runnel morphology may be as varied as these environmental conditions. From the analysis of several hundreds of beach profiles from three ridge and runnel beaches in Britain and northern France, MASSELINK and ANTHONY (2001) also suggested that differences in ridge location and height on the intertidal profile may reflect the diversity of the environmental contexts of these beaches.

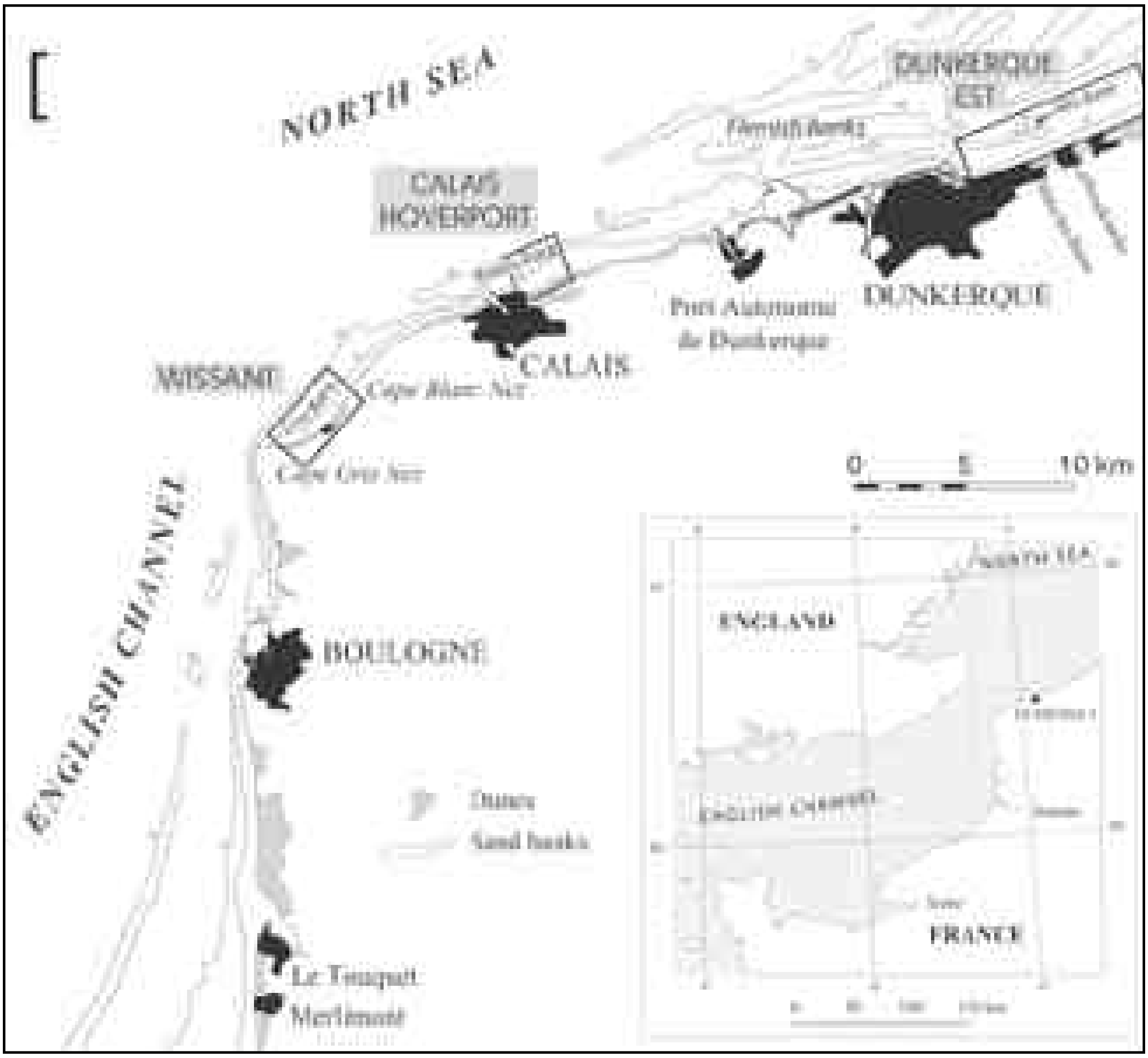

Figure 1. General location of the three ridge and runnel beach sites in northern France.

The present paper is concerned with both the spatial and short-term diversity of ridge and runnel beach morphology, and is based on the analysis of numerous beach profiles from three coastal sectors in northern France (Figure 1). The aim of the paper is to draw attention to the large diversity of intertidal ridge and runnel morphology and profile mobility, and to attempt to account for the conditions responsible for this diversity. Variability is illustrated both at the spatial level (intra-site and inter-site) and over the short-term (weeks to months). The discussion of ridge and runnel morphological diversity insists on the importance of wave energy levels and the relative beach sediment budget situation (stability, accretion, erosion). The possible role of the cross-shore ridge and runnel system in favouring morphological stability or instability is also evoked.

STUDYAREAAND METHODS

The extreme northern coast of France borders both the Dover Strait and the southern North Sea (Figure 1). The results discussed in this paper concern essentially the three beach sites of Dunkerque-Est (Dunkirk), facing the North Sea, and Calais-Hoverport and Wissant Bay, facing the Dover Strait. The study area is affected by semi-diurnal tides whose range increases westward, 5.6 m at spring tides in Dunkerque, 6.4 m in Calais-Hoverport and 7.2 m in Wissant Bay. Wave observations by MeteoFrance show that the dominant approach directions for this coast are from a north-northeast to northwest window (> 70 %), the rest coming from west to west-southwest. Although south to southwesterly winds are largely dominant on this coast, fetch and coastal orientation conditions restrict the incidence of southwesterly waves. Offshore wave periods from a wave rider buoy deployed by the Port Autonome de Dunkerque range from 3 to 6 s, typical of a fetch-limited environment. Offshore wave heights range from 0.25 to 1.5 m during modal conditions, and may attain up to 3 m during storms. The offshore zone consists of numerous tidal banks, the Flemish Banks. These are elongate sand ridges whose dynamics are controlled by a combination of strong longshore tidal currents with a northeasterly flood-dominant residual towards Belgium and storm waves (TESSIER *et al.*, 1999). These nearshore banks variably dissipate and refract the impinging waves, especially the afore-mentioned southwesterly waves, resulting in low modal breaker heights (Hb <0.25 m) on all three sites. Mean current velocity records from instrument deployments on beaches throughout this coast show that wind forcing significantly enhances the mean velocities (ANTHONY *et al.*, 1999). Typical peak spring tide velocities attain up to 70 cm/s, while peaks during conditions of significant wind stress (sustained wind speeds > 11 m/s) attain up to 140 cm/s. These records also confirm the fact that wind conditions in this fetch-limited environment are a good surrogate for the estimation of sea-state conditions.

The data base from which this study has been constructed comprises nearly 200 beach profiles obtained from 21 transects using the same instruments and procedures since 1996, as part of a coastal surveillance programme of the Nord-Pas de Calais coast. These on-going high precision topographic beach surveys were carried out using total electronic stations, whose errors are within ±3 mm for distance and ±0.0015° for direction. Surveys were carried out between the foot of the dune, or the sea wall in a few cases, and the low water mark at the time of each survey, and were systematically related to a benchmark of the French National Geodesic Service (IGN 69). Only profile series spaced less than 6 weeks apart were retained for short-term comparisons in this paper. For various reasons, notably loss of profile heads linked to the bench marks, some surveys were discontinued or are irregularly spaced. In order to determine mobility rates and trends, the individual ridges on the profiles were isolated on the basis of breaks in slope and heights. Each profile is composed of several points, each with x,y,z coordinates, linked by segments separated by breaks in slope. Ridges typically consist of seaward- and landward-facing slopes linked by a surface which attains a maximum local height in the profile. This maximum height point was retained as that representing ridge crest position. This procedure also facilitated the identification of a crest when the ridge visually appeared to be a flat surface on the profile. Field observations were carried out during each survey on wave breaking characteristics and swash behaviour, and on meso- and micro-scale bedforms. The sediment characteristics of the various beaches have also been determined from numerous samples collected at various intervals along each profile.

RESULTS

Dunkerque-Est

The Dunkerque-Est beach is the most stable of the three beach sites discussed in this paper. The beach in the western part of this partially urbanised coast is backed by an embankment that protects the highly frequented resort of Malo-les-Bains (Figure 1). Following the construction of the eastern extension of the port of Dunkerque, the beach in this area underwent rapid erosion as a result of drift perturbation. Nourishment and a series of breakwaters in the early 1980s have resulted in complete stabilisation of the beach fronting this resort. Further east towards Leffrinckoucke (Figure 1), the beach is backed by dunes that shows signs of very mild erosion to stability. Mild dune scarping in winter in this area is often followed in spring and summer by limited embryo dune formation. The western half of the Dunkerque-Est beach is largely protected by the most shoreward of the nearshore sand banks in this sector, the Hills Bank, which has a length of 9.5 km and a maximum width of 2.7 km. The crest of the Hills Bank is exposed at spring low tide levels. The proximal tip of the bank is located a few hundred meters from the base of the beach at Malo-les-Bains and runs offshore to a distance of 1.8 km. This skewed orientation is typical of sand banks in this area (TESSIER *et al*., 1999). Beyond the proximal tip of the bank, the beach is exposed to deeper water. The dune front shows more pronounced erosion, and various blockhouses built during the 2nd World War now lie on the beach.

In order to compare adjacent beach segments over the short-term, three typical profiles from this sector spaced 1 km apart are shown in Figure 2. The ridge and runnel expression is muted in the western part of this site (profile MK) where the beach is jointly protected from storm waves by breakwaters, the Dunkerque east port pier and the Hills Bank. Ridge and runnel morphology becomes pronounced eastward of profile MK where the beach is completely devoid of structural defences and less sheltered by the Hills Bank. The ridges and runnels are best expressed on the mid-beach and become more subdued in the seaward direction. Apart from the muted morphology of the highly sheltered profile MK, spatial variations in morphology are minor. The overall gradient of the intertidal beach, including profile MK, is uniform, about 0.01, and the seaward slopes of the ridges in profiles HM and DM have gradients of 0.02–0.04. The beach is characterised throughout by fine to medium, well to very well sorted quartz sand (D50 = 0.17–0.32 mm). The sand tends to be slightly coarser and less well sorted on the upper beach. The ridges generally consist of coarser sediments than the runnels but the differences are small due to the homogeneity of the material.

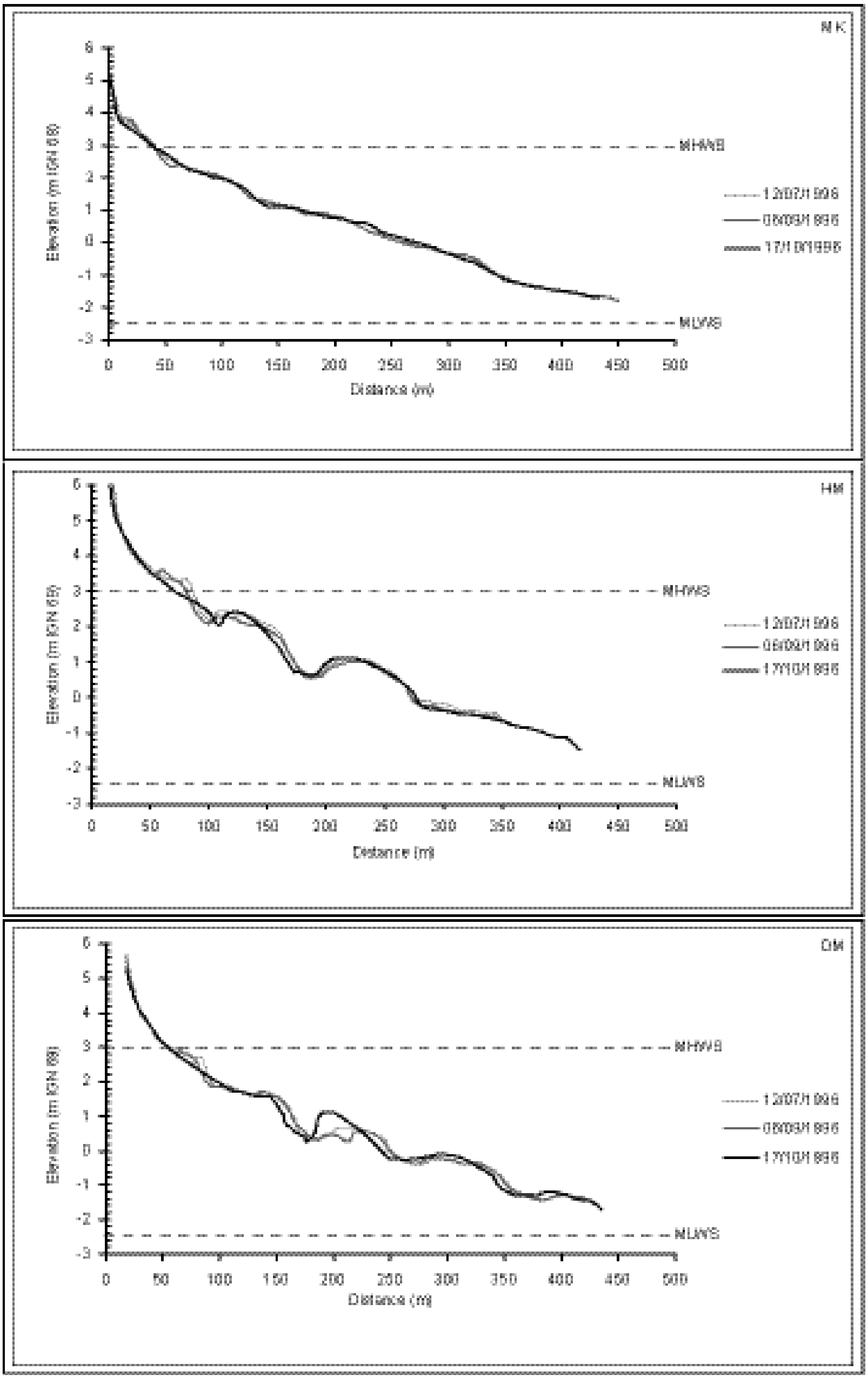

Figure 2. Successive profiles of three beach transects in the Dunkerque-Est sector.

The ridge and runnel morphology shows little longshore variability. The most marked changes in Figure 2 are associated with the more wave-exposed profile DM. The mobility registered by the October 1996 profile occurred in response to a late September storm associated with the highest spring tides of that year (with a coefficient of 115 out of a maximum of 119). To the west, in the more wave-protected sector, profile HM shows better resistance to short-term mobility in spite of the importance of this September storm. Numerous other profiles from this beach show that short-term (< 2 months) ridge mobility is only triggered when successive storm events occur, especially when they coincide with large spring tides. Observations show generally that isolated storm events lasting a couple of days are not enough to induce a notable change in the beach profile when they coincide with low tidal ranges, even when significant wave heights attain up to 1.5 m. However, single exceptional storm events (Hs up to 3 m) may result in significant profile changes. Significant storm events have a greater cumulative effect in winter, imprinting a seasonal mobility pattern that is clearly manifested in all the surveyed transects since 1996. Volumetric changes in the profiles over the period 1996-2000 are insignificant.

Calais-Hoverport

The Calais-Hoverport sector (Figure 1) is one of the rare actively accreting sectors of coast in the extreme north of France. The profiles from this sector differ considerably from those of Dunkerque-Est in terms of their gross morphology, and also exhibit more spatial and temporal heterogeneity (Figure 3). The most striking feature of these profiles is the presence of a 100 to 400 m-wide upper beach sand flat, with a uniform gradient of 0.2 that is linked to the foredune (Figure 3). Observations of aerial photographs show that accretion has occurred through the accumulation of this sand flat over the last century in an area that was hitherto subject to erosion. Accretion has been due to the onshore migration of a massive sand bank, the Ridens Bank, that has welded onto the coast, serving as an important subtidal sand reservoir for the dunes, while attenuating storm waves. Below the sand flat occur three to six prominent ridges that are limited to a 300 m-wide mid-beach section with an average gradient of 0.65. This mid-beach section is generally linked to a relatively steep (1.02) lower beach section that shows very mild ridge and runnel development. The variations in morphology are matched by

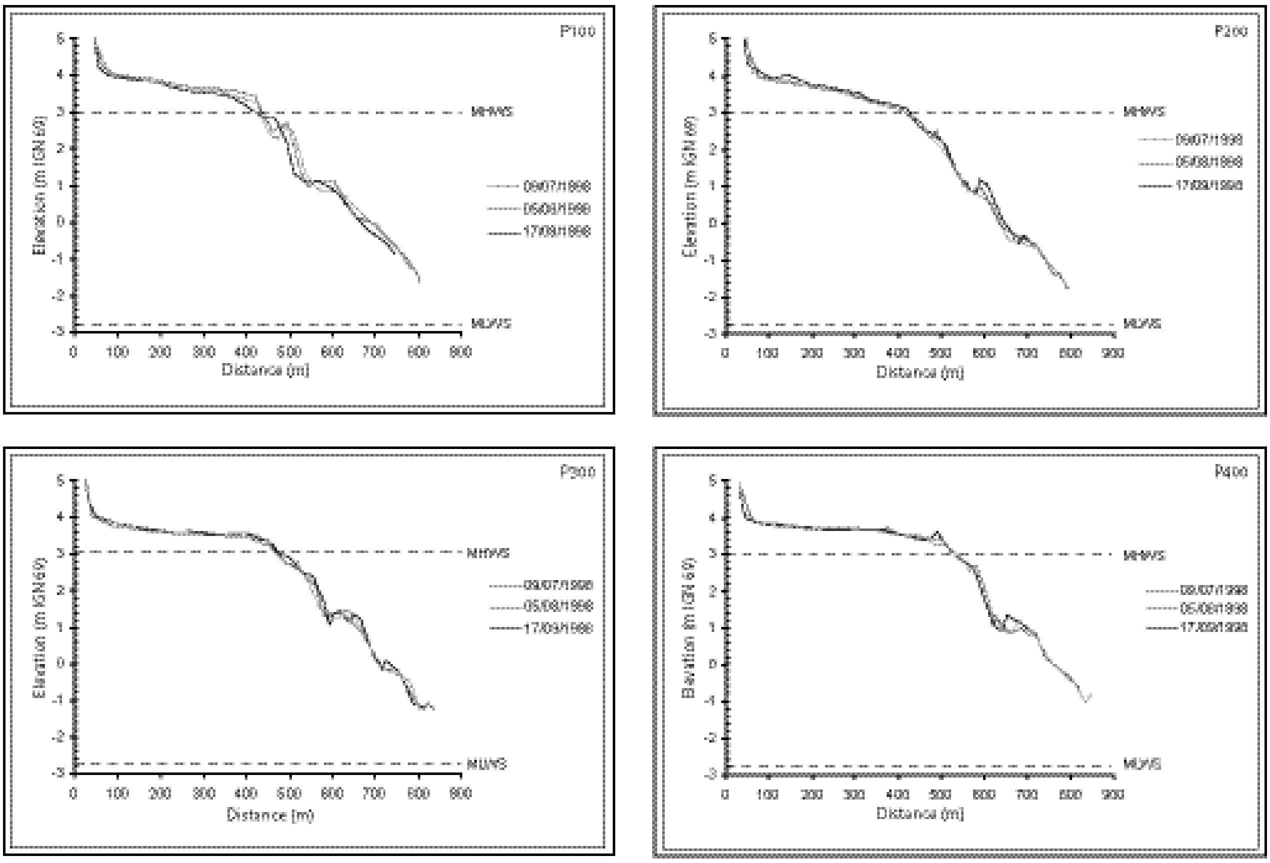

Figure 3. Successive profiles of four beach transects in the Calais-Hoverport sector

a sharp cross-shore textural variation that also contrasts with that of the Dunkerque-Est sector. The upper beach flat exhibits a heterogeneous sand and fine gravel fraction rich in shelly debris. Active aeolian winnowing of fine quartz sand for foredune accretion is common, leaving a very porous surface. The mid-beach and lower beach segments are characterised by more homogeneous fine to medium, well sorted sand.

Short-term profile mobility is variable alongshore and is essentially limited to the mid-beach ridges and runnels (Figure 3). Notwithstanding the important accretion of the foreshore over the last decades, both short (months) and longer-term (1998-2001) volumetric changes in these profiles are insignificant. This suggests that the sand inputs may be modest and diffuse over the short-term, and are not captured as morphological changes by the profile surveys. It may also suggest that these sand inputs are rapidly recycled to the foredune where developing embryo dunes are constantly observed.

Wissant Bay

Wissant Bay (Figure 1) is located in the most rapidly eroding sector of coast in France, with retreat of the dune front of over 100 m in the last eighty years. The reasons for the onset of dune erosion in this once stable area of sandy shoreline are still not clear. They seem to involve (ANTHONY and DOLIQUE, 2001) interactions between offshore bank development, longshore sand transport in the coastal corridor of which this bank is a part, and the activity of current gyres related to the projecting headland of Cape Gris Nez (Figure 1). The offshore shoal, known as the Line Bank, has been eroding over the last century. This shoal formerly served as a temporary storage zone for sand that was transferred shoreward to feed the dune barrier of Wissant Bay. This process also meant that the shoal protected the dune barrier by dissipating storm wave attack. The sand starvation may be due to both depletion of sand transported coastward by large-scale hydrodynamic

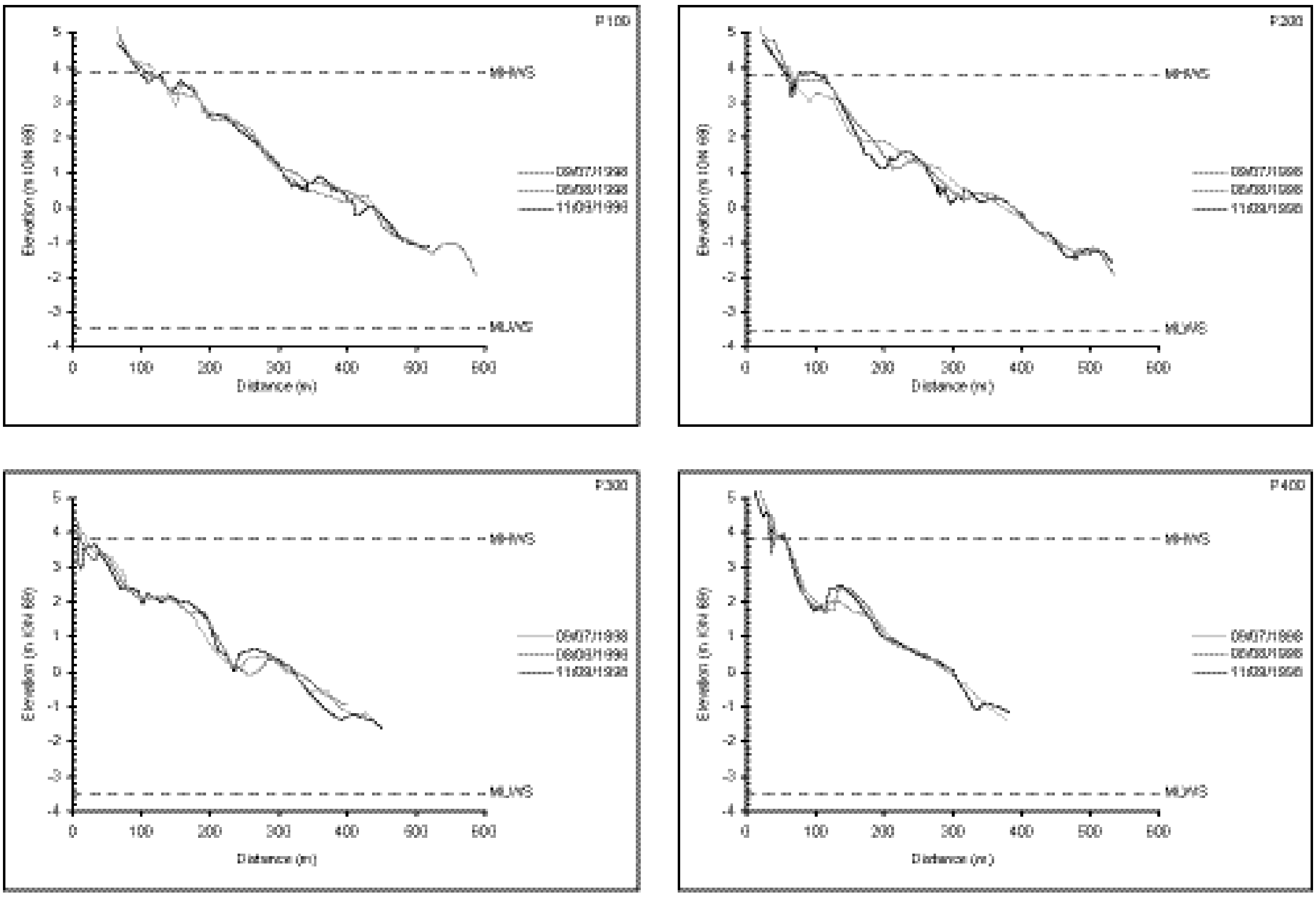

Figure 4. Successive profiles of four beach transects in Wissant Bay.

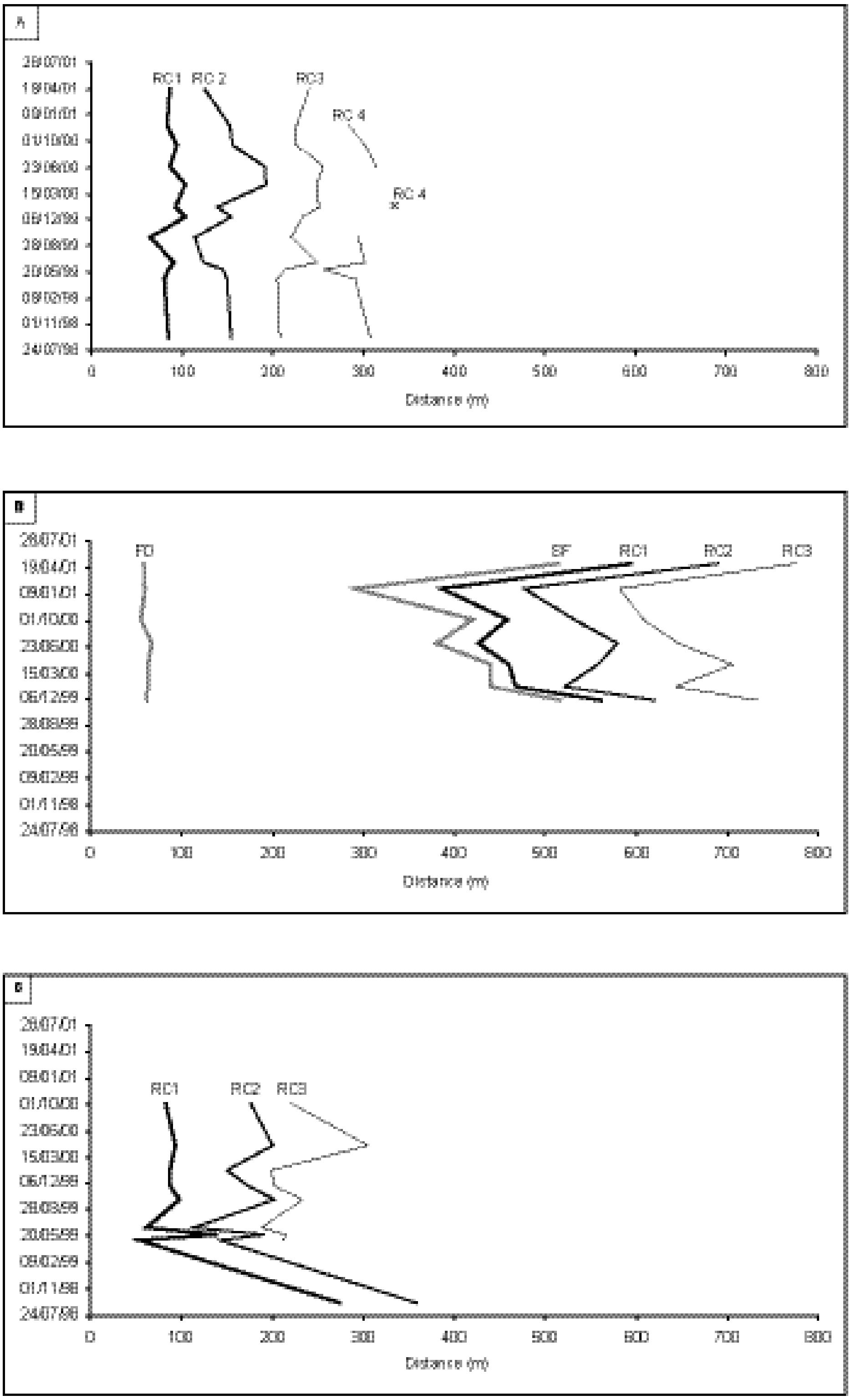

Figure 5. Variability of ridge crest mobility rates for representative profiles from the three beach sectors: A. Leffrinckoucke, Dunkerque-Est (profile P100); B. Calais-Hoverport (profile P100); C. Wissant Bay (profile P500). RC1 - RC4: Ridge crests 1 to 4; FD: Foredune; SF: Sand flat edge.

processes in the eastern English Channel and capture by the rapidly accreting sand-choked estuaries to the south. As lowering of the Line Bank has occurred, storm wave energy dissipation has largely been transferred to the ridge and runnel beach and dune barrier. These have been rapidly retreating, releasing sand which is then transported alongshore towards the central part of Wissant Bay. This central part of the bay is now a zone of accretion, after being a sand-starved zone in the past when the western part of Wissant Bay was either accreting or stable. In the western sector, gravel derived from the nearby cliff outcrops of Cape Gris Nez is being assembled and concentrated alongshore into a distinct bermed upper beach deposit that migrates landward into the eroding dune front as the ridge and runnel beach sand volume decreases.

Wissant Bay appears to be more exposed to waves than the other two beach sectors. It is, however, subject to much the same wave energy conditions as several other beaches in northern France that are not directly protected by shallow banks nor eroding as a result of this relatively greater exposure. The chronic erosion of the western half of the bay, where surveying has been carried out, has resulted in a beach that is much lower than that of Calais-Hoverport and with less than half the sediment volume of the latter. The Wissant beach profiles in the eroding sector show volumetric losses locally exceeding 10% between 1998 and 2000.

Wissant Bay shows the most irregular ridge and runnel morphology (Figure 4) of the three sites. Notwithstanding the close spacing of the profiles (200 to 500 m apart), they are also extremely variable spatially. The ridges range from narrow to wide, with narrow runnels. Where they occur, these irregular and deep narrow runnels act as high flow gutters in which rapidly migrating 3-D dunes are generated from sand reworked from the neighbouring ridges. Field observations show that these runnels actively recycle sand downslope. In spite of this irregular morphology, the beach shows a relatively homogeneous and well sorted fine to medium quartz sand. Coarse shelly debris is locally concentrated in the runnels.

The ridge and runnel beach in Wissant Bay also shows marked short-term mobility (Figure 4). The variations shown by the July and August 1998 profiles were associated with low wave energy levels, a condition observed by other workers elsewhere.

DISCUSSION AND CONCLUSIONS

The database of profiles from beaches in northern France shows large ridge and runnel morphological variability that is expressed at the inter- and intra-site levels, as well as by short-term changes. The data also show that there are marked differences in ridge crest mobility between the three sites that are summarised in Figure 5 by the comparison of three representative profiles. The most plausible explanation for such variability is the operation of site-specific environmental conditions, as suggested in previous studies (MULRENNAN, 1992; MASSELINK and ANTHONY, 2001). Among these are exposure to wave energy and the stable, accretionary or erosional status of the coast. The data from Dunkerque-Est suggest that ridge and runnel morphology is strongly controlled by the degree of exposure to waves, within an overall context of relative sediment budget stability. Exposure to wave energy in turn depends on the nearshore topography, notably the proximity of the Hills Bank, and the presence of artificial beach structures. The greater the protection from waves, the more muted the ridge and runnel morphology. As wave energy increases, ridge and runnel morphology becomes better expressed and more mobile. However, the winter profiles show that high wave energy events coinciding with spring tides may lead to flattening of the ridges, as other workers have observed (KING, 1972; MULRENNAN, 1992; SIPKA and Anthony, 1999). There thus appears to be a low to moderate wave energy window that favours stability of ridge and runnel morphology (KING and WILLIAMS, 1949; KING, 1972; MULRENNAN, 1992).

The profiles that come closest to the ‘classical’ ridge and runnel morphology (i.e., morphology displaying a regular set of proportioned intertidal ridges or bars alternating with runnels or troughs) are those of the Dunkerque-Est sector (Figure 2). Such regular intertidal features are probably close to the most robust ridge and runnel morphology that develops in equilibrium response to a favourable combination of specific wave energy (low to moderate), wave steepness (short period waves), tidal range (meso- to mega-tidal), sediment availability (balanced sediment budget) and grain-size (fine to medium sand) conditions. It is not within the scope of this paper to discourse on the mechanisms of ridge formation. Once formed, however, the ridge and runnel morphology is important in determining adjustments between the profile and the hydrodynamic forcing by forming a diversified set of cross-shore fluid-bed domains involving not only wave action but also channel flows in the runnels. This involves, in the first place, marked shore-normal changes in reflection and dissipation and in the activity of surf and swash processes that depend on the changes in depth and slope that waves undergo during both the rising and falling tides. Secondly, the runnels are affected, especially during rising and falling tides, by strong flows driven by a combination of channelled swash bores, tidal discharge (SIPKA and ANTHONY, 1999) and groundwater discharge. Flow velocities in these runnels may attain up to 2.5 m/s. Strong swash and tidal flows over the lower back slopes of the ridges, and concentrated swash bores, tidal discharge and groundwater discharge in the runnels create complex 3D micro-scale (wave and current ripples) and meso-scale bedforms (notably dunes) during the falling tide. The intensive reworking of these bedforms involves dissipation of wave energy and tidal currents during the rising tide, thus providing a mechanism that may retard macro-scale ridge reworking and migration. In essence, the shore-normal morphodynamic diversity of the regular ridge and runnel form assures large-scale stability of the system, enabling resistance to change even under relatively energetic but isolated events. The relatively long phases of low wave energy, related in part to the wave climate and to filtering by the banks offshore, and the equilibrium sediment budget conditions favour this stability. Depending on factors such as tidal range and grain-size gradients, the slope, number and height of the ridges may vary from one beach to the other, while retaining the 'regular' ridge and runnel form. Merlimont beach (Figure 1), for instance, which shows a relatively stable medium-term sediment budget, shows a regular but more pronounced ridge and runnel topography than the Dunkerque-Est beach, probably as an adjustment of the beach sediment prism to a larger spring tidal range (9 m). This beach, like many other ridge and runnel beaches in northern France, such as those of Dunkerque-Est, is similarly resistant to change.

While sediment budget stability appears to favour, under the right set of tidal and grain-size conditions, classical ridge and runnel morphology, the processes by which sediment budget changes affect this morphology are not clear. MULRENNAN (1992) deduced from her beach study site in Portmanock that profile changes were independent of volumetric changes. However, a direct relationship between the two may be masked by the shorter-term profile changes due to variations in wave energy, especially where the ridge and runnel morphology is prone, as a result of site-specific environmental conditions, to rapid short-term change. This, of course, may be expected where large volumetric changes affect the beach. The role of a declining or increasing beach sediment budget must be viewed at longer time scales wherein accommodation of the sediment gains or losses is imprinted in the permanent morphological expression of the beach. The overall morphology of Calais-Hoverport beach (Figure 3) no doubt reflects a medium-term adjustment to slow sediment inputs from the Ridens Bank. Intertidal to supratidal accommodation of this excess sand has resulted in significant progradation of the beach in the form of a large sand flat, while the combination of low to moderate modal wave conditions, the macrotidal range and the fine to medium sand grain size have maintained a mid-beach system of ridges and runnels. The Calais-Hoverport beach morphology resembles that of the ridge and runnel beach between Donna Nook and Mablethorpe on the north Lincolnshire coast in England. Like the former, this beach exhibits an upper beach sand flat and is in a sector of net coastal accretion (MASSELINK and ANTHONY, 2001).

Paradoxically, the cross-shore morphological diversity that favours stability of ridge and runnel systems may also weaken the resistance of these systems to change. This occurs during conditions of sustained high wave energy, when the bed flow domains become dominated by wave and wind forcing. This leads to the perturbation of the fine balance between surf-swash processes and channelled flows. The wave-dominated flows tend to plane down the beach face by flattening the ridges and infilling the runnels. This situation would also occur when the beach is in a state of chronic erosion, as in Wissant Bay (Figure 4). As sand is slowly removed from the ridge and runnel beach, the system adjusts to increasingly more intensive fluid bed stresses, even though absolute wave energy levels do not increase. This leads to progressive perturbation of the cross-shore morphological diversity, which is tantamount to irregular profiles. The greater control vested in waves may explain the commonly massive ridge morphology associated with highly concentrated channelled flows in the runnels on Wissant Beach. These conditions explain not only the irregular ridge and runnel morphology but also profile mobility even under low wave energy conditions (Figure 5). Further studies addressing the role of the beach sediment budget in affecting profile patterns and ridge mobility of ridge and runnel beaches will need to look at a variety of field sites such as those in northern France, in stable, accretionary or erosional coastal settings.

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