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Short-term Morphological Expression of Dune Sand Recycling on a Macrotidal, Wave-Exposed Estuarine Shoreline

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ABSTRACT

A topographic survey of the north bank shoreline of the Authie estuary, in northern France, was carried out between 1997 and 1999 in order to determine the short-term morphological organisation, within the estuary, of sand eroded from this chronically retreating north bank. The data complement meso-scale analyses of aerial photographs that highlighted a recycling of this sand, eroded from coastal dunes lining the estuary, into the intertidal inner estuarine sink. The beach at the foot of these dunes serves as an important temporary storage zone for this sand and may show substantial short-term accretion. Much of this sand is, however, transported into the inner estuary by the westerly winds that build up longitudinal dune ridges over a shallow intertidal inner estuarine sand platform that forms the long-term sand sink on this northern shoreline. Sand transported from these ridges ends up as diffuse sand sheets that impinge on muddy sediments derived from upland. Over the longer-term, these dune ridges are recycled into this inner estuarine sediment sink by winds, wave erosion and changes in the position of the Authie channel. In this highly accreted estuary, where minor transport of sand towards the inner estuary by weak flood currents is balanced by seaward evacuation of sand in the main channel, this beach and dune sand transport pathway constitutes the major infill pathway of the estuary. The accretion of sand in the intertidal estuarine sink engendered through this transport pathway is also important in encouraging fine-grained deposition and salt marsh development by providing a shallow substrate. This example shows that accelerated silting of a sandy wave-exposed estuary may occur without the intervention of meso-scale changes in tidal transport.

ADDITIONALINDEXWORDS: *coastal dune erosion, topographic survey, estuarine sink, Authie, Northern France.*

INTRODUCTION

Estuaries are potentially complex coastal entities because they may come under the influence of waves and tides (DALRYMPLE *et al*., 1992), as well as rivers (COOPER, 1993), which not only transport the sediments essential to long-term estuarine infill, but also provide the process inputs for short-term estuarine change. Macro-tidal estuaries (with spring tidal ranges >4 m, DAVIES, 1980) are generally considered as essentially tide-dominated (PETHICK, 1984). However, certain macro-tidal estuaries may also experience significant wave influence, resulting in morphologies and sediment transport patterns that reflect joint tide-wave domination. The tidal signature, in terms of infill morphology and sediment bodies, is best expressed in such estuaries by linear tidal ridges along the axis of the estuary mouth, separated by mutually evasive flood or ebb dominated channels (WRIGHT, 1977; WELLS, 1996). Infilling in such estuaries may be favoured by flood-dominant tidal currents (DRONKERS, 1986; VAN DEN BERG *et al*., 1996; VAN DER SPEK, 1997). The wave input may occur through recycling of sand drifting alongshore into the estuary mouth, often derived from dune reworking (CARTER, 1990; BURNINGHAM and COOPER, 1998). The mix between this wave and tidal influence generally results in broad estuary-mouth shoals subject to wave reworking, separated by tidal channels. This morphology may become blurred over time as accretion leads to shallow channels between shoals. In sandy estuaries, at this stage of estuarine infill, the tidal currents responsible for transporting sand into the inner estuary may shift towards ebb domination as the flood tidal wave becomes increasingly retarded by the infill (DRONKERS, 1986; VAN DEN BERG *et al*., 1996; VAN DER SPEK, 1997). In highly accreted estuary mouths, this situation might be expected to result in equilibrium conditions wherein tidally-induced infill slows down or even becomes reversed. This balance may, however, be perturbed by extraneous processes such as empoldering or dredging that affect the sediment budget. Another source of perturbation

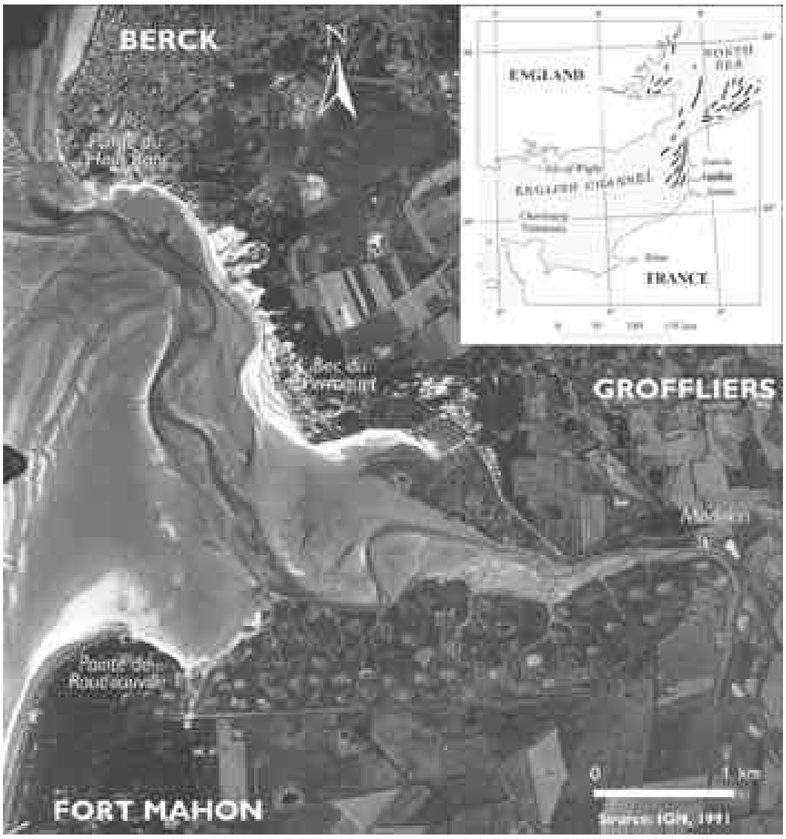

Figure 1. The Authie estuary, northern France.

may occur naturally where storm waves attack non-estuarine sediments lining the estuary, such as dunes, thus providing excess sand inputs that are recycled into the estuarine sink.

This process of recycling of dune sand lining an inner estuary has been identified in three estuaries subject to a mixed tide-wave process regime, including the Authie, in northern France (Figure 1). The long-term erosion of coastal dunes lining the north bank of the Authie estuary has been described by ANTHONY and DOBRONIAK (2000) from aerial photographic data. They considered this process as a long-term morphodynamic adjustment to concentration of the tidal flux against this dune shoreline by massive estuary-mouth accretion. The aim of the present paper is to focus on the short-term morphological organisation of the sand stocks released by storm wave erosion within the estuary. It is shown that this mechanism constitutes, in the face of advanced estuary-mouth accretion, the major pathway of present infill of the inner estuary.

STUDYAREA

The Authie estuary is located on a low-lying dune coast in northern France (Figure 1). The estuary forms the terminus of a relatively short (98 km-long), straight coastal river that drains a low-gradient Mesozoic limestone plateau catchment covering an area of 989 km^2. River discharge data are relatively sparse but show regular flow, characteristic of a small temperate catchment. The mean liquid discharge over the years 1983-85 ranged from 10.4 m^3/s to 14.1 m^3/s. Catchment erosion provides the only sediment brought down to the sea by the Authie. This is exclusively fine-grained suspension load. Like all the other estuaries on this coast between the Somme (Figure 1) and Belgium, the Authie is a shallow estuary that shows advanced sandy infill. The shallow estuary mouth exhibits a massive sand deposit (Figure 2), comprising a spit and a spit platform, that confine the main Authie channel towards the north bank, which is composed of a massive dune barrier that extends northwards up the coast. This wide dune barrier also stretches several kilometres inland along this north bank of the estuary. Mudflats and salt marshes occur in the inner estuary (Figure 2). DALLERY (1955) showed from historical documents and maps that this spit platform has

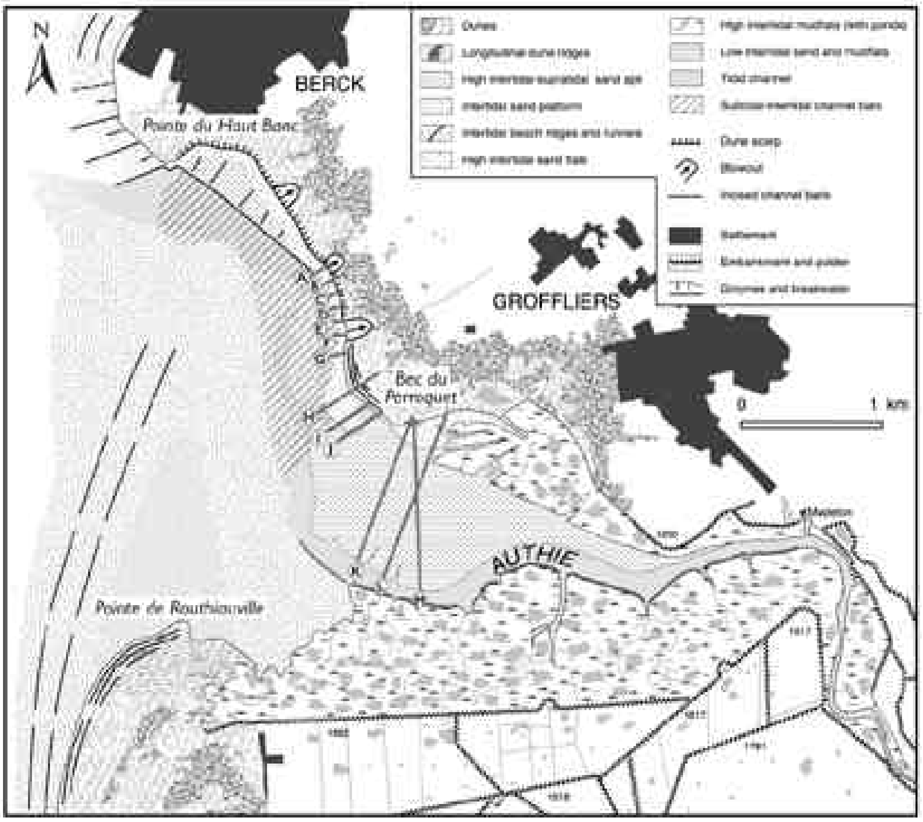

Figure 2. Morphology of the Authie, showing the advanced estuarine infill. A-M: Topographic profiles.

progressively extended northwards over the last three centuries, diverting part of the Authie channel towards the north bank and constraining it against the thick dune fields on this bank, where erosion has been a long acknowledged problem. This platform grades seaward into shallow linear coastal sand banks. The estuary exhibits a single 10 to 200 m-wide channel whose present position is controlled by the major accumulation features at the mouth of the estuary, notably the sand platform and the north bank intertidal flats of Bec de Perroquet (Figure 2). Near the mouth, the channel evolves into a 0.2 to 0.5 km-wide feature comprising a deeper narrow subtidal channel flanked by lower intertidal sand flats and sand bars. Channel depths in this deeper section are less than 3 m below mean spring low water. This narrower and deeper channel is quite mobile but stays confined within the wider intertidal channel zone constrained between the south bank spit platform and the north bank dunes.

Sands throughout the estuary mouth are homogeneous fine to medium (D_{50}=0.2-0.6 mm) quartz grains with shelly debris, except in parts of the main Authie channel where coarse sand and gravelly lag deposits rich in shelly debris are present. The finest sands are associated with the dunes. Sands are generally clean on the estuary-mouth sand platform but, on exposed intertidal sand flats on both banks of the estuary, they are less well sorted and admixed with upland-derived silt-sized materials brought down by the Authie.

The Authie is located on a macro-tidal coast subject to semi-diurnal tides. The mean spring and mean neap tide ranges at the mouth of the estuary are respectively 8.54 m and 4.89 m. These ranges decrease to around 4 m and 1.8 m, respectively, 7 km up the estuary. The spring tidal influence goes up to 16 km inland. Offshore of the estuary the water circulation shows bi-directional coast-parallel flow with clear domination by northward-directed flood currents of up to 1.5 m/s at spring tides (DOBRONIAK, 2000). Numerical modelling and sand tracer experiments of nearshore sediment transport in this area show a concentration of sand, derived from the English Channel, along a coastal transport corridor between the Somme estuary (Figure 1), and Belgium (BECK *et al.*, 1991; GROCHOWSKI *et al.*, 1993). This transport corridor is associated with numerous coastal sand banks that serve as conduits for residual sand transport to the north. It has been suggested that this sand transport 'belt' has directly sourced the massive dunes and infilled estuary mouths in northern France between the Somme estuary and Belgium during the Holocene (ANTHONY, 2000).

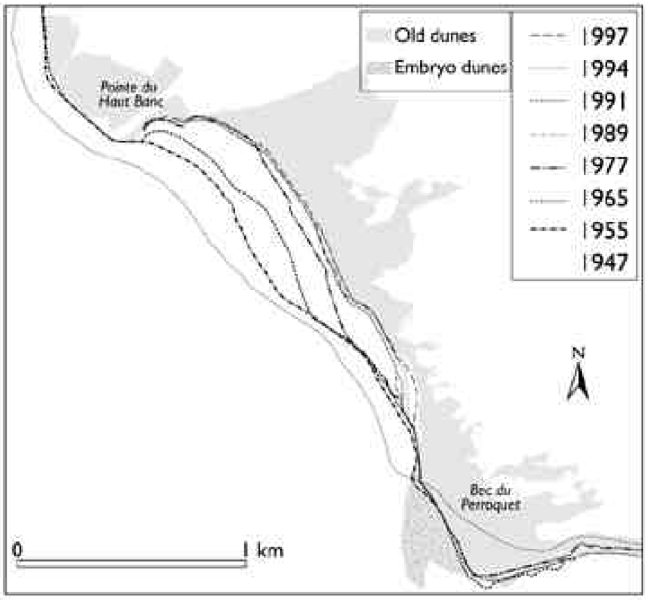

Figure 3. Changes in the position of the dune-bound northern shore of the estuary from scale-rectified aerial photographs.

At the mouth of the estuary, the highest predicted tides have a range of 9.99 m and are expected at the time of the spring and autumn equinoxes. Storms associated with low pressure zones in the western English Channel in winter can lead to rises of predicted water levels by over 1 m (DOBRONIAK, 2000). The large waves often associated with such storms lead to marked changes in channel and bar morphology at the mouth of the Authie. Wave records from pressure sensors deployed near the mouth of the estuary show that the coast is affected by short, dominantly westerly wind waves generated in the English Channel (DOBRONIAK, 2000). Wave periods range from 3 to 7 s, and significant wave heights from 0.25 to 1.5 m, commonly exceeding 2.5 m during storms. Because of the exposure, waves affect the north bank shoreline up to 3 km inland, providing the main mechanism for erosion of the north bank dunes. Winds play an important role in the mobilisation of intertidal and supratidal sediment within the estuary. The dominant winds affecting the estuary are from a south-westerly to westerly direction.

The meso-scale evolution of the north bank shoreline, summarised in Figure 3 from several series of scale-rectified aerial photographs, has involved pivoting of this shoreline towards a north-south orientation in the inner estuary, as a result of differential accretion and erosion (ANTHONY and DOBRONIAK, 2000). The photographs show that this involves a southward transfer of sand embedded within a mobile sediment cell characterised by an updrift erosional sector that feeds a depositional one further downdrift (Figure 3). Shoreline retreat has particularly affected the north bank up to profile D, while shoreline advance has been occurring further south, leading to the formation of the inner estuarine spit of Bec de Perroquet (Figure 2).

METHODS

The short-term morphological responses of the sediment stocks released by the long-term erosion of the north bank shoreline of the estuary have been monitored essentially through topographic profile surveys. The surveys were carried out from the dune front to the channel banks, over a one or two-year period from June 1997 to June 1999 using a high-resolution electronic total station (errors within ±3 mm for distance and height and ±0.0015 ° for direction). In order to highlight differences in shoreline behaviour from the mouth to the inner estuary, a total of eleven profiles (whose locations are shown in Figure 2) were surveyed. Each profile was tied to a benchmark of the French National Geodesic Service (IGN 69). The topographic survey data was also used to generate digital elevation models (DEMs) of the shoreline in the inner estuary, where significant sediment storage has been observed.

RESULTS

The long-term trend identified from the historical data and aerial photographs (Figure 3) is confirmed by the profile surveys between 1997 and 1999. Eight profiles have been selected from the original eleven to illustrate the progressive longshore variations in morphological responses to the long-term patterns of erosion and sedimentation (Figure 4). Profiles A and D, located in the erosion zone, highlight differences in the degree and rates of shoreline retreat. The profiles show, however, that a distinction needs to be made between short-term shoreline retreat and the beach sediment volume, especially in profile D. In both of these profiles, significant short-term retreat of the dune shoreline is accompanied by highly variable accretion of the beach. This trend is further confirmed by profile F (Figure 4), which shows significant beach level fluctuations that are more important, volumetrically, than the losses due to retreat of the dune cliff face. A relatively more stable configuration is exhibited by profile G, which shows more moderate dune face retreat and beach accretion. Profiles H, I and J, mark a clear change in morphology (Figure 4). On profile H, the beach segment in profile G is replaced by a highly irregular morphology consisting of a succession of semi-vegetated embryo dunes ranging in height from around 8 m near the beach to 12 m for the innermost ridge. At the outer edge of this complex of longitudinal dunes is a pronounced single ridge nearly 7 m

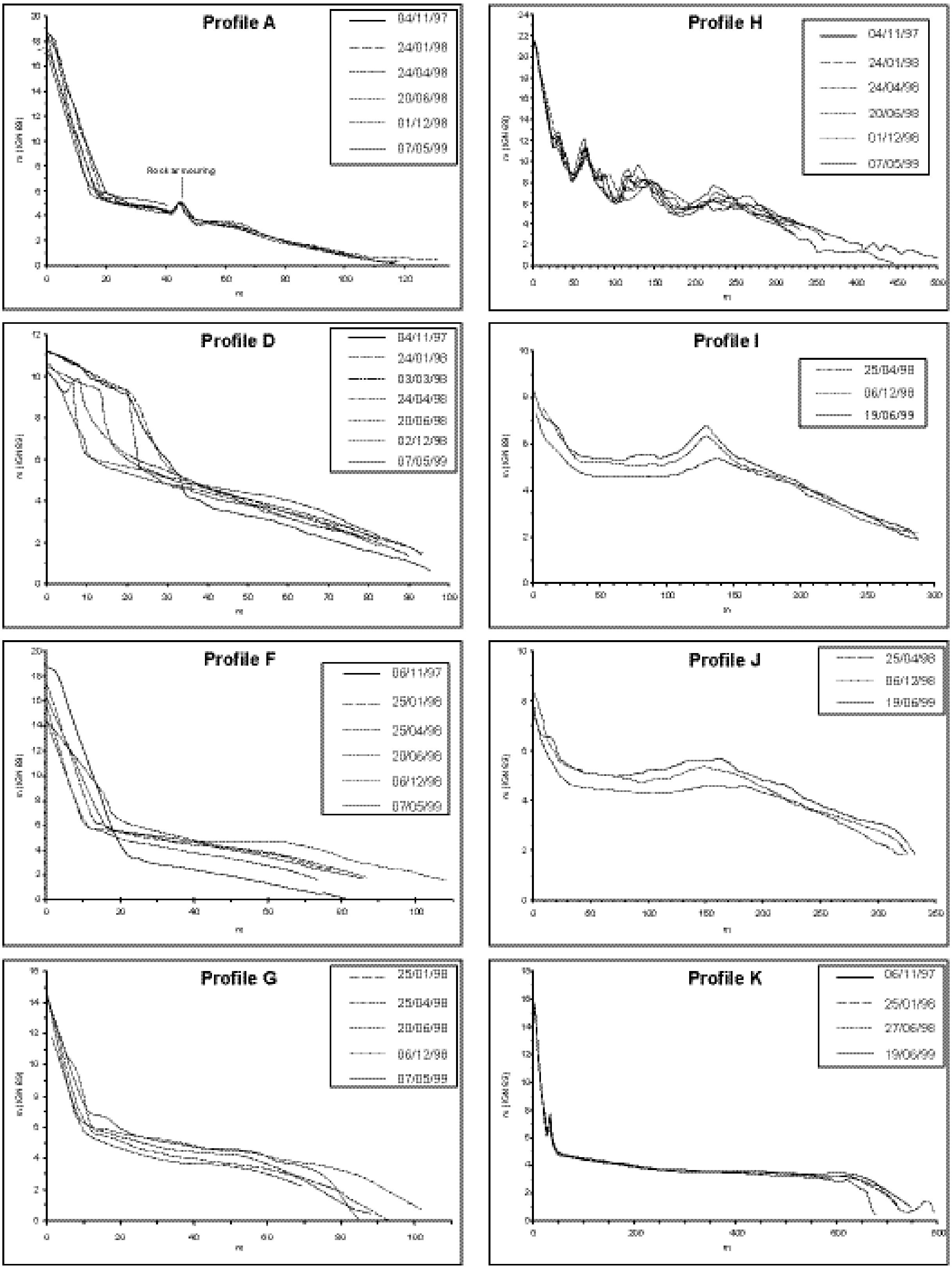

Figure 4. Profiles showing the variability of short-term erosion and accumulation on the north bank of the estuary. Height scale is relative to French sea-level datum (IGN 69).

high (Profile I). This then gives way to a relatively large and unpronounced dune ridge that attains a maximum height of nearly 6 m on profile J. Between profiles J and K is a transitional zone that has not been surveyed. This zone, designated mudflat in Figure 2, is characterised by muddy sand with isolated mounds of sand representing remnant aeolian dunes. Profile K (Figure 4) and the other profiles from this zone exhibit a completely different and monotonous morphology. Below a relatively stable dune occurs a gently sloping platform of muddy sand that gently grades seaward into a mudflat. The outer extremity of this mudflat is bounded by the sandy channel of the Authie. Bed level changes in the profiles from this zone are insignificant at the scale of these short-term topographic surveys, except near the channel, where changes are much more marked. Profile K, in particular, shows a significant retreat of the mudflat bordering this channel. However, this zone shows more significant overall meso-scale accretion that will be discussed below.

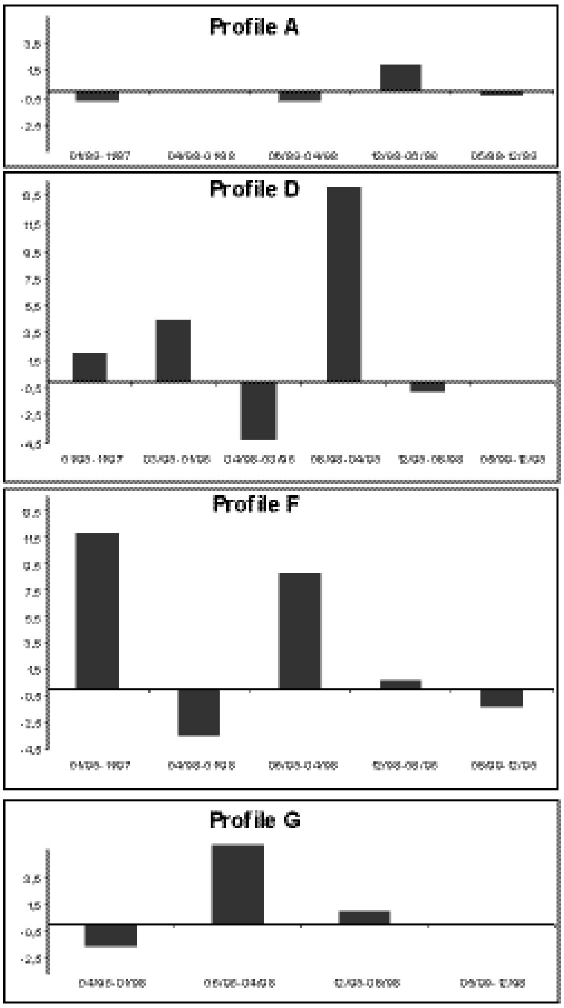

Figure 5. Beach volumetric fluctuations for selected profiles.

DISCUSSION

The data from the profile surveys show that the short-term morphological responses to the long-term alternations of erosion and sedimentation affecting the north bank of the Authie estuary vary alongshore. Profile A is a zone of moderate dune face erosion (Figure 4). Accumulation on the beach, both in front of, and behind the rock armouring put in place in the 1980s to protect the dune, is also rather moderate. It is clear from both morphological and hydrodynamic evidence from this sector that the breakwater, built together with this dune base protection, limits wave attack of the dune cliff face (DOBRONIAK, 2000). The aerial photographic evidence shows that this wave-exposed sector was hitherto the most strongly eroding zone of the Authie estuary (Figure 3). Further east, on profile D, dune cliff retreat is extremely variable, but may attain important short-term rates. In the face of stabilisation of the profile A sector, satisfaction of sand supply continuity has led to a downdrift shift in the erosion (and source) zone, and explains the massive shoreline retreat in the unprotected sector of profile D (Figure 4). Short-term variability is essentially dependent on the local hydrodynamic conditions. It reflects, in particular, the variability of the coincidence of storms with high spring tides that are most favourable to dune scarping (ANTHONY and DOBRONIAK, 2000). While wave activity is most pronounced at the mouth of the estuary, storm wave effects are felt well within the estuary. Waves from a westerly direction, i.e. those with the largest fetch and from which come the higher waves, can be particularly effective against this part of the estuary.

Within this framework of short-term shoreline instability, the beach serves as an important temporary storage zone for sand released by dune erosion. Hence the substantial short-term accretion shown by profiles D and F. The marked variability of the beach level in these profiles implies large beach volume fluctuations (Figure 5) that clearly point to sand recycling, essentially towards the inner estuary. In places, such recycling may occur through blowouts formed by wind erosion of the dune front, such as between profiles F and G (Figure 2). Much of the sand, however, is transported alongshore southwards towards the Bec de Perroquet spit platform. This progressive southward shift of the sand mass released by dune erosion is highlighted by three successive digital elevation models covering the profile survey sector (Figure 6). The DEMs show significant short-term downdrift extension of the sand load derived from this dune retreat. The reason for the massive accumulation of sand in this zone resides in the temporal alternations of episodic events of storm wave set-up associated with high spring tides, and long periods of calm conditions during which sediment mobilisation is restricted to the Authie channel. Mobilisation of this sand is assured

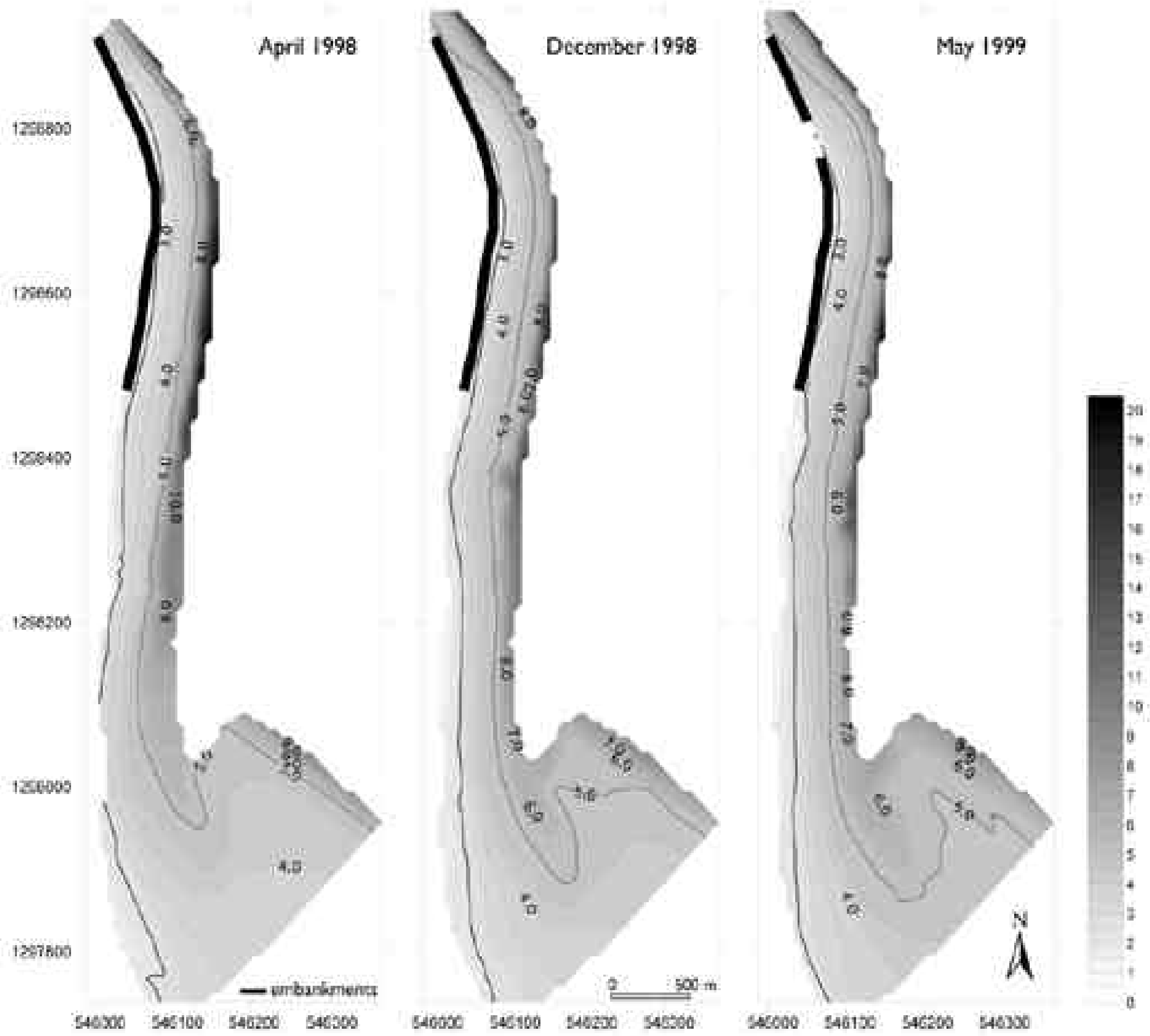

Figure 6. Digital elevation models of the north bank shoreline covering a one-year period. Note the significant southward progression of the tip of the sandy accumulation.

by both waves and currents associated with tides and wind forcing, and by wind blowing of exposed sand at low tide.

Over time, this excess load has built out and aggraded to form the Bec de Perroquet platform. The basal part of the platform is a shallow sand sheet whose superficial, supratidal part has been moulded by westerly winds into the longitudinal dune ridges on profile H, the most recently formed of which consist of highly mobile sand. The short-term southward progression of the sand load from which this platform has been built up is recorded in the mobile dune ridge on profiles I and J (Figure 4). Profile J shows the low distal tip of this presently developing ridge. Field observations show that the tip of this dune ridge is accreting over the sandy-muddy transitional substrate to the mudflat zone of profiles K and M. Profile J is thus succeeded downdrift by an area of sand spill-over onto the mudflat zone. The tip of this dune ridge may eventually become progressively dismantled and recycled by storm waves and tidal currents into the intertidal estuarine sediment sink fronting the Bec de Perroquet, as suggested by the eroded remnant dune mounds found on the transitional sandy-muddy platform.

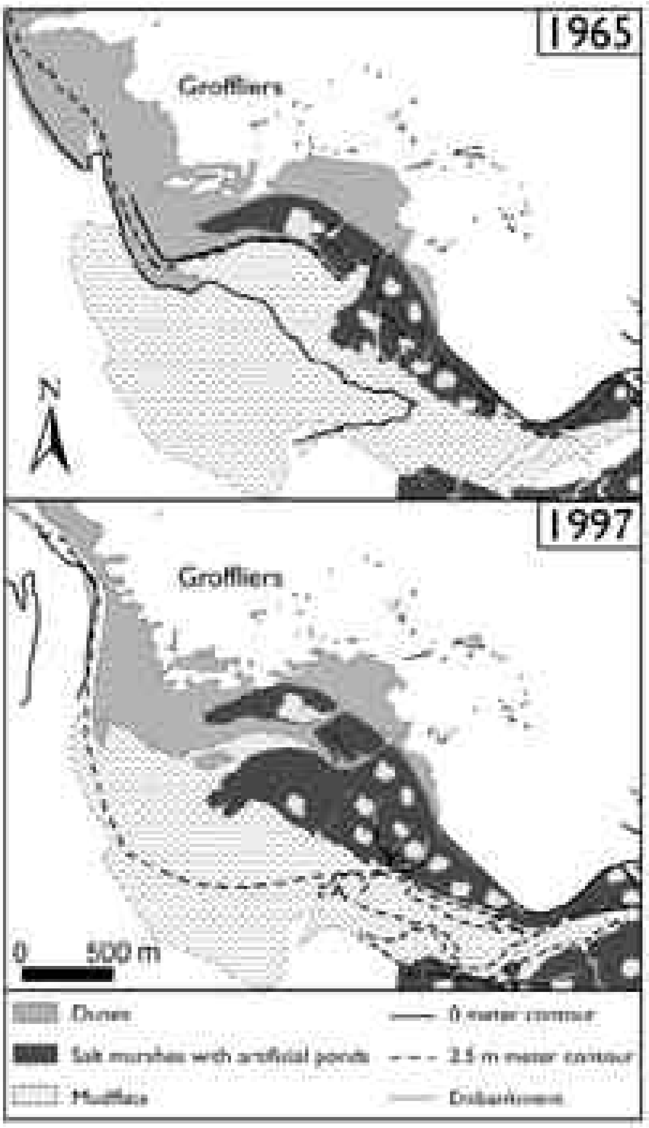

Figure 7. Morphological changes in the accumulation zone of Bec de Perroquet between 1965 and 1997. The 1997 map shows significant accretion of the mudflats and extension of the salt marshes. Accretion has been largely assured by recycling of the dune sand accumulations bordering the Authie channel in 1965 into the intertidal estuarine sink.

This aggradational process is clearly highlighted by a comparison of two maps covering this part of the estuary (Figure 7). The 1997 chart shows recycling of the longitudinal dunes present on the 1965 map into the intertidal estuarine sink, leading to the build-up of the area formerly covered by the 0 m contour and the important extension of salt marshes. The annual accretion rate in this zone deduced from the change in this contour line attains up to 1 cm/yr, insufficient to be detected by a two-year topographic profile survey, but sufficiently high at the meso-scale as to engender significant morphological changes. The superficial sediment cover and shallow cores (<0.5 m) obtained from these sediments show that the sand derived from dune erosion is incorporated into sandy-muddy intertidal deposits that provide a shallow substrate for rapid fine-grained sedimentation. Much of the sand eroded from the north bank of the Authie thus ends up feeding accretion of the tidal flats south of Bec de Perroquet, bringing the surface of these flats close to mean high spring tide level in places. This is enabling widespread salt marsh development. The progressive southward extension of the embryo dunes and dune ridge towards the Bec de Perroquet shelters the mudflats and salt marshes from direct wave attack. However, recycling of the sand from this dune sand reservoir into the intertidal estuarine sink may locally lead to stifling of salt marsh vegetation.

CONCLUSIONS

The foregoing analysis shows that the sand released during storm wave attack of the dune-lined north bank of the Authie estuary is recycled successively as beach, dune, and finally estuarine deposits. The sand is temporarily stored on the intertidal beach, and then transferred onto longitudinal dune ridges further inside the estuary, by both wave-current reworking and winds, although limited back-cycling may occur into dune blowouts. This sand finally ends up building up mudflats and salt marsh substrates. Although no overall sediment budget analysis has been undertaken for this estuary, the transport pattern along the north bank shoreline shows that this is an important source and pathway for the infill of the inner estuary. Hydrodynamic measurements, sediment transport monitoring and bedform observations show that bedload transport towards the inner estuary through the main mouth pathway is weak, probably in response to massive past accretion of the estuary-mouth sand platform, and is largely compensated by strong ebb evacuation of sand within the main estuarine channel (DOBRONIAK, 2000). As a result, the north bank shoreline transport pathway probably constitutes the present major infill pathway of the inner estuary. Since much of the suspension load within this estuary comes from upland, brought down by the main channel, the accretion of sand engendered through this transport pathway is also important in encouraging fine-grained deposition within this inner part of the estuary. This important input of dune sand into the intertidal estuarine sink, and the enhanced mud accumulation and salt marsh development it causes, accelerate the silting up of this estuary.

ACKNOWLEDGEMENTS

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