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Beach-dune systems of the North of France: a dynamic equilibrium?

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Key words: aeolian dynamics, foredune, macrotidal sandy beaches, dynamic equilibrium, Côte d'Opale

Abstract: Beaches and foredunes belong to morphologic systems, which depend not only upon marine and aeolian dynamics, but also upon sediment supply. In the North of France, two sites have been studied during the last ten years: Merlimont and Bray-Dunes. Both are macrotidal sandy beaches with well developed foredunes and incipient dunes. The effect of storm events strongly depends upon the tidal environment. The immediate consequences of a storm can be spectacular, with sand cliff formation and several meters shoreline retreat. Nevertheless, on a longer time scale, German bunkers and aerial photographs prove a remarkable stability over the last 60 years. Thanks to an abundant nearshore sand supply, there is a rapid adjustment of the beach and foredune profile leading to a morphologic equilibrium of Merlimont and Bray-Dunes coastal systems. Equilibrium mechanisms work only if sediment exchanges and natural processes are not inhibited by human interventions.

Introduction

All over the world, beaches constitute an important regional tourism resource. So users and managers have to know if beaches and dunes, which border them, are threatened by coastal erosion. The degree of resilience of coastal systems (their ability to resist to disturbances) is a very important property to take into account for a sustainable development and management. To resolve this problem, the geomorphologists have a decisive role, because they can give sound information on the beach and dune dynamics and estimate the sediment budget. To give relevant data to the managers, they must consider the whole coastal system and not only the beach alone. The example of the northern French coast will serve to illustrate this way of thinking.

The 160 km long Côte d'Opale extends along the French coast of eastern English Channel and southern North Sea, from the Authy estuary to the Belgian border (Fig. 1). Beaches and dunes are present on two thirds of this coast (Battiau-Queney et al., 2001). Two sites are specially considered in this paper: 1°) Merlimont Beach, which represents the Picard type: dunes are organised in two distinct fields; the shoreline is approximately south-north (perpendicular to the prevailing winds); 2°) Bray-Dunes Beach, which typifies the Flemish coast. It is characterized by only one dune field. The coast is WSW-ESE, then nearly parallel to the western prevailing winds.

The beach-dune system

A beach-dune system is just a peculiar type of morphologic system (Fig. 2). It works thanks to a source of energy, which enters permanently into the system, but with large spatial and temporal variations. This energy keeps the marine and aeolian dynamics up. When working the system creates landforms within a spatial unit called the morphosedimentary cell. Along the Côte d'Opale, the morphosedimentary cell includes

- the foredune,
- the beach (strictly speaking), which is here the intertidal zone, limited inland by the swash upper limit and seaward by the lowest sea level;
- the nearshore (as opposed to the backshore including beach and dune) (*avant-plage* or *petits fonds* in French), which is the wave shoaling zone, where sediment is transported to the beach or exported seaward.

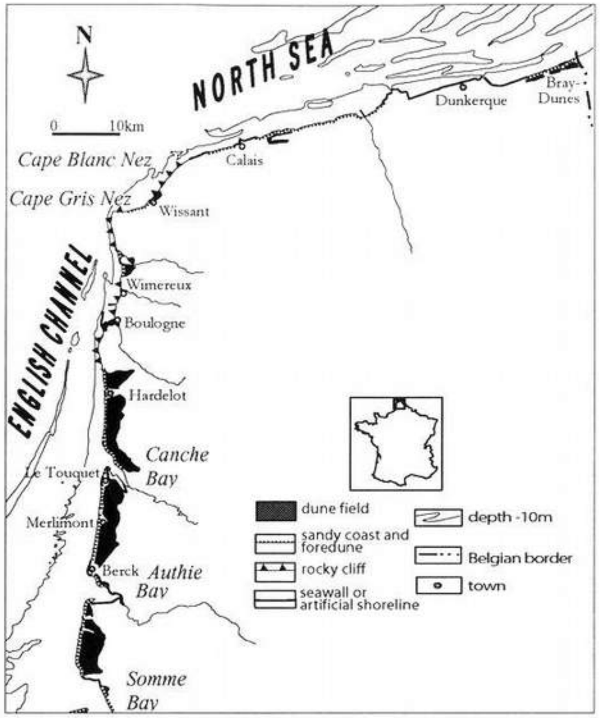

Fig. 1. Location map

Foredune, beach and nearshore are not independent from each other, but, on the contrary linked through continuous sediment exchanges. Their boundaries are neither impervious nor stable: they migrate continuously, at least on a short time scale.

Morphosedimentary cells are not closed: the coastal system is an open system. All along the Côte d'Opale, fluvial inputs are negligible, but the cells receive sediment either from the longshore drift or transverse currents from offshore. They lose sediment either offshore or through the longshore drift. On the Côte d'Opale beaches, the sediment transport by the longshore drift is considered to be balanced (in each coastal cell, inputs equal outputs). On the contrary inputs and outputs from and to the lower shoreface and offshore are less well known, despites their importance in the sediment budget of the coastal system. Other uncertain data concern the volume of sand, which is trapped in the foredune, which works as a sedimentary sink.

The effect of tide on the beach-dune system

At Merlimont, spring-tide ranges exceed 8 m giving very wide (up to 900 m) gently sloping beaches (0.5 to 0.6°) (Fig. 3a). The prevailing winds blow nearly perpendicularly to the shoreline. Bray-Dunes has a lower spring-tide range (from 4 to 5 m); the intertidal zone is 400 to 450 m wide (Fig. 3b). The prevailing winds blow close to the direction of the shoreline, but there are also a few strong storms coming from the North. At Merlimont and

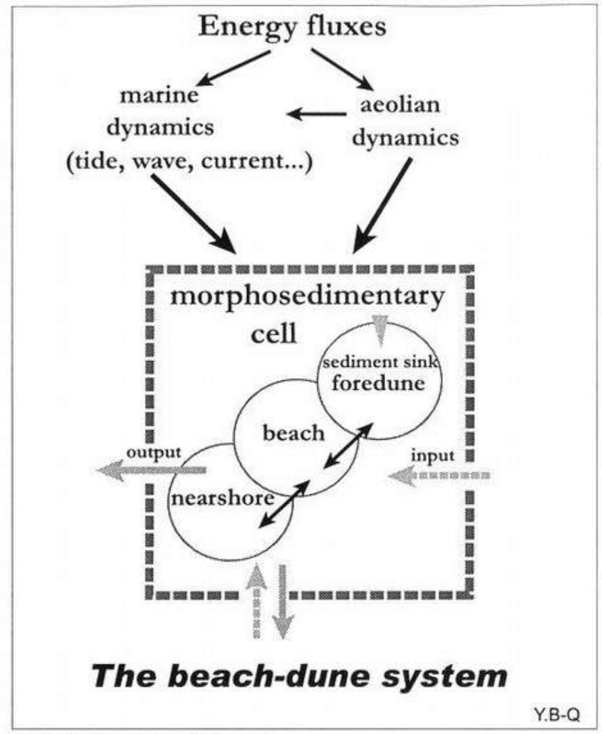

Fig. 2. Sketch of the beach-dune system

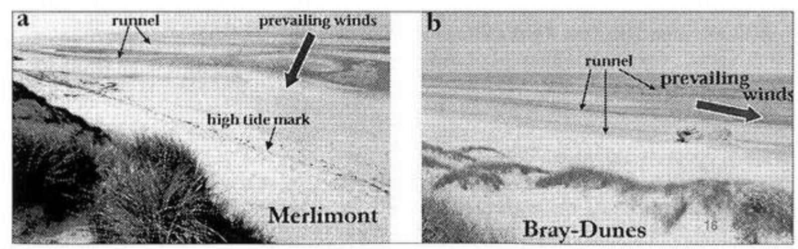

Fig. 3. Typical ridge-and-runnel morphology of macrotidal beaches at low tide.

a. Merlimont beach. The north-south oriented shoreline is almost perpendicular to the offshore prevailing winds. In front of picture, the foredune is covered with dense *Ammophila arenarium*.

b. Bray-Dunes beach. Here the prevailing winds and shoreline have nearly the same orientation. The bunker located on the beach dates from the First World War. It was already in this position 60 years ago and was used for the training of German soldiers. In front of picture, incipient dunes with *Elymus farctus*.

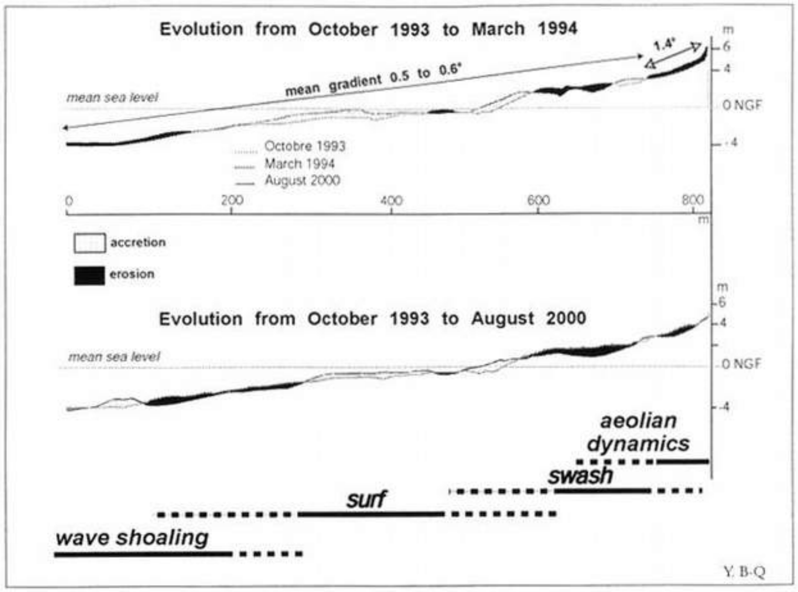

Fig. 4. Beach-profiles and dynamics zones at Merlimont

These profiles were realised respectively in October 1993, March 1994 and August 2000, from the lowest sea level to the foredune foot, during a large spring tide. The intertidal zone is more than 800 m wide. The different dynamics zones (wave shoaling, surf, swash and aeolian) are indicated below. They migrate twice on the beach profile, during a single tide cycle. The swash processes work only a very short time on the upper beach, except when a storm event coincides with high tide.

Bray-Dunes, the ridge and runnel morphology is well developed (Sipka, 1998; Levoy et al., 1998; Corbau et al., 1999) and the high tide mark (*laisse de mer)* is at several dozen metres from the dune foot. The beach sand is well sorted, fine or medium-fine (median around 250 microns).

Macrotidal ranges have an important effect on the beach morphodynamics (Masselink & Turner, 1999). Beach profiles are presented here (Fig. 4), which were realised on Merlimont Beach from the lowest sea level to the foredune foot, during a large spring tide. The intertidal zone is more than 800 m wide. During a single tide cycle (12 hours and 20 minutes), the surf and swash zones migrate twice on the beach profile. The rising tide lasts 5h 15 environ, the falling tide is longer (approximately 7h 05). So, the rate of tidal translation is faster when the tide is rising (150 m per hour). The swash processes work only a very short time on the upper beach: less than 2 hours, during the flood settling lag.

Storms add a non-periodic component to the tide effects. When they occur during neap tide they have a negligible effect. On the contrary, when they occur during a high spring tide, a surge can add 1 to 1.5 m to the «normal» sea-level, with two main consequences: 1°) a longer period of swash processes on the upper beach, 2°) deeper water increasing the wave energy in the surf and swash zones. So storm hazards are much more infrequent in case of macrotidal beaches, than in case of microtidal beaches. From these considerations we propose the concept of «morphogenic storms».

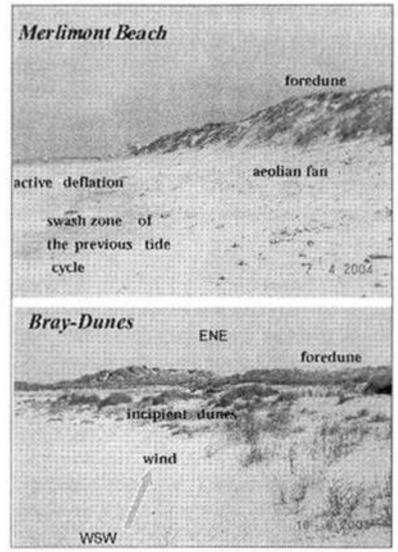

Fig. 5. Active aeolian dynamics on the upper beach

Above, Merlimont beach; the picture was taken during a very high tide, in April 2004.

Below, Bray-Dunes beach during a high spring tide; aeolian dynamics create incipient dunes thanks to a dense pioneer vegetation. *Cakile maritima* and *Elymus farctus* are the most frequent species. In the rear, dune fences are partially buried.

The effect of wind on the beach-dune system

Along the Côte d'Opale, the foredune foot is generally (that is in "normal" conditions, and not in storm conditions) not situated within the swash zone. During the tide cycle, a wide part of the beach is directly affected by aeolian dynamics (Battiau-Queney, 2004). The swash upper limit (or high water mark) is normally located at a few tens metres from the foredune foot. Runnels act as sand traps, which are efficient when the wind is moderate. But when the wind speed reaches or exceeds 50 km/hour (stage 7 on the Beaufort scale), aeolian deflation is active on the whole middle and upper beach, especially in winter when runnels are less deep. In fact, a huge volume of sand is exported inland from the beach. Along the Côte d'Opale, each summer, several ten thousands cubic metres have to be removed from the sea-front area of the main seaside resorts (40,000 to 120,000 m^3 at Le Touquet) (Dewailly, 1980).

Sand is transported and deposited on the upper beach and supplies the foredune. It creates an aeolian accretion fan at the foredune foot or/and incipient dunes associated with the pioneer vegetation (Fig. 5). At Bray-Dunes, dune fences are rapidly buried and a series of topographic profiles revealed that the foredune height has increased considerably during the last 5 years (Brulez, 2002). It is a general evolution on many Côte d'Opale beaches. So the foredune and upper beach act as a sedimentary sink, which contributes to morphodynamics adjustment after storm disturbances.

Morphogenic adjustment of the beach-dune system

Marine erosion of the foredune and upper beach is active in case of combined storm and high spring tide (Fig. 6). On the top pictures showing the Merlimont Beach, a storm event was associated with high spring tide. The sea level rose unusually and swash processes created a sand cliff in an ancient aeolian fan at the foot of the dune. Incipient dunes were destroyed. The storm effect was spectacular. Most people at that time thought that it proved a rapid marine erosion and shoreline retreat, leading eventually to the destruction of the foredune itself.

Nevertheless this prediction was not confirmed at all: on the same site 7 years later, the beach and dune profile has completely changed. The system had enough time to adjust toward equilibrium, despite high spring tide a week before and several slight storm events the years before. It clearly appears that the Côte d'Opale beach dune systems have a short geomorphic relaxation time. The dune sand reserve is immediately put again into circulation within the coastal system, when a storm occurs. It is important to note that the construction of a dyke at the emplacement of

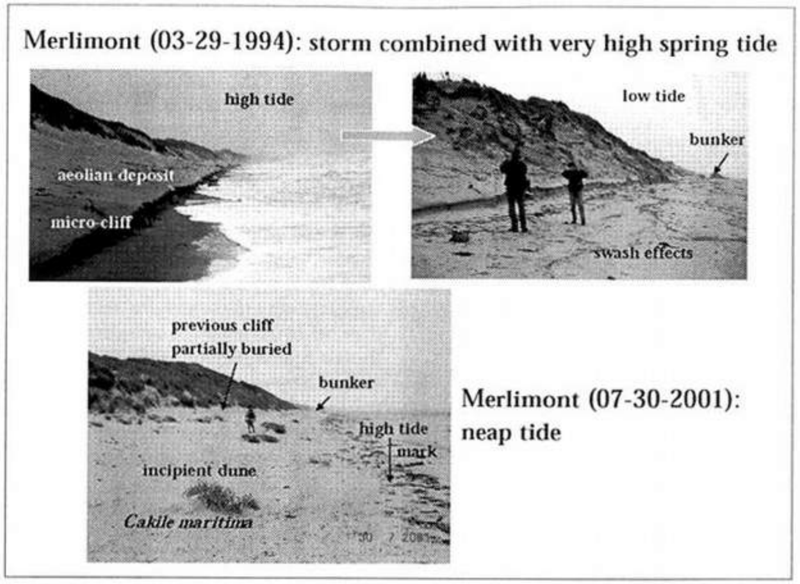

Fig. 6. Short time resilience of upper beach morphology at Merlimont

On the top, spectacular effect of a storm event associated with high spring tide. The sea level rose unusually and swash processes created a sand cliff in an ancient aeolian fan, which formed at the foot of the dune. Incipient dunes were destroyed.

Below, same site 7 years later. The beach-dune system had enough time to adjust toward equilibrium.

the foredune will prevent any natural adjustment of the beach profile after a storm. It leads to major erosion problems, sand shortage and beach profile lowering, as it is presently observed at Wimereux, Wissant and Hardelot (Clabaut et al., 1986; Battiau-Queney, 2003).

If sand exchanges were just active between beach and foredune, the volume of sand in the foredune and the beach level would not vary notably after each adjustment following a morphogenic storm. In fact, another evolution was observed: on a longer time scale (60 years), the height of the foredune has increased despite a relatively stable beach profile. At this time scale different methods are used to evaluate the shoreline retreat rate and foredune change. The first of them is the comparison of aerial photographs, once they are ortho-rectified and put at the same scale. Analysis of the first aerial photographs (1942-1947) shows the absence of foredunes on several parts of the coast, contrary to the present situation. Large parabolic dunes were directly linked with the beach. Today, these parabolic dunes are located inland and separated from the beach by the foredune. They can no more be supplied by the beach sand. Bunker archaeology is another original method. German bunkers, which were built in 1942-1944 are good tools and references, if their original military purpose is known (Lanoy-Ratel, 1998, 2004). If they are correctly used, German bunkers indicate not only the position of the ancient shoreline but also the precise foredune geometry in 1942-1944 (height and profile). Applied to the Bray-Dunes Beach, bunker archaeology proves two things: 1°) the shoreline retreat was negligible over the last 60 years; 2°) the foredune height and volume

increased more or less severely. Just after the War, human interventions (dune fences) help to raise the foredune, but this phenomenon would have been inefficient without natural processes. Applied to the Merlimont Beach, along the Biological Reserve, bunker archaeology reveals just a slight shoreline retreat (less than 30m over the last 60 years).

While the foredune was thickening, the relative or total stability of the shoreline means that the beach profile has not seriously lowered since the last War. There is not only a rapid adjustment (a few years) of the beach profile after each geomorphic storm event but also, on a longer time scale (50-60 years), a morphologic equilibrium. It implies considerable sand supply to compensate the foredune sediment sinking. So another sediment reserve exists, which nourishes the upper beach and foredune. This reserve is located nearshore where is a wide complex of sand bars (Larsonneur et al., 1982). Nevertheless the precise adjustment mechanism, which leads to the beach profile equilibrium and foredune development, is unknown. Some research has still to be done to explain sediment exchanges between nearshore sand bars and the beach. We do not know also why foredunes have rapidly increased after the War, along many Côte d'Opale beaches. The spreading of myxomatosis after1952 and nearly extinction of rabbits could have been a factor, which added to human interventions to help sand trapping.

Conclusion

The macrotidal beach-dune systems of Merlimont and Bray-Dunes seem to be in dynamic equilibrium:

- Storm effects depend upon the simultaneous tide range: heavy storms are inefficient if they happen during neap tide.
- Rapid adjustment is observed after an «efficient» storm: wind-transported sand accumulate on the upper beach and foredune sea face. The foredune acts as a sediment reserve, a part of which goes back to the beach during an efficient storm.
- The beach receives abundant sand supply from nearshore bars.
- In the present regional morphodynamics environment, most beaches of the Côte d'Opale are not threatened by marine erosion. On the contrary, strong erosion problems occur when foredunes were destroyed, built or replaced by dykes.

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Caractérisation d'erreurs sur un modèle numérique de terrain en fonction de zones morphologiques des versants

Frederic ROUSSEAUX[1], Florina GRECU[2]

Mots clés: modèl numérique de terrain, methode d'interpolation, talwegs, versant, erreur altimetrique

Caracterizarea erorilor pe un model numeric al terenului în funcție de unitățile morfologice de versant. Articolul prezintă impactul pe care le au erorile unui model numeric al terenului asupra simulării inundațiilor. Obiectivul principal al articolului este studierea repariției spațiale a erorilor, a cauzelor acestora. Repartiția spațială a erorilor depinde de relief, de cantitatea de informații pe care o include acesta și care poate fi redată în MNT. Astfel, în modelul realizat, interfluviile plate, talvegurile, versanții denivelați prin alunecări profunde prezintă erori datorită echidistanței dintre curbele de nivel. Stabilirea arealelor cu erori și apoi eliminarea acestora sunt deosebit de importante și din punct de vedere practic-aplicativ, cum ar fi riscul la inundații.

Introduction

Dans cet article, nous traitons de l'impact des erreurs dans le cadre de simulations de risque. Les modèles numériques de terrain (MNT) sont souvent utilisés dans ce type d'applications sans que l'utilisateur n'aie quantifié l'impact de ces erreurs sur ses résultats de simulations (Wechsler, 1999). Selon (Hottier, 1990), et plus récemment (Wise, 2000), l'exactitude d'un MNT est liée au mode d'acquisition des données et à son mode de construction. Nous ne traitons pas ici des erreurs liées aux données qui ont servi à la construction du MNT. De nombreux travaux ont déjà montré l'importance de la précision des données initiales sur la qualité globale des MNT (Carter, 1992 ; Chang et al, 1991). Par ailleurs, il a aussi été montré que le type d'interpolation choisi, à partir du même type de données en entrée, donne des résultats similaires en termes de précision globale (Carrara et al, 1997).

L'objectif de cet article est d'étudier la répartition spatiale, puis l'impact des erreurs qui sont récurrentes quelque soit le type d'interpolation choisi. Une erreur est la différence entre la mesure d'une grandeur et sa valeur réelle. A partir des mêmes données en entrée (courbes de niveau), nous comparons un MNT avec des valeurs de contrôle exogènes supposées plus « exactes » pour localiser, puis évaluer ces erreurs sur le MNT. Nous utilisons comme donnée altimétrique de référence un MNT à très haute résolution acquis grâce à la technologie LIDAR.

Nous supposons que la répartition spatiale des erreurs les plus importantes n'est pas dépendante du choix de l'interpolation mais du type de relief. Dans un premier temps, nous mettons en évidence la similarité des zones d'erreurs récurrentes sur différents types de MNT. Nous montrons, dans un second temps, l'impact des erreurs sur ces zones et leurs effets sur les principaux paramètres topographiques (altitude, pentes). Ces zones d'erreurs sont généralement liées à un manque d'information sur les structures importantes du terrain (crêtes, talwegs). Mais, même si il existe des méthodes pour résoudre ces problèmes (Jaakkola et al, 2000), elles ne sont globalement prises en compte que par une faible minorité d'utilisateurs (Wechsler, 1999).

Nous concluons par une discussion sur les avantages qu'apporterait une caractérisation