Journal of Coastal Research	17	3	694–704	West Palm Beach, Florida	Summer 2001

Neglected Effects of Eolian Dynamics on Artificial Beach Nourishment: The Case of Riells, Spain

Maria Angels Marqués†, Norbert P. Psuty‡, and R. Rodriguez§

†Department of Geodynamics and Geophysics
Faculty of Geology
University of Barcelona
Zona Universitat
Pedralbes
08028 Barcelona, Spain

‡Institute of Marine and Coastal Sciences
Rutgers University
New Brunswick, NJ 08903, USA

§Department of Astronomy and Meteorology
Faculty of Physics
University of Barcelona
Zona Universitat, Pedralbes
08028 Barcelona, Spain

ABSTRACT

MARQUÉS, M.A., PSUTY, N.P., and RODRIGUEZ, R., 2001. Neglected Effects of Eolian Dynamics on Artificial Beach Nourishment: The Case of Riells, Spain. *Journal of Coastal Research,* 17(3), 694–704. West Palm Beach (Florida), ISSN 0749-0208.

Beach nourishment projects have been systematically analyzed from a number of perspectives. However, although studies have evaluated the suitability, performance, and impacts of beach nourishment, the analyses seldom include wind effects. The eolian transport triggered by beach nourishment is examined at Riells, Spain, where the beach was augmented to accommodate tourism. This case study focuses on the unprecedented geomorphological impacts associated with eolian processes and the large quantities of sediment (*ca.* 20 m^3/m of beach) mobilized within the nourishment area to be transferred to the upper beach and some into the adjacent road and residential community. Geomorphological research from the area provides a perspective on past and present eolian dynamics. The analysis at Riells describes the environmental conditions for the geomorphological response to the beach surface area increase and hence sand availability. Thus, it provides information on an ancillary outcome of beach nourishment and identifies a need to incorporate eolian transfers in the evaluation of impacts and cost of beach nourishment.

ADDITIONAL INDEX WORDS: *Beach fill, beach fill evaluation, eolian transport, coastal sedimentation, Mediterranean coast, Catalonia, coastal management.*

INTRODUCTION

Beach nourishment is a widely-used technique in coastal management. Appropriate application of this approach requires an adequate knowledge of the following: its interaction with the ambient conditions, its technical feasibility, and an economic cost-benefit analysis of the complete beach nourishment project.

Existing literature on the evaluation of sand loss and sand transport after beach nourishment concentrates on the marine processes (NATIONAL RESEARCH COUNCIL, 1995). Winnowing of fine material, slope adjustments, losses from the ends of the fill (including the effects of structures if present), and previous erosive processes are the most prominent causes of modifications to the emplaced fill (DEAN, 1983). The compressibility of marsh deposits under fill loading has also been considered as a factor affecting the performance the sand unit (DEAN, 1983). However, with the exception of an early observation by DRAGA (1983), an inclusion within a total loss calculation by PHILLIPS, *et al.* (1984), and a site specific study by VAN DER WAL (2000) there are few references to sand losses from the fill as a result of eolian processes.

The removal of sand from the source area and its deposition on the beach are of prime importance in the analysis of short-term and long-term environmental impacts associated with artificial beach nourishment. According to the Committee on Beach Nourishment and Protection (NATIONAL RESEARCH COUNCIL, 1995), most of the evaluative emphasis was placed on beach impacts, with less attention paid to the recovery of offshore sand sources and associated biota. The conditions of change and recovery were seen as areas of major concern to this Committee and the members strongly recommended suitable multidisciplinary programs to evaluate changes in the physical and environmental conditions attendant to beach nourishment projects. However broadly this analysis was intended, the resulting review of beach nourishment contains no reference to the effects of eolian processes on the modification of the emplaced fill nor the environmental and social impacts of eolian transport out of the beach system.

Conceptually, the understanding of the specific processes forcing responses in a particular stretch of coast has both intellectual value as well as importance for management decisions and coastal utilization. The full gamut of knowledge of sediment mobilization associated with beach nourishment should be part of the decision-making process. PASKOFF (1992) indicates that both the understanding of short term and local effects and the knowledge of large-scale coastal behavior provide the necessary background for designing a program of coastal management. This approach incorporates the oppor-

99114 received 19 December 1999; accepted in revision 17 October 2000.

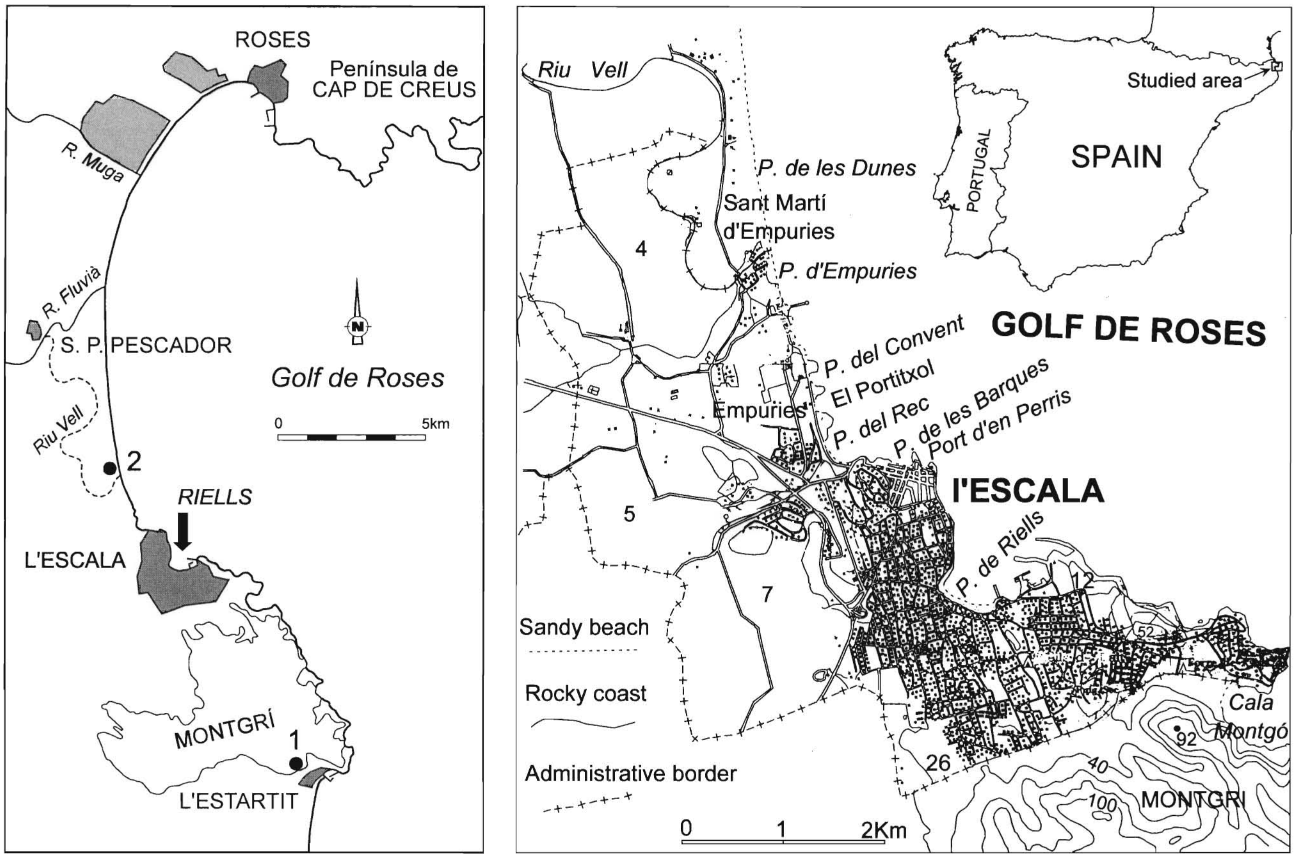

Figure 1. A) General study area with the Gulf of Roses and locations of L'Escala, Riells Beach, the meteorological station in the Montgri massif (point 1) and the zone of sand mining (point 2). B) Details of the L'Escala municipality, with locations of pocket beaches (such as Platja (P.) de Riells).

tunity for changing environmental conditions which could have a detrimental effect on human facilities and activities. He stresses the importance of a historical perspective and the need to study shoreline evolution from anthropomorphic and sedimentologic points of view through the past century. This current study attains these objectives by identifying the site and situation of sediment mobility at Riells Beach in the context of the modern beach nourishment episode and by placing it within the geomorphological regime of eolian sediment transport associated with historic and pre-historic intervals of sediment delivery at Riells.

RESEARCH PROBLEM

This paper considers the conditions and characteristics of a beach where an artificial beach nourishment project was undertaken to enlarge the beach for the purposes of tourism, not to counteract beach erosion. The beach fill subsequently interacted with the ambient processes resulting in large quantities of eolian transport inland. Whereas the sediment transfers surprised the local authorities, an analysis of the historical coastal geomorphology provides a background and understanding of the importance of eolian processes in this setting. Specifically, this study examines: a) the role of eolian processes in the performance of a beach nourishment project; b) the inclusion of these processes in the design and monitoring of beach nourishment; and c) the application of information furnished by existing regional geomorphologic research in the management and decision-making processes.

STUDY AREA

Economic development on the Mediterranean coast in Spain is mainly based on tourism. In Catalonia (northeastern Spain), as in many other countries, sandy beaches are of prime importance to the tourist industry (GENERALITAT DE CATALUNYA, 1984). The general characteristics of the Costa Brava (rugged or wild coast) consist of a rocky coastline with cliffs exceeding 100 m in height, interspersed with numerous sandy pocket beaches and coves in which the opportunities for tourism may be limited by the physical dimensions of the beach. The two largest beaches in northern Catalonia are the Gulf of Roses (approx. 16 km in length) (Figure 1) and Pals beach (about 10 km in length). Given the weather and the vacation period in Europe, the tourist season is short and intense and tourism is concentrated in locations offering appropriate amenities.

In the 1980s, the General Directorate of Ports and Coasts (a division of the Ministry of Public Works (MOPU, Ministerio de Obras Públicas y Urbanismo)) brought about a

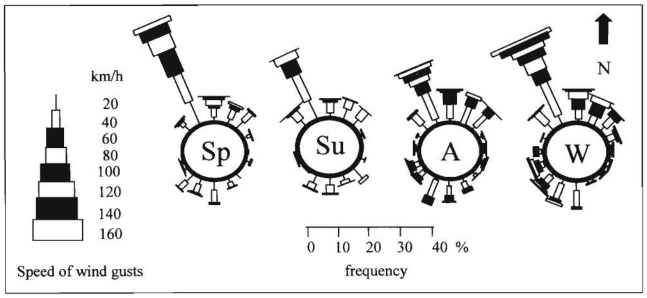

Figure 2. Seasonal wind roses and the per-cent frequency of daily maximum wind gusts in particular speed categories for each compass direction (period 1988–1994). Sp = Spring, Su = Summer, A = Autumn and W = Winter.

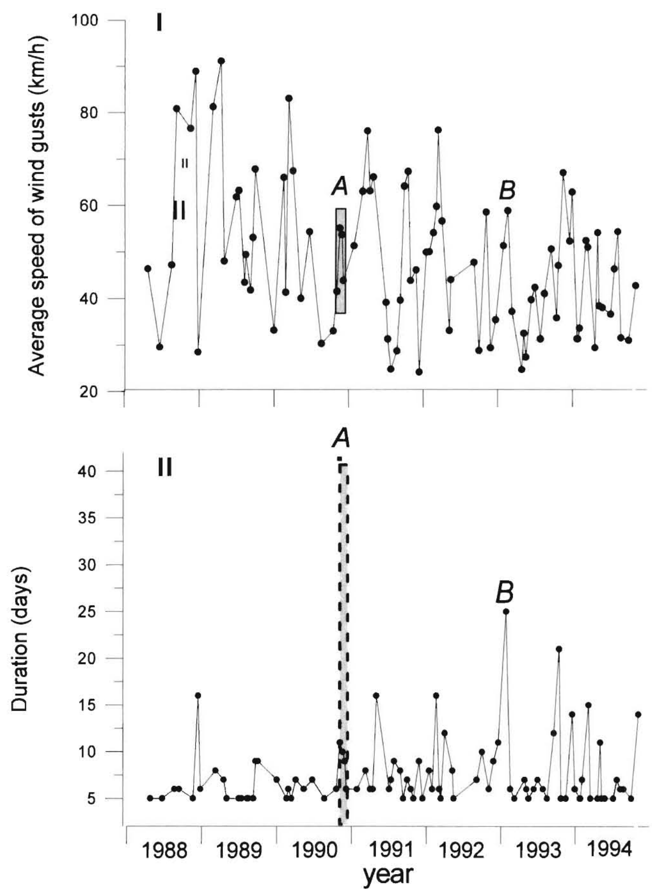

Figure 3. Episodes of wind gusts with speeds equal to or in excess of 20 km/h and a permanence equal to or in excess of 5 days. Graph I depicts an average speed and the incidence of each episode. Graph II depicts the duration of the same episodes.

change in coastal policy in accordance with the new goals of the Government. An attempt was made to make the coastal areas more environmentally friendly (MOPU, 1985), *i.e.*, creation of green spaces, nature reserves, improvement in water quality, restoration of degraded dunes, control and construction of infrastructure, delimitation of a Public Littoral Fringe (Dominio Publico Litoral). A campaign denouncing the degraded condition of the coastal environment was also launched. This campaign culminated in the enactment of a new Coastal Law in July 1988 (ESPAÑA LEY DE COSTAS, 1988). Considerable sums of local and national monies were subsequently invested with an objective of improving the coastal infrastructure. The enlargement of a beach specifically for tourism derives from this policy.

BACKGROUND

Environmental Dynamics

The area of investigation is Riells Beach (Platja de Riells) located in the town of L'Escala at the southern end of the Gulf of Roses (Figure 1). The Gulf of Roses faces eastward and is situated between the headlands of Peninsula de Cap de Creus to the north and the Montgrí massif to the south.

The Costa Brava has a typical Mediterranean climate. The mean annual temperature is about 16°C, the summer average is 23°C and the winter is 10°C. The diurnal temperature range is low, about 6 °C. The annual precipitation is about 600 mm with an equinoctial regime (210 mm in autumn and 190 mm in spring). Convective precipitation in September and October has been recorded as greater than 100 mm/24 hr.

The tidal regime is microtidal. The spring tidal range is about 0.15 m, which is characteristic of the Mediterranean region. The coastal processes of the Gulf of Roses are the products of the seasonal weather systems and associated frontal winds. The net longshore drift in the Gulf of Roses is from north to south. There are occasionally stronger easterly winds associated with cyclonic storms known as *Llevantades*. The cold and strong wind from the north-northwest, the *Tramontana,* is the most prominent feature of the regional meteorology and is a very important factor in the sand transport dynamics of this area (speeds of up to 100 km/h are not uncommon). The maximum speed recorded was 172 km/h (it could have been much higher had the anemometer not broken, MACAU, pers. comm). The *Tramontana* exerts a strong influence over the morphology of the beach and coastal zone.

Wind data (Figure 2) from the nearby Roca Maura meteorological station (site 1, Figure 1a) located 6 km south-southeast of Riells at an altitude of 220 m in the Montgrí massif demonstrate the seasonality and magnitude of gusts in the region. The highest frequencies and magnitudes are from the north-northwest throughout the seasons, with winter having greater values in all directions. Applying these data to the situation at Riells, the onshore winds account for 62% of the total frequencies, and have a mean wind gust speed of 43 km/h.

Continuity of the direction of wind gusts also is important in affecting sediment transport. Data available on *Tramontana* wind gusts from the northern quadrant (from the NW to the NE) with speeds equal to or in excess of 20 km/h and with a duration equal to or in excess of 5 days show that these severe situations account for 20% of the gusty conditions (Figure 3). Episodes A and B in Figure 3 are prominent because of their duration. Episode A extended from November 13 to

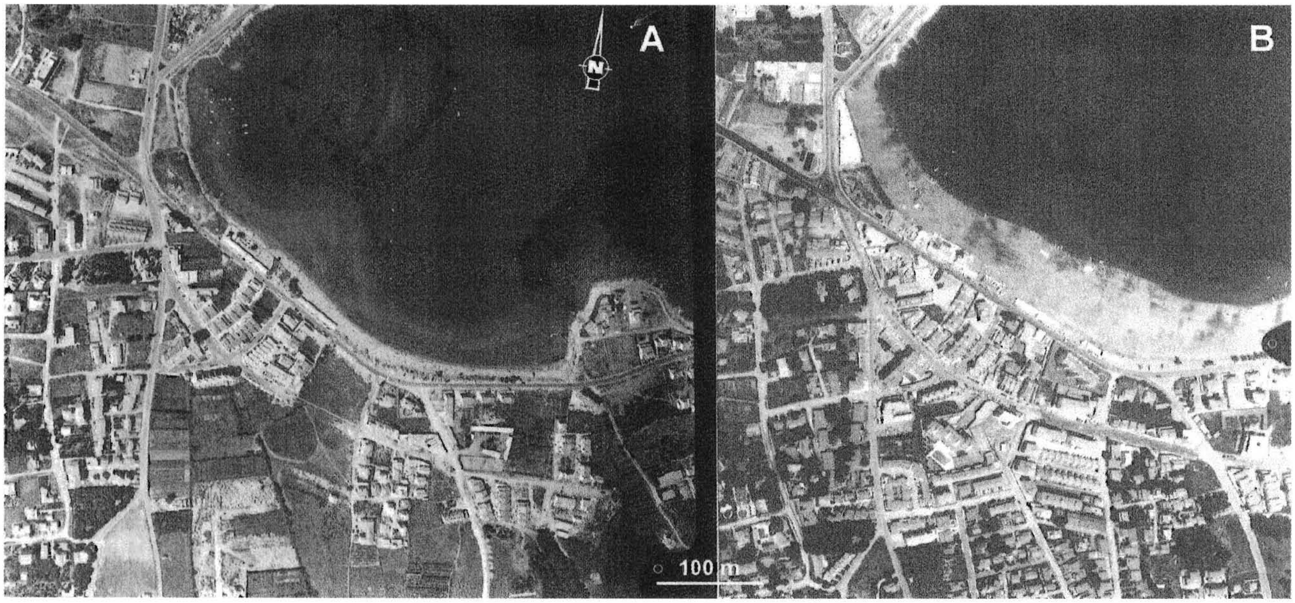

Figure 4. Aerial views of Riells Beach and part of a housing development. A) photograph taken in 1971 prior to beach enlargement with a predominance of fields. B) photograph taken in 1989 after artificial beach nourishment portraying the increase in beach size and expansion of residential development.

December 24 1990. The total duration (including minor interruptions) was 42 days. The average speed of the four successive wind events in this time period was 48 km/h. Episode B had an interrupted duration of 25 days, with a mean speed of 51.3 km/h (Figure 3). This was the longest period of gustiness during the seven years of record. As portrayed in Figure 3, there are usually one major and several minor *Tramontana* events annually. The combination of wind direction and magnitude associated with the *Tramontanas* will drive sediment transport for extended periods.

Within the arcing beach of the Gulf of Roses (Figure 1), there are three beach zones of form and processes related to eolian dynamics: the northern, central, and southern zones (MARQUES and JULIA, 1986c). The northern zone has a shoreline orientation that is primarily east-west and it is situated perpendicular to the strong northerly winds. The main geomorphological characteristic of the northern zone is sand deflation and sand transport to the sea. In the central zone, the northerly winds are parallel to the shoreline. The geomorphological response is the development of a barchan dune field in the beach that migrates alongshore. The main characteristic of the southern zone is the general east-west orientation of the coast and a series of pocket beaches that begin just to the south of the former mouth of the River Fluvià (Riu Vell). Consequently, in this zone dunes and sand sheets migrate landward if they are not fixed. L'Escala forms part of this zone.

Inland invasion of wind-blown sand, from the Riu Vell mouth to Platja del Rec (Figure 1b), was not uncommon in the past. The Montgrí massif is partially draped with a cover of Early-to-Late-Quaternary-age wind-blown sand dunes and sand sheets that migrated from the Gulf of Roses depression, transgressing the southern margin of the embayment (MARQUES and JULIA, 1986b; 1986c). Further, the continuing mobilization of sand was a recognized problem at an earlier time in the human use of the area because of conflicts with land reclamation and development. More recently, at the turn of the century, the problem was studied and a dune stabilization program was implemented (FERRER, 1895). The dune control program is still in force today.

Eolian transport is presently not possible in the two beaches located in the old nucleus of L'Escala (Platja de les Barques and Platja del Port d'en Perris, Figure 1b), which face the north, because in these two locations the beach sediments consist of pebbles and cobbles.

Riells Beach

The town of L'Escala (Figure 1) was previously a small fishing village situated on a rocky headland of the Montgrí massif. Since the 1960s, L'Escala expanded along the coast because of tourism. In the 1991 census, the number of permanent residents was 5,178, but in July and August, the population exceeds 47,000, according to a study on the seasonal variation of population in Catalonian municipalities (MENDIZABAL *et al.*, 1993). The natural shape of Riells Beach compartment (Figure 4a) was a gentle double arc which was almost symmetrical. It is exposed to the north and located between a rocky promontory to the west and another rocky node, which has a harbor, to the east. The shallowest area was located in the middle of the beach at the mouth of a small river. In this compartment, the 2 m isobath was about 200 m from the shoreline. The natural sandy beach had a mean width of 12 m with a total area of about 6,500 m^2.

Tourists, in general, prefer to be accommodated within easy reach of the beach. The problem at L'Escala was that there were only two very small beaches in the urban area. These beaches were formerly used for mooring fishing boats (Port d'en Perris and Platja de les Barques). In 1957, L'Escala was a small urban area on a headland surrounded by fields. By 1971, scattered residential development had expanded into the fields (Figure 4a). Over the last two decades, the rapid expansion of built-up areas on the coastline (hotels, residential development, shops and recreation centers) has led to over-crowding within the finite coastal compartment.

When the tourists first began to arrive, the two small beaches located in the old part of the town and the narrow beach of Riells, on the outskirts, satisfied the demand for recreational space. By the 1980s, the built-up areas had expanded to such a degree that the spatial dimension of these beaches could no longer cope with the demand in summer, resulting in overcrowding and discomfort. The other beaches of the L'Escala municipe (Empuries, del Convent, El Portitxol, del Rec, Figure 1b) are located as much as 2 km to the north of the town. Thus, the General Directorate of Ports and Coasts decided to undertake the enlargement of the beach at Riells to accommodate the increasing demand for local beach-oriented recreation and tourism.

BEACH NOURISHMENT AT RIELLS

In Spain, the responsibility for the protection and management of the coastal environment formerly resided with the national Ministry of Public Works (MOPU). Since 1996, it now rests with the national Ministry of Environment (Ministerio de Medio Ambiente), except for some functions that are delegated to Autonomous Governments.

The Spanish Ministry studied the most suitable option for the enlargement of the sandy beach in accordance with the enunciated new goals and directives (MOPU 1985, ESPAÑA LEY DE COSTAS, 1988). Beach nourishment was recommended as the most suitable option. Artificial beach nourishment provides distinct advantages (esthetic, environmental) over other methods. Artificial sand nourishment offers an alternative which conforms more closely to natural processes (CHARLIER and MEYER, 1998). Formerly, the technique of breakwater construction was widely used in Spain to control erosion and to enhance sand accumulation (MARQUES and JULIA, 1986a; MARQUES, 1988; MARQUES and PEÑA, 1989; PEÑA, *et al.*, 1994). However, there has been a debate amongst the proponents of shoreline stabilization at national (PEÑA and PARIS, 1994) and international forums (KOMAR and MOORE, 1983; MOPU, 1985; PASKOFF, 1994) that the application of beach fill is a "better" solution to the erosion problem than structures. Nevertheless, there are continuing issues associated with beach nourishment, such as design characteristics, environmental degradation in the sand source areas, and the high cost of maintenance. SILBERMAN and KLOCK (1988) propose a methodology to evaluate the positive recreational benefits of beach nourishment. The report of the NATIONAL RESEARCH COUNCIL (1995) attempts to provide a balanced evaluation of beach nourishment but eventually concludes that each site must be researched thoroughly and that nourishment be considered in full light of the longer term costs to the environmental, economic, and social systems. There is general agreement that beach nourishment is conceptually a much more dynamically-compatible approach to the problem of beach erosion than structures because the sand can retain the ambient morphology and ecological systems. However, the NATIONAL RESEARCH COUNCIL also acknowledged that there are a suite of technical, environmental, economic, and political factors which may affect the decision to apply beach nourishment. Further, a report from THE HEINZ CENTER (1999) raises the issue of hidden costs in any beach project and suggests that beach nourishment is considerably more costly in economic, environmental, and social terms than is generally realized and challenges much of its present day application.

Figure 4a is an aerial view of the Riells beach area taken in 1971, *i.e.,* prior to artificial beach enlargement. Figure 4b is an aerial view of the beach in 1989 after beach nourishment. A comparison of the photos illustrates the dimensional change in the beach and also presents a very noticeable growth in residential development and accompanying infrastructure during the intervening period. As a result of beach nourishment, the width of the beach was enlarged up to 85 m and the mean width increased to 70 m. The length of the sandy beach was also increased to 525 m because the western end was rocky and not utilizable before enlargement. The total surface area after nourishment increased to about 32,000 m^2. This artificial enlargement means an increase of more than 25,000 m^2 and therefore an increased tourist capacity.

The sand obtained for the beach nourishment (about 60,000 m^3) was excavated from a subaerial source 4 km north from Riells (site 2, Figure 1a). This source area was the beach located near the southern end of the Gulf of Roses alongshore transport cell and within the site of southwardly-migrating barchans and barchanoid dunes in the beach (FERRER, 1895, MARQUES and JULIA, 1986b, 1986c). This location is at Les Dunes beach (Figure 1b), on the north side of a former River Fluvià mouth (Riu Vell).

The central portion of the beach on the Gulf of Roses, between the modern and the former River Fluvià mouths, is affected by low-frequency, high-energy easterly storms (*Llevantades*). These storms play an important role in the beach-dune morphology for a number of reasons. Larger waves and storm surge give rise to: a) flooding of the backshore and adjacent inland areas; b) flattening of the previous dune field morphology, of barchan type; and c) onshore transport of organic detritus. Subsequently, northerly winds and especially the *Tramontana* conditions of strong alongshore winds produce the reconstruction and migration of barchan and barchanoid dunes in the beach (MARQUES and JULIA, 1986b, 1986c). This southward eolian transport is a natural input of sediment to the sand-mining zone. Given this natural supply and the very active processes of destruction-construction of the dune field, the resulting topography consists of a highly-mobile sand surface with a minimum of vegetative cover. Thus, intercepting and removing the sand in transit may have a modest effect on the geomorphology of this area. Nevertheless, the beach-dune sediment budget could be affected and the dunes and the ecologic system could sustain some damage if the southernmost dunes became scarped, as per the models of PSUTY (1986, 1988) and PYE (1990), and undercutting were to create remobilization of the stabilized dune forms in and around Empuries.

The two beaches, Riells and the excavation zone, belong to the same physiographic unit, *i.e.,* the Gulf of Roses. The natural sand supply of both sites is derived from the southward longshore drift. For this reason, there should be close compatibility between the emplaced and the autochthonous sands. Grain-size analysis shows that both share the same size distribution and composition, thus providing a good match. The Riells sand was mainly made up of quartz grains (50.2%) and bioclasts (30%). Feldspars (16.6%) and heavy minerals (2.8%) were minor constituents. It was a well-sorted sand (sorting coef. 1.29) with a mean diameter of 0.377 mm and a median of 0.362 mm. The source area sand was also well-sorted (sorting coef. 1.22) with a mean diameter of 0.375 mm and a median of 0.361 mm.

The cost of the artificial beach nourishment was relatively low (about $130,000 (US), MOPU, 1987). This was due to a number of factors. First, the relative shallowness of the shoreface at Riells reduced the volume of sand needed (about 60,000 m^3). Second, structures, such as breakwaters, etc., were not required because the beach was not affected by marine erosion. Third, the nourishment was performed by sand extracted from the subaerial zone of extensive nearby beaches at a distance of 4 km, transported by trucks, and distributed along the beach by bulldozers. Lastly, future renourishment was not deemed to be necessary because the beach of Riells was situated between headlands forming a pocket beach with a history of minor gains and losses.

THE INTERACTION OF BEACH NOURISHMENT WITH EOLIAN DYNAMICS

The City Council and the majority of the inhabitants and visitors to L'Escala were satisfied with the new beach. However, not all inhabitants were happy because it was not long before it became clear that beach enlargement also brought problems associated with sand drift.

The transfer of sand from the beach landward took place during wind storms, especially the *Tramontana* events of strong flow from north to south. There were plants (Tamarix) and buildings between the beach and the road bordering it. The sand accumulated partly in the lee side of these obstacles, in the road, and in some cases invaded the adjacent houses and streets. The accumulation of sand in front of, next to, and inside buildings constituted a major nuisance to the owners of the houses, stores, cafes, and other facilities adjacent to the beach. Obstacle-related dunes predominated, and a large diversity of forms of leeward and windward accumulations developed (sand shadows, horseshoe-shaped dunes, echo dunes, small climbing and falling dunes, *etc.*). Moreover, during sand storms it was very disagreeable to be on the beach or in the surroundings because of sand blasting, physical discomfort, effect on equipment, *etc.*

Figure 5 is a striking example of sand drift and sand invasion. In this case a large amount of sand left the beach, invaded the roads, and accumulated in the vicinity of and within many buildings, *i.e.,* in driveways, gardens, on staircases, and also to some extent inside the houses. Some inhabitants took to sealing doors and windows with sticky tape during the winter and when the houses were unoccupied.

Eolian transport was carried out by rolling, surface creep, saltation, and suspension depending on wind speed. Clouds of sand, with grain sizes up to 0.3 mm in diameter, have been observed in the field. For example, on June 11, 1994, sand clouds exceeded a height of 2 m, causing considerable nuisance by penetrating eyes, nose, ears, *etc.* The number of these sand storms varied from year to year, depending on the number of strong storm wind events (see detailed frequency data and wind speed in Figures 2 and 3) and the status of the wind barrier devices.

On the basis of the sand volume accumulated in the fences and in various parts of the village, it is estimated that the maximum sand volume that could be mobilized by the wind during one year would be about 10.000 m^3 (procedure described later). This quantity of transported sand is of significant magnitude (up to 16%) relative to the initial volume of emplaced sand of approximately 60,000 m^3. Without human intervention to restore the mobilized sand to the nourished area, the beach probably would return to its initial size. By comparison, the values attributed to eolian transfers at other locations were 2% of the total fill at Sandy Hook, New Jersey (PHILLIPS, *et al.*, 1984), and 5% of the upper 20 cm of the fill surface over two years at a Netherlands site (VAN DER WAL, 2000).

RIELLS SAND DRIFT MANAGEMENT

The problem of sand control at Riells produced a conflict in achieving objectives. On one hand, there was the need to retain the sand on the beach, to prevent or reduce beach deflation, and therefore to decrease the quantity of sand invading the urban environment. On the other hand, there was also the need to have a broad sand beach available for beach users in the summer; this means a sand surface uncluttered by vegetation, fences, *etc.* As a result, the construction of vegetated buffer zones or brushwood fences, among other systems, was not considered to be a viable management option. Although the beach was widened to 75 m or so, the establishment of vegetated dunes would have compromised much of that gain, and thus the construction of a dune buffer was not a management option, either. The central problem was that the conditions of strong northerly winds favored the deflation and inland transfer of sediment from the widened sandy beach into the resort community.

The plan ultimately adopted by the City Council was to trap as much sand as possible mainly in winter and spring with temporary barriers. This was the time of the year when the frequency and speed of the northerly winds were the highest and when the human utilization of the beach was the lowest. The sand accumulated in the traps was returned and subsequently distributed along the beach in late spring or early summer.

The selected strategy was to install fences throughout much of the beach to create local sand deposition. The type of fence chosen was nylon mesh. This system was the most suitable because it was easy to install, remove, and store.

Figure 5. An example of sand translocation and accumulation. The mobile sand invaded the streets and accumulated in a large variety of obstacle-related dune forms.

This was an important advantage given that the fences had to be re-utilized year after year.

Several rows of fences, 1.25 m high, were set up on the beach, extending alongshore approximately 400 m. The nylon mesh fences were quite successful in trapping sand (Figure 6). The annual volume of sand accumulated by the fences was about 6,000–8,000 m^3, or 12–16 m^3/m of beach. This volume was calculated by a sampling of the height of the sand in the fences, the width and height of the accumulation between the fences, and extending these values over the entire length of the fences. The annual accumulation varied depending on storm frequency and magnitude. In addition, some sand did go beyond the fences and into the community.

The fence system appeared to function in a fairly satisfactory manner, although problems arose in two general situations. In one situation, very strong storms would transport great quantities of sand and overwhelm the trapping capability of the system of fences. For example, the storm of December 6–21, 1988, had a maximum speed recorded of 141 km/h from the north-northwest. The average wind speed between Dec. 6–20 was 61.4 km/h. During part of Dec. 12–13, the average speed reached 66 km/h and the migrating waves of sand overwhelmed the low fences and spilled into the streets and adjacent properties. The other situation arose when the fences had been removed (mainly in summer) and this period coincided with strong northerly wind episodes. This was most unwelcome when it happened during the tourist period. For example, in June 9–12, 1994, the NNW wind had a mean velocity of 49.9 km/h, lasting about 69 h. This storm event mobilized great quantities of beach sand and invaded streets and houses.

In both of these situations, the sand was partially collected from within the infrastructure of the community and restored to the beach. The problem did not result in much economic hardship because the expenses incurred in constructing sand traps, collection of sand accumulations in the streets, and the subsequent redistribution of the sand on the beach were modest. The local Public Works staff conducted the activity as part of their annual routine. Further, returning the sand to the beach counteracted the decrease in volume of the fill. However, there were other problems of physical discomfort undergone by people living or working near the beach, additional maintenance of properties, and the temporary closure

Figure 6. Alignment of nylon mesh fences installed parallel to shoreline and approximately perpendicular to the predominant winds blowing from the northern sector.

of the street along the beach. Despite these problems the City Council evaluated the result of beach nourishment positively.

GEOMORPHOLOGICAL ASSOCIATION OF EOLIAN PROCESSES AND FORMS WITHIN THE REGIONAL AND LOCAL CONTEXT

The adverse eolian effects that arise from the location in the Gulf of Roses are products of the wind dynamics interacting with sediment availability. A systematic and comprehensive geomorphological investigation can facilitate the identification of the ambient processes and improve understanding of the present-day dynamics. This knowledge would allow an assessment of the potential sediment transfers from nourished beaches due to eolian processes.

The magnitude of eolian transport of sediment from the beach fill during an entire year can be approached through a series of measurements and calculations. One component of this quantity is the accumulation in the fences during the period from October through April. Measurements taken at the end of this seasonal accumulation around the fences in the beaches attain values on the order of 6,000 to 8,000 m^3. That is the quantity of sand that is caught and remains trapped during the *Tramontana* events.

A second component of the annual mobilization is the quantity of sand blown into the streets both during the period when fences are in the beach and when they are removed. This sand volume is derived by measuring the accumulations in selected areas along the street and promenade parallel to and immediately inland of the beach. These are locations where barriers exist, such as walls and houses, as well as opportune portions of the street with sizeable masses of sand (Figure 7). These measurements from the selected areas are calculated as an accumulation per meter length of parallel street and extrapolated to represent the entire transport along the entire length of the promenade into the street and beyond for some time interval. In the measured instances, the sand volumes in the street and against the barriers varied from 1.2 to 3.4 m^3/m length of parallel street. Extending this value to the entire promenade and adjusting for areas of optimized trapping, the accumulation in the adjacent community was 480–960 m^3 per event.

And yet a third component of the annual transport occurs in the beach after the fences are removed. This quantity is derived by a comparison of the beach profile immediately after the fences are removed and the beach is graded by bulldozing with profiles later in the summer which show a prism of sand rising from the beach toward the barrier created by the promenade. This prism at the inner portion of the beach can be the product of a number of smaller *Tramontanas* over the summer season. In one summer, the volume incorporated in this prism was on the order of 2.400 m^3 (*ca.* 5 m^3/m of beach).

Thus, during the annual cycle, a series of *Tramontana* events mobilizes sand to accumulate in the fences when they are installed in the beach, transfers sand into the community both when fences are present and when they are not, and in the summer builds a ramp of sand leading from the beach to the level of the promenade. Through the combination of these three areas of accumulation, it is possible that approximately 10,000 m^3 (*ca.* 20 m^3/m of beach) of sand could be mobilized from the fill to the fences and into the community.

In the decades prior to artificial nourishment, Riells Beach was not a site of substantial inland transfer of wind-driven sand. At this time, the dynamic morpho-sedimentological balance was retained because of the much narrower beach. Thus, during the period of strong northerly wind, much of the beach was wetted by storm surge and wave setup and the exposed portion was narrowed. Therefore, the conditions of broad exposures of dry beach were not coincident with the strong winds from the north and the inland transfers were severely limited at Riells Beach. By contrast, when the beach width was artificially increased, the availability of a dry sand beach increased and hence the magnitude of the sand transport changed as well.

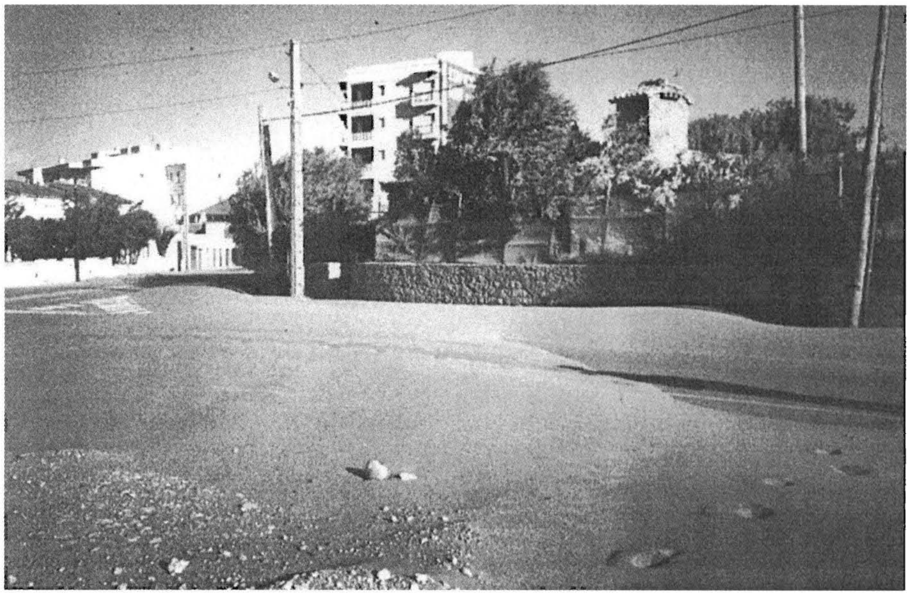

Figure 7. Sand accumulation in the street and surrounding a house immediately inland from the beach, total volume at this site is approximately 45 m^3, following a severe Tramontana event.

As CARTER, *et al.* (1990) clearly state: "the key to understanding the geomorphology of dunes is in recognizing that they are dynamic and opportunistic forms, developing rapidly where and when conditions are favourable". The beach width and hence the sand availability can change as a result of natural or cultural causes. Artificial beach nourishment was the cause of the present favorable conditions. Therefore, the present sand transport at Riells Beach is a product of the regional wind regime and the local mix of available sand and the absence of vegetation cover, a situation conducive to the eolian transport and dune development (PYE and TSOAR, 1990; KLIJN, 1990). As evidenced by the abundant high wind speeds from the north (Figures 2 and 3), the wind regime at Riells has a high sand drift potential. Further, there is now a super-abundance of sand without vegetation cover on this beach. Thus, under these conditions the potential and the real sandflow from this beach could be regarded as similar and maximized.

Intermittently during the Quaternary, when sand availability increased during lower sea levels, the region was affected by substantial inland eolian transfers (MARQUES and JULIA, 1986b). Thus, there is a geomorphological history of dune forming conditions and eolian inland transport when sand is available in the southern portion of the Gulf of Roses.

CONCLUSIONS

The case study of Riells is an example of the impact of the eolian processes on an artificially nourished beach. Although beach enlargement was undertaken to solve the problem created by a high density of beach users on a small beach, it subsequently led to two adverse consequences due to eolian sand transport:

a) sand invasion onto the roadways and nearby buildings with a temporary closure of the road along to the beach, and discomfort to the inhabitants;
b) loss of sediment from the beach and a possible return to the prior narrow state.

The sand control measure adopted was sand retention by seasonally-removable nylon mesh fences. The need for an unobstructed beach that maximized user space in the tourist period ruled out other retention methods. The control measure of a temporary fence failed in two storm wind scenarios: when sand overwhelmed the trapping capability (mainly in winter), and when the fences were absent (mainly in summer).

Eolian dynamics and dune morphological patterns result from the interaction of winds with sand supply. Any variation in the sand availability involves changes. The Riells beach-dune system reacted to the increase of the free sand surface created by the artificial beach nourishment. The response was beach deflation and active translocation of sand landward. This was a return to a system for producing migrating dune forms, as happened in the past.

The artificial broadening of a sand beach is usually a temporary adjustment in the dynamic morpho-sedimentological balance between ambient processes and sediment mobility. Monitoring of this condition has hitherto been largely directed toward wave and current mobilization of the beach fill. However, the presence of the fill surface is also subject to an increased eolian interaction because of the much larger expanse of mobile sands unencumbered with vegetation or stabilized dune forms. Therefore, it is proposed that systematic inclusion of eolian processes in an artificial beach nourishment project become a part of the evaluative procedures, incorporating the costs of stabilizing the sand as well as costs of removal and replacement. This is especially appropriate when the planned beach profile lacks a dune zone or any type of vegetated barrier or screen. As a planning guide, wind rose data should be part of the background information associated with a beach nourishment project and if the wind vectors show an opportunity for substantial inland transport there should be some procedures to mitigate the effects. Further, it is apparent that geomorphological research of past and present processes at a site provides a major contribution to our understanding of on-going processes and can assist in the programmed management of changes brought about by artificial beach nourishment.

ACKNOWLEDGEMENTS

We wish to thank Josep Pascual, head of the meteorological station at Estartit, for providing the wind data used in the study. We are also indebted to Emma Sainz Amor for the mineralogical study of the sand. The research was partially funded by Comissionat per la Recerca, Generalitat de Catalunya (Grup de Recerca de Processos Geodinàmics Superficials 3130-UB.06 (1999-0065). Professors Robert Young and Andrew Short provided very helpful critical reviews of an earlier version of the manuscript.

LITERATURE CITED

CARTER, B.; NORDSTROM, K.F., and PSUTY, N., 1990. The study of coastal dunes. *In:* NORDSTROM, K.F.; PSUTY, N., and CARTER, B. (eds.), *Coastal Dunes: Form and Process.* Chichester: John Wiley and Sons, pp. 1–14.

CHARLIER, R.D. and DE MEYER, CH.P., 1998. *Coastal Erosion: Response and Management.* New York: Springer Verlag, 334p.

DEAN, R.G., 1983. Principles of beach nourishment. *In:* KOMAR, P.D. and MOORE, J.R. (eds.), *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, pp. 217–231.

DRAGA, M., 1983. Eolian activity as a consequence of beach nourishment—observations at Westerland (Sylt), German North Sea coast. *Zeitschrift für Geomorphologie, Supplement Band,* 45, 303–319.

ESPAÑA LEY DE COSTAS, 1988. *Boletín Oficial del Estado* (BOE) 181, Ley 22/1988 de 28 de julio. Madrid.

FERRER, J.D., 1895. *Proyecto de fijación y repoblación de dunas procedentes del Golfo de Rosas.* Madrid: Imprenta R. Rojas.

GENERALITAT DE CATALUNYA, 1984. *Estat d'Utilització de les Platges del Litoral Català.* Barcelona: Generalitat de Catalunya, Dep. Política Territorial y Obres Públiques, 95p.

THE HEINZ CENTER, 1999. *The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation.* Covelo, California: Island Press, 210 p.

KLIJN, J.A., 1990. Dune forming factors in a geographical context. *In:* BAKER, Th. W., JUNGERIUS, P.D., and KLIJN, J.A. (eds.), *Dunes of the European Coasts.* CATENA, Supplement No. 18, pp. 1–14.

KOMAR, P.D. and MOORE, J.R. (eds.), 1983. *CRC Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, 305p.

MACAU, F., 1970. Engineer, Servicio Geológico de Obras Públicas, MOPU. España, personal communication.

MARQUES, M.A., 1988. Spain: Artificial structures and shorelines. *In:* WALKER, H.J. (ed.), *Artificial Structures and Shorelines.* Dordrecht: Kluwer Academic, pp. 187–191.

MARQUES, M.A. and JULIA, R., 1986a. Littoral processes and defense structures on the Costa Daurada. *Thalassas* 4, 123–134.

MARQUES, M.A. and JULIA, R., 1986b. Fluvià and Muga delta plain: geomorphological features and evolution (Empordà-Gulf of Roses). *In*: MARQUES, M.A. (ed.), *Symposium on Man's Impact on Coastal Environment. Guidebook NE Spanish Mediterranean coast.* Barcelona, pp. 7–30.

MARQUES, M.A. and JULIA, R., 1986c. Sant Pere Pescador beach-dune interaction. *Journal of Coastal Research,* Special Issue No. 3, pp. 57–61.

MARQUES, M.A. and PEÑA, C., 1989. CORINE coastal erosion: Spain, final report. *CCE Project CORINE Coastal Erosion.* Bruxelles: Commission of European Communities, Directorate-General.

MENDIZABAL, E.; AJENJO, M.; BLANES, A., and SANCHEZ, E., 1993. *La Població Estacional en els Municipis de Catalunya.* Barcelona: Unpublished report, Departement de Medi Ambient, Generalitat de Catalunya.

MOPU, 1985. *Política de Costas. Plan de Actuaciones 1983–1990.* Madrid: Serie Documentos. Servicio de Publicaciones Ministerio Obras Públicas y Urbanismo, 209p.

MOPU, 1987. *Costas y Señales Marítimas, Actuaciones 1986.* Madrid: Ministerio Obras Públicas y Urbanismo. Dirección General de Puertos y Costas, 242p.

NATIONAL RESEARCH COUNCIL, 1995. *Beach Nourishment and Protection.* Washington, D. C.: National Academy Press, 334p.

PASKOFF, R., 1992. Sandy beaches evolution and management in North Africa. *UNESCO Technical Papers in Marine Science,* 64, 187–195.

PASKOFF, R., 1994. *Les Littoraux. Impact des Aménagements sur leur Evolution.* Paris: Mason, 256p.

PASCUAL, J., 1993. Els Vents a la Zona del Montgrí. Pub. Ajuntament de Torroella de Montgrí, *Festa Major 1993,* nnp.

PEÑA, C.; FERNANDEZ, M., and PARIS, C., 1994. Degradación y regeneración de playas. *TecnoAmbiente,* 40, 51–54.

PHILLIPS, J. D., PSUTY, N. P., and MCCLUSKEY, J. M., 1984. *The Impact of Beach Nourishment at South Beach, Sandy Hook, New Jersey.* New Brunswick, New Jersey: Center for Coastal and Environmental Studies, Rutgers University, 30 p.

PSUTY, N. P., 1986. Principles of dune-beach interaction related to coastal management. *Thalassas,* 4, 11–15.

PSUTY, N.P., 1988. Sediment budget and dune/beach interaction. *Journal of Coastal Research* Special Issue No. 3, pp. 1–4.

PYE, K., 1990. Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, northwest England. *In:* NORDSTROM, K.F.; PSUTY, N.P., and CARTER, B. (eds.), 1990. *Coastal Dunes. Form and Process.* Chichester: John Wiley and Sons, pp. 339–359.

PYE, K. and TSOAR, H., 1990. *Aeolian Sand and Sand Dunes.* London: Unwin Hyman, 391p.

SILBERMAN, J. and KLOCK, M., 1988. The recreation benefits of beach renourishment. *Ocean and Shoreline Management,* 11, 73–90.

VAN DER WAL, D., 2000 Grain-size-selective aeolian sand transport on a nourished beach. *Journal of Coastal Research*, 16, 904–916.

□ RESUMEN □

Los proyectos de alimentación artificial de playas se han analizado sistemáticamente desde diferentes puntos de vista. Sin embargo, aunque los proyectos evalúan la adecuación, el funcionamiento y los impactos de la alimentación artificial de las playas, raramente incluyen los efectos del viento. El desequilibrio desencadenado por la alimentación artificial de la playa se examina en Riells, España. Esta playa fue ensanchada para adaptarse a las necesidades del turismo. Este estudio se centra en los impactos geomorfológicos, sin precedentes, asociados a los procesos eólicos. Se trata de la mobilización de grandes cantidades de arena (20m^3/m de playa) dentro de la zona realimentada, que se transfieren hacia la parte alta de la playa y que parcialmente invaden la zona urbanizada. La investigación geomorfológica obtiene información sobre la dinámica eólica actual y pasada. El análisis de Riells describe las condiciones ambientales para la respuesta geomorfológica al aumento de la superficie de la playa y, por tanto, de la disponibilidad de arena. Así pues, aporta información sobre las consecuencias de la alimentación artificial de playas y pone de manifiesto la necesidad de incorporar el transporte eólico en la evaluación de los impactos de esta alimentación.

□ RESUMÉ □

Les projets d'alimentation artificielle des plages ont été systématiquement analysés d'après différentes approches. Malgré que ces projets évaluent l'adéquation, le fonctionnement et les impacts de l'alimentation artificielle des plages, rarement les effets du vent sont inclus. Le déséquilibre déclenché par l'alimentation artificielle est examiné à Riells, Espagne. Cette plage a été agrandie pour s'adapter aux besoins du tourisme. Cette étude montre les impacts géomorphologiques, sans précédents, liés aux processus éoliens. Il s'agit des mobilisations de grandes quantités de sable ($20m^3/m$ de plage) dans la zone d'engraissement, qui se transfèrent vers la partie haute de la plage, envahissant partiellement la zone habitée. La recherche géomorphologique obtient une perspective sur la dynamique éolienne actuelle et passée. L'analyse de Riells décrit les conditions pour prévoir la réponse géomorphologie a l'augmentation de la surface de la plage, et par conséquent de la disponibilité de sable. Tout ceci fournit des informations sur les conséquences de l'alimentation artificielle des plages et prouve la nécessité de considérer les transports éoliens dans l'évaluation des impacts dans ces alimentations.