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Monitoring beach nourishment based on detailed observations with video measurements

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ABSTRACT

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Monitoring the performance of beach nourishment is necessary to test its usefulness and improve its efficiency. In summer 2002 Barcelona city beaches (NW Mediterranean, Spain) were nourished after a very energetic period that produced widespread beach erosion. In this study two of these beaches –La Barceloneta and Bogatell- were monitored for a year and a half after the filling (i.e., the moment when the beach area reached values similar to that before the nourishment) using video image measurements to examine their behaviour. The nourishment in La Barceloneta beach produced an increase of the emerged area of 5000 m^2 with a mean advance of the shoreline of 14 m, whilst in Bogatell, the area increased by 12750 m^2 and the mean advance of the shoreline position was 20 m. The video monitoring allows assessment of the effect of individual storm events that would be missed with traditional survey methods. The recorded storms caused mainly beach rotation but did not significantly reduce the beach area overall. After the nourishment both beaches showed a reduction in their beach areas with mean losses, calculated for a year and a half later, of 22 m^2/day in La Barceloneta and 18 m^2/day in Bogatell.

ADITIONAL INDEX WORDS: *Artificial beach, coastal morphodynamics, shoreline erosion.*

INTRODUCTION

Coastal erosion is a worldwide problem that has been approached in different ways. In recent years, soft engineering projects (such as beach replenishment) are taking the place of hard engineering ones (e.g. construction of shore-protection structures) in some regions because they may represent less environmental and visual impact in the adjacent area and preserve the beach resource. The success of both types of engineering projects needs a previous knowledge of the area where they are going to be implemented and, besides this, subsequent studies (including monitoring of beach performance) are also needed in order to improve the performance of successive interventions (HANSON *et al*. 2002).

Replenishment has been a common practice in the Mediterranean Spanish coast, mainly as an answer to the erosion problems caused by a decline in the sediment inputs to the coastal system and the interruption of the littoral drift produced by the construction of hard structures. During the last 20 years, 600 nourishments have been performed in 400 different sites in Spain with a total sand supply of approximately $110x10^6$ m^3 (HANSON *et al*., 2002).

Due to the fact that some of the nourishment projects were not successful, but mainly as a consequence of the scarcity of sand borrow areas in the Spanish Mediterranean continental shelf and the serious environmental problems related to their exploitation, nourishment projects must be now restricted. This fact generates conflicts with the increasing demand for sand from managers of the tourist coastal areas because wide and sandy beaches are the main tourist attraction. This controversy implies that nourishment projects should be carefully designed and evaluated in order to obtain optimum results.

Differential GPS, airborne laser mapping, amphibious vehicles and video imaging were specified by HAMM *et al*. (2002) as some of the recently developed techniques that can be taken as the most capable procedures in monitoring nourishment performance. ELKO *et al*. (2005) tested the use of video images with traditionally surveyed beach profiles to monitor nourishment performance finding differences between video-estimated and traditionally surveyed shoreline (MSL) position of 3.0 m on average. They concluded that video images were a worthy complement to traditional beach survey, allowing the identification of morphologic changes that are not evident in survey data.

In most of the Spanish cases the evaluation of the nourishment evolution is based on topographic and/or bathymetric surveys carried out weeks, months or years after the replenishment. However, it is obvious that a number of short-term processes cannot be identified under this sampling strategy. For this reason, the objective of this paper is to evaluate the beach nourishment carried out along Barcelona city beaches in June-July 2002 using daily images obtained by video cameras. The analyzed period extends from June 2002 (two weeks before the nourishment) to December 2003, when the shape of the shoreline was similar to the pre-nourishment one.

STUDY AREA

The Catalan coast (Western Mediterranean) is a micro-tidal zone (tidal range < 20 cm) where the annual mean significant wave height (Hs) is lower than 1.0 m and storms can reach maxima Hs near to 6 m, with Hmax reaching 10 m (CENDRERO *et al*., 2005). Wave height in the region is characterized by a cyclic behaviour, with storm periods (October-April) separated by periods of minor storm activity (May-October). The most important storms are those from the east with a typical duration of few days and often associated with the cyclonic activity in the Western Mediterranean.

The Barcelona city waterfront (NW Mediterranean) is divided into several sections with the Barcelona Harbour in its southern part followed by La Barceloneta beach (separated from Somorrostro beach by a double dyke), the Olympic Marina and several smaller beaches in the Northern side, Nova Icaria, Bogatell, Mar Bella and Nova Mar Bella. This paper is focused in two of the beaches -La Barceloneta and Bogatell- and their behaviour in response to the summer 2002 nourishment (Figure 1 and Table 1).

These beaches were created more than ten years ago from a previous degraded shoreline occupied by small industries, garages and industrial warehouses. As part of the 1992 renewal plan of the city's waterfront, the distribution of more than 1 million m^3 of sand was undertaken. La Barceloneta beach was filled with 69000 and 139000 m^3 of sand during 1991 and 1992, respectively and Bogatell beach was filled with 300000 and 88000 m^3 of sand during years 1988 and 1992, respectively (MOPU, 1994). Therefore, the nourishment considered in this paper follows 10 years with no significant delivery of sand.

METHODOLOGY

The morphologic changes produced by the nourishment were monitored using an Argus video system (HOLMAN *et al*., 1993) located atop a building close to the Olympic Marina at around 142 m high (Figure 1). This Argus station is part of the Coastal Monitoring Station of Barcelona (http://elb.cmima.csic.es) and is composed of five cameras pointing at the beaches and offering a 180º view of the coast. In order to obtain quantitative data from the images the distorted 2D screen coordinates were rectified to real-world coordinates. The extraction of the shoreline location from the images will then allow the derivation of shoreline mobility data and emerged beach area time series that will be used to assess the evolution of the beach nourishment.

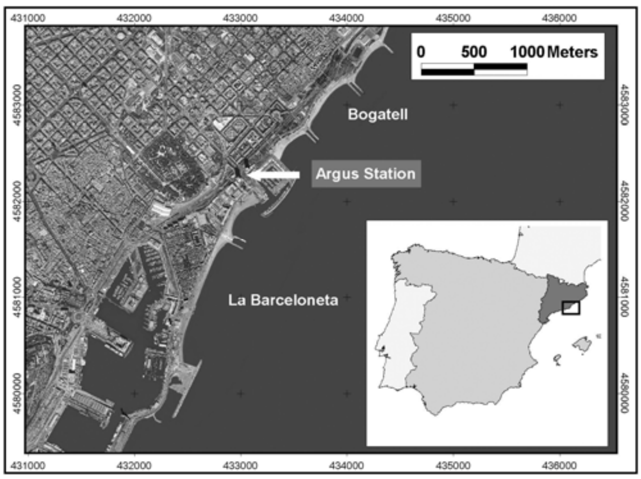

Figure 1. Location of the study area.

Table 1: Main features of the study beaches.

Beach	Length	Orientation	Volume of sand nourished in 2002
La Barceloneta	1100 m	N20°E	39539 m^3
Bogatell	600 m	N45°E	71282 m^3

Given that the number of images and information generated by the system is too large, a selection of the images will be used in this study with a time lapse between images varying from one to 15 days depending mainly on the wave energy and the proximity in time to the nourishment. Animations of the daily images were also produced to visualize, in a fast way, the important incidents occurring on the beaches, allowing the in-depth study of the relevant episodes.

Errors due to sea level variations and to the analysis process itself (to the way the shorelines were obtained) were minimized by analyzing more than one shoreline per day and using, instead of single shoreline position, the average of the daily values. In total, 173 shorelines of Barceloneta beach and 156 shorelines of Bogatell beach were measured, corresponding to 77 and 84 sample days respectively.

Once all the shoreline positions were obtained, beach mobility information and area variability were derived. Due to the hard structures limiting the back and lateral part of the beaches, the emerged beach area data were easily obtained. A software program was implemented which reduced to a mean the daily values of the shoreline and calculated beach area values. Since the extremities of the beaches were not always clearly visible, the program included the elongation of the beach limits by fitting the last plotted positions to a line and expanding the line to the lateral limit of the beach. The farthest section (<100 m) in the south part of La Barceloneta beach is not included in the analysis because the camera resolution was not good enough.

Beach behaviour was analyzed through the evolution of the shoreline position and the beach area. To facilitate the observation of the changes in the shoreline mobility, a series of cross-shore transect –with a distance between consecutive transects of 100 m in La Barceloneta and 50 m in Bogatell- was tracked along each of the beaches.

Wave height data was obtained from the Generalitat de Catalunya buoy located off the Llobregat River (south of the study area). The measurements were taken on an hourly basis with maximum time gaps in the series in March and May 2003. The interruptions of the wave data were solved using data taken from WANA model data set (Puertos del Estado, http://www.puertos.es) and also the Argus images of these days were analyzed in order to check the important events occurring during these periods. During the study period the most important storms in terms of Hs were those of mid and late October 2003; the former with ESE direction and Hs almost reaching 4 m and the later with S direction and Hs > 3.5 m (Figure 2).

RESULTS

Description of the nourishment

From November 2001 to May 2002, a number of storms produced strong erosion in Barcelona city beaches (OJEDA AND GUILLÉN, 2005). Since these beaches receive several million users per year and most of them visit the beaches during the summer

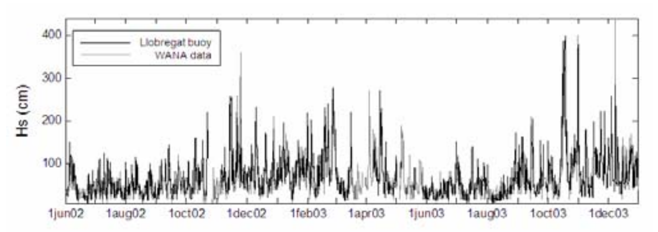

Figure 2. Significant wave height measured near Barcelona city during the study period.

season, urgent action on the beaches was requested by different social sectors. In response to these demands, approximately 135000 m^3 of sand were distributed along the city beaches during June and July 2002. The sand borrow area was located around 20 km northern of Barcelona city. The median grain size of the sand ranged between 0.45 and 0.9 mm and it was pumped to the emerged beach from a ship (Figure 3). Typically, the ship transported about 1000 m^3 of sand from the borrow area to the filling area, carrying out 3-4 sediment discharges per day. The Bogatell beach received 71282 m^3 of sand in 22 days (between 13th June and 5th July 2002) and La Barceloneta beach 39539 m^3 between 5th and 17th July 2002. Figure 3 shows the characteristic beach configuration immediately before and during the nourishment works.

The nourishment in La Barceloneta beach was only accomplished in the northernmost part of the beach where it caused a mean advance of approximately 13.6 m (Figure 4). The mean advance of Bogatell shoreline was 20 m with values ranging between 10 and 30 m along the whole beach (Figure 5). Considering that the nourished part of La Barceloneta was approximately 350 m long and that the length of the Bogatell beach is 600 m, the rate of sediment supplied was 113 and 118 m^3/m of sand respectively. The increase in the beach area was 5000 m^2 in La Barceloneta and 12750 m^2 in Bogatell (Figure 6). Therefore, the volume of sand required for increasing the area of the beach 1 m^2 was 7.9 and 5.6 m^3 in La Barceloneta and Bogatell, respectively and the mean sand volumes needed to increase 1 m the beach width along filled areas were of 2768 m^3 and 3354 m^3, respectively.

Beach evolution after the nourishment

Shoreline evolution

The extent of the changes produced by storm events in the shorelines of both beaches were of the same magnitude and, although there is a difference in the orientation of the beaches, the behaviour of La Barceloneta and Bogatell in response to storms occurring during the studied year and a half period were similar.

The most evident storm effects on the two beaches are due to

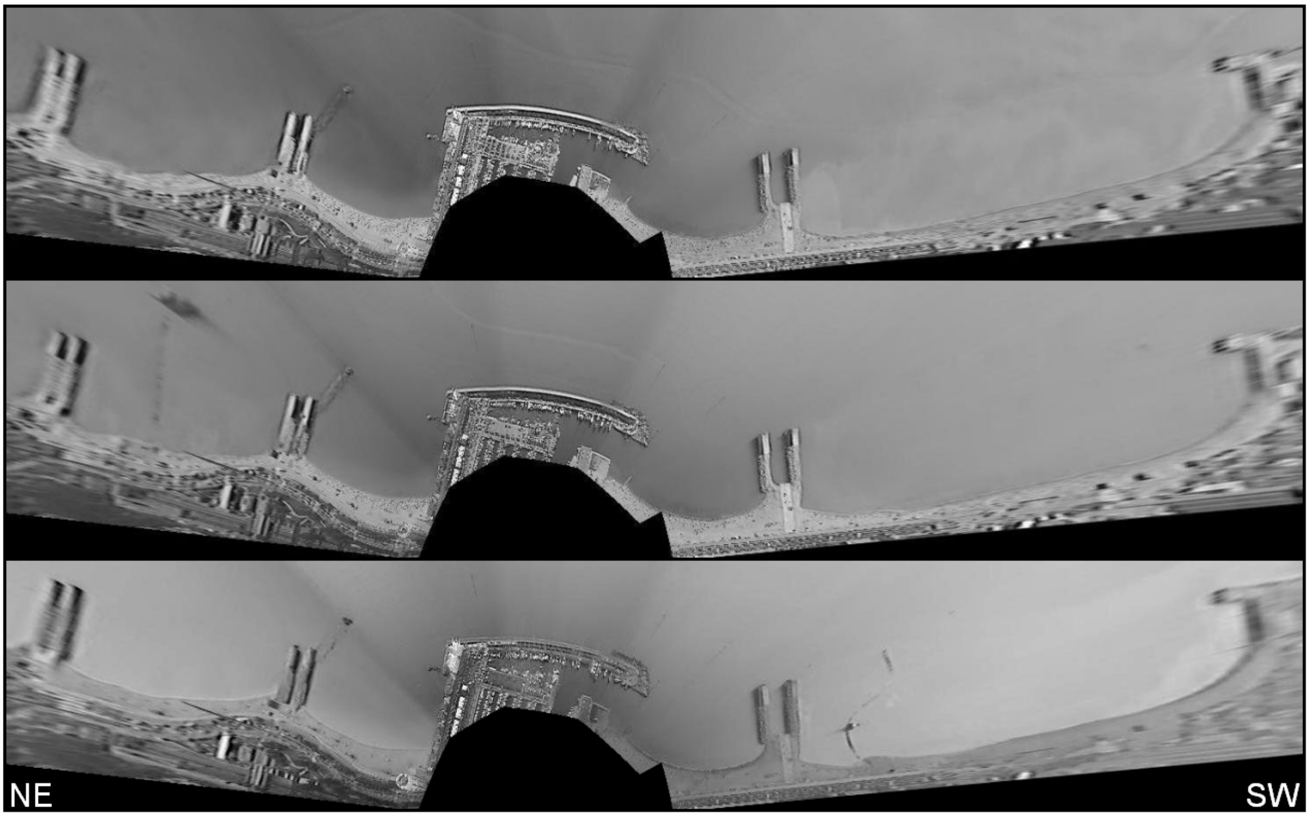

Figure 3. Plan views of the beaches in summer 2002. Top: 1st June, before the start of the nourishment works. Center: 19th June, nourishment taking place in Bogatell beach with the ship discharging sand. Bottom: 13th July, nourishment taking place in La Barceloneta beach with presence of the ship in its northernmost section.

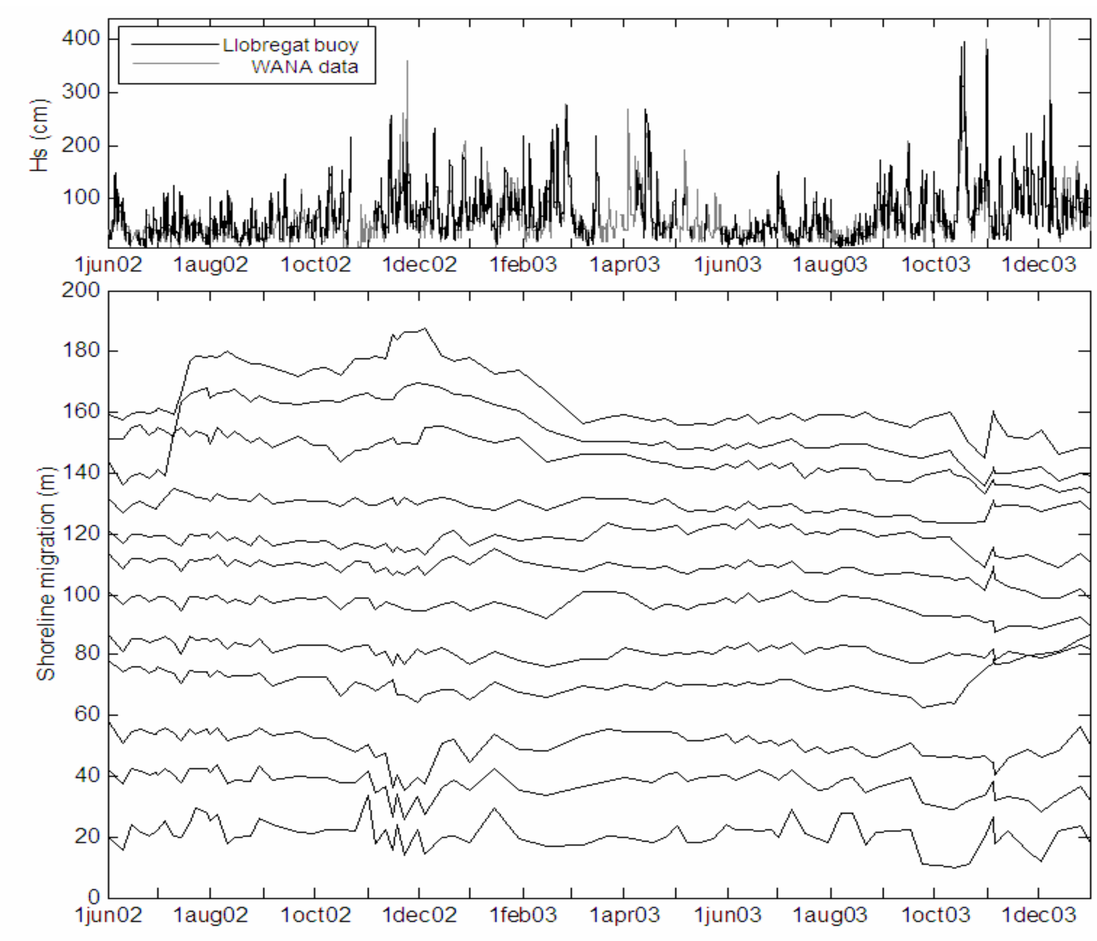

Figure 4. Shoreline evolution of La Barceloneta beach. Upper illustration: significant wave height. Lower illustration: time series of shoreline position changes along control transects in La Barceloneta (Y axis gives the variation along the transect in meters).

beach rotation, i.e., to the lateral movement of sand towards alternating ends of the beach (SHORT AND MASSELINK, 1999). The mid November 2002 storm (S direction) produced a similar beach rotation pattern on the two beaches, with almost no effect in the central transects, an advance in the northern sections, and a retreat in the south of tens of meters in both cases. Several consecutive storms took place at the end of January and along February 2003, the most energetic ones in the second fortnight of February, producing different effects on the beaches. After these storms, the shoreline in the northern section of La Barceloneta retreated to values approaching those before the nourishment was implemented, whilst in the southern part the effect was almost imperceptible (Figure 4). Bogatell beach reacted to this sequence of storms in a different way, with beach rotations that imply a total beach retreat in northern Bogatell in the order of 15 m and advance in the south of the beach (approximately 10 m), with no effect in the central section (Figure 5).

In the following months there were no important disturbances of the shoreline position along the beaches almost until October 2003 when two energetic storms with ESE and S directions produced opposite beach rotation in Bogatell. The first one (mid October 2003, ESE) caused erosion in the northern part of the beach and, accretion in the southern one. The second storm (late October 2003) caused an opposite rotation: accretion on the northern side and erosion on the southern side. However, neither of these two storms caused a significant effect in the beach area (Figure 6).

The effect of these two storms in La Barceloneta beach was a retreat in the north section of the beach caused by the ESE storm, with no effect in the southern sector. The second storm (S) produced an advance of the whole shoreline position but with different rates along the beach. In addition, a megacusp located in the fourth transect (starting from the S of the beach) developed after this storm, probably through the evolution and onshore displacement of the offshore bar.

Moderate storms occurred in December 2003 causing beach rotation in both beaches, although no significant changes in beach configuration and shoreline evolution trends occurred.

Emerged beach area

In contrast to the shoreline behaviour, emerged beach area data are quite different in both beaches (Figure 6). Besides the dissimilarity in the nourishments, La Barceloneta presents greater variability in the emerged beach area during this study period than Bogatell; although the main characteristic in both beaches is a continuous area decrease after the nourishment, interrupted by the effect of different storms but usually the beach recovers after them following its decrease pattern.

La Barceloneta showed a reduction in emerged beach area of approximately 22 m^2 per day between 1^{st} August 2002 and 31^{st}

December 2003. Since the southern part of this beach was not included in the data analysis, there is the possibility that the sand was being transported to the southern section, increasing the area in this part of the beach. However, analysing the whole beach area (including the southernmost data) also yielded a negative trend in the beach area after the nourishment, with a higher value of 23 m^2/day. Therefore, most of the eroded sand from the nourished area did not continue in the dynamics of the emerged beach and was transported offshore.

The implications of the Bogatell beach nourishment in the beach width and area can be observed in Figure 6. Right after the first adjustment of the nourished sand, the beach readapted its shape with some slight movements of the shorelines but no change in the beach area. It was at the beginning of September 2002 when the beach area started to decrease with the main shoreline retreat occurring in the south of the beach. In this case the rate of beach area loss between 6th July 2002 and 31st December 2003 was 18 m^2 per day. The beach area became more stable from April to September 2003, corresponding with the lower wave energy period, but after this period the beach negative trend resumed.

DISCUSSION

Beach nourishments performed along the Spanish Mediterranean coast usually are designed for combating beach erosion in a medium-term perspective (LECHUGA, 2003; GALOFRE *et al.*, 2004). For instance, ESCARTIN *et al.* (2003) studied the evolution of a sand nourishment of $3.8x10^6$ m^3 along the Maresme coast (North of Barcelona). They reported a sediment loss of approximately 47000 m^3 on the 10 months following the nourishment and that in 7 years 13% of the initial material had left the system due to alongshore and cross-shore transport, meaning that the volume of sand disappearing of the system was approximately 500 000 m^3 (less than 15% of the filled sediment).

However, the nourishment carried out in Barcelona in the summer 2002 had some special characteristics because it was a fast, urgent undertaking to restore the subaerial beach before the tourist season rather than a typical nourishment project. From a tourism-economical perspective, the 2002 nourishment *saved* the summer tourist season of Barcelona beaches, although from a coastal management point of view their positive effects only were detected for a short period of time. In contrast, the nourishment

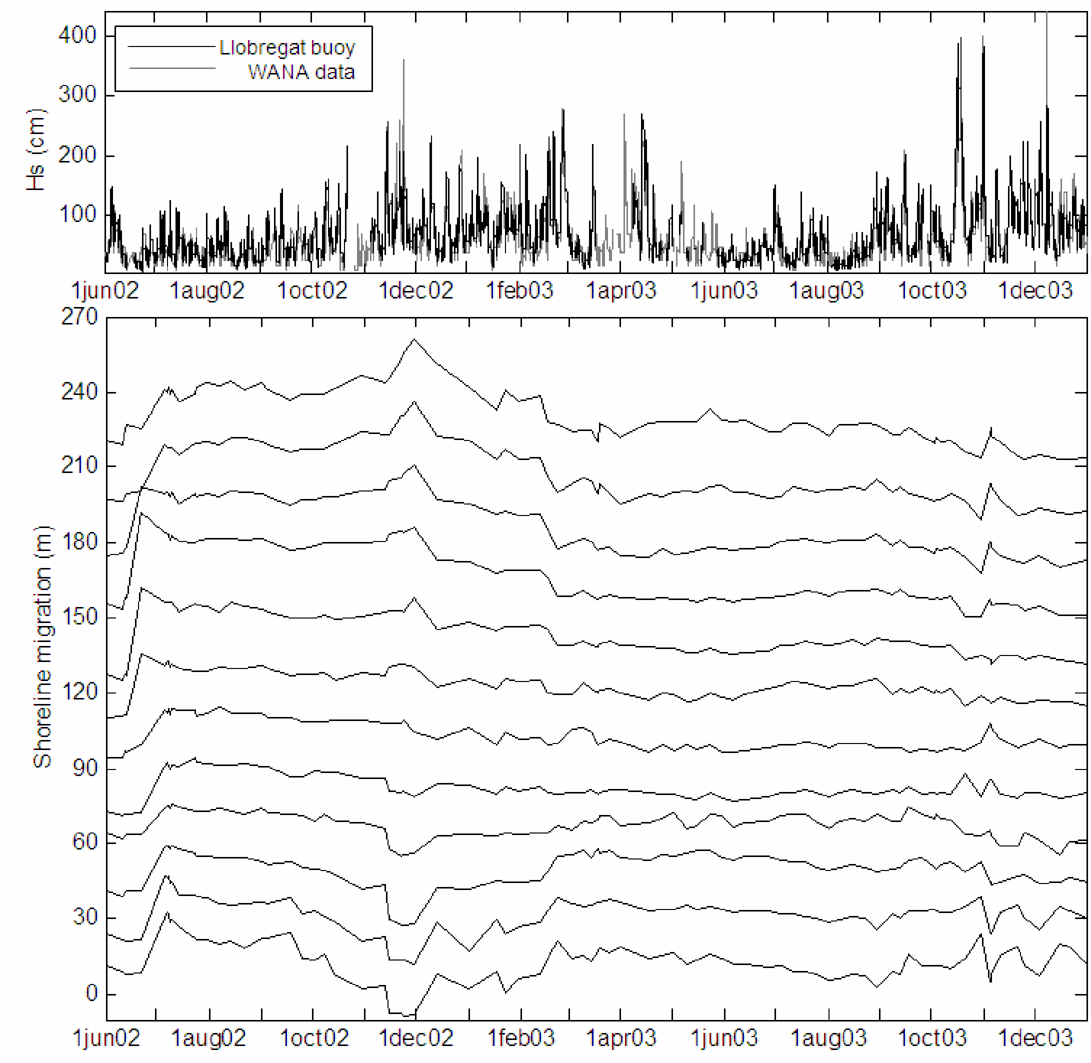

Figure 5. Shoreline evolution of Bogatell beach. Upper illustration: significant wave height. Lower illustration: time series of shoreline position changes along control transects in Bogatell (Y axis gives the variation along the transect in meters)

that was implemented in the city beaches during the period 1988-1992 allowed these beaches to remain *useful* for ten years. The main difference between those nourishments and the sand filling of 2002 is the amount of sediment supplied, which was one order of magnitude higher in the first one. Consequently, the results suggest that the future design of beach nourishments in Barcelona beaches should include a volume of sand significantly higher than the volume used in the 2002 nourishment in order to achieve convenient beach behaviour in a medium term perspective (several years).

DETTE *et al*. (1994) established that expanding the interval between consecutive replenishment implies a rapid increase in the required annual volume of sand; maybe this is also an additional important factor to take into account in the studied case; the possibility of performing minor regular nourishments as an alternative to the ten-years *interruption* of the beach management response. This idea is in accordance with the MUÑOZ-PÉREZ *et al*. (2001) study on reef-protected beaches, where small yearly nourishments similar to the yearly losses are recommended with the intention of attaining economic saving and a better use of the natural resources

Beach evolution of Barcelona city beaches during the study period shows that the shoreline in December 2003 was similar to the pre-nourishment situation, suggesting that the beach tends to reach an *equilibrium* shape. Fast changes in beach morphology after the nourishment had mainly been caused by storms of different characteristics, whose most important effects were advances and retreats in the shoreline position due to beach rotation, i.e., movement of sand from one side of the beach to the other but not involving sediment losses.

Concerning the beach area data, the effect of the storms was not as evident as in the shoreline position. After the nourishment, both beaches experienced almost continuous area reduction for several months. Erosion trends of the emerged beach area calculated after the nourishments were 22 m^2/day in La Barceloneta and 18 m^2 in Bogatell. Further research is ongoing to determine the path followed by the eroded sand, whether it is being transported offshore in such a way that it is being lost of the system or the sand is being stored at a certain depth but there are still possibilities of reincorporating it into the littoral system and subsequently reaching the beach. Another possibility is the presence of alongshore sediment transport, although we are dealing with apparently closed beaches (individual cells). To answer these questions fieldwork is currently being carried out with bathymetric and topographic surveys in a joint study of the subtidal bar behaviour using the Argus system.

The almost continuous loss of surface in La Barceloneta and Bogatell beaches after the nourishment suggests a strong disequilibrium of the beach that is compensated by the erosion. In fact, the shoreline retreat -represented by losses of surface of the

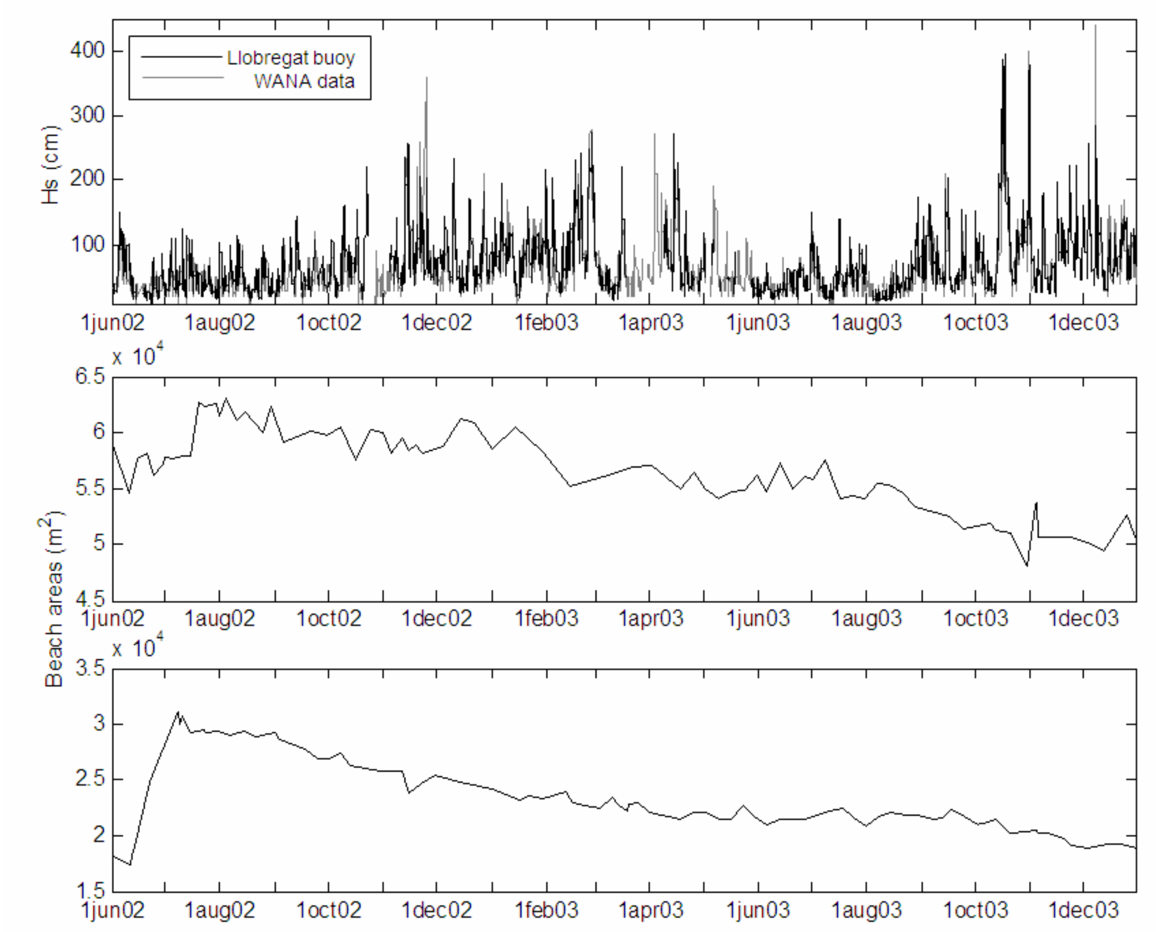

Figure 6. Emerged beach area evolution of La Barceloneta and Bogatell beaches. Upper illustration: significant wave height. Central illustration: time series of La Barceloneta emerged beach areas. Lower illustration: time series of Bogatell emerged beach areas.

subaerial beach- was not triggered by a strong storm, but it started almost immediately after the nourishment was accomplished in both beaches and it remained continuous -although with different rates- until the beach reached a configuration similar to the pre-nourishment one. Changes in the shoreline shape associated with storm effects seem to be superimposed on the general trend of subaerial beach losses associated with the beach evolution toward some equilibrium shape. The erosion of the beach nourishment was a fast process, since 100% of the filled sand was lost approximately one year and a half after the nourishment.

CONCLUSIONS

The nourishment of Barcelona beaches carried out in summer 2002 was only effective from a very short-term perspective, given that the shoreline configuration was similar to the pre-nourishment situation approximately one year and a half after it. The limited amount of sand used in the filling and probably the generation of a beach profile strongly in disequilibrium with morphodynamic conditions during the nourishment works were the main reasons for this fast erosive response.

Storms from different directions produced the rotation of the La Barceloneta and Bogatell beaches with alternative erosion and accretion in both sides whereas no significant changes occurred on the central part of the beaches, suggesting that the alongshore transport plays a relevant role in the evolution and configuration of these embayed beaches.

The evolution of the shoreline location after the nourishment corresponds to beach area loss of 22 and 18 m^2/day in La Barceloneta and Bogatell beaches, respectively. This implies an approximate volume loss between 103 and 174 m^3/day in both beaches until an equilibrium configuration was reached. Maximum erosion was not directly related to the strongest storms, but depended on the time elapsed since the nourishment and the wave approach direction. Changes in beach area related to storms are superimposed on the general decreasing trend.

The example of Barcelona city beaches shows that the beach nourishment evolution can be successfully analyzed using video monitoring techniques, an easy, low-cost technique that allows an increase in sampling frequency, which gives the opportunity of a detailed analysis of the beach behaviour identifying relevant events and their effect on the coast evolution.

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