Impact of storms along the coastline of Emilia-Romagna: the morphological signature on the Ravenna coastline (Italy)

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ABSTRACT

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The coastal zone of the Emilia-Romagna region in Italy is exposed to risk from coastal flooding and erosion during storms. The vulnerability of this coastline is a topic of interest for future planning as this area provides large revenue for coastal communities and the whole region. An assessment of the historical record of storm events for the period 2000-2004 was carried out using a wave prediction model, forced by archived atmospheric circulation data. High-resolution air-borne laser detection technology (LIDAR) and video-monitoring (ARGUS) were used to undertake a feasibility study for the assessment of coastal erosion and flooding patterns along one of the best-preserved dune systems of the area. The object of the work was the comparison between two LIDAR flights at an interval of one year (July, 2003-September, 2004) with the second flight carried out after a major storm occurred in September, 2004. Following this event the whole coastal system was severely eroded. The study presented in this paper suggests that for the coast of the Emilia-Romagna region the critical factor that controls dune destruction and inland flooding is the joint occurrence of storm waves and surges. Beach slope is the main morphological control on wave run-up and the impact evaluation for the exceptional event has proved that a wide beach can provide a factor of safety. A small beach replenishment (33,000 m^3) was undertaken on the test site but this resulted to be ineffective because of the small volume. Larger-scale beach recharge schemes should be undertaken at the site on a regular basis to provide wider beaches at the dune toe.

ADDITIONAL INDEX WORDS: *LIDAR Surveys, Wave forecasting, Beach recovery, Video imagery*

INTRODUCTION

Although the study of coastal changes using cartography and aerial photography provides some general clues about large-scale coastal changes, the quantification of processes over time-scales longer than five years becomes difficult, as it requires long-term datasets of waves and morphology which are not always available.

To quantify the impact of coastal storms, it is quite rare that pre-storm surveys are available, unless routine monitoring is foreseen by competent authorities. In the case of the Emilia-Romagna region (RER), beach profiles are surveyed on average every five years, clearly not enough to describe the impact of extreme events and not even suited to quantify seasonal changes. Some authors (e.g. FERREIRA, 2005) have recently concluded that the implication of variability in storminess on coastal morphologies remains badly described in the scientific literature. The main limitation is the availability of representative datasets regarding the morphology. Despite the limited tidal excursion of the Adriatic Sea, much discussion is taking place in RER about which reference feature *(proxy shoreline)* should be used to identify erosive beach states. A recent paper by MOORE *et al.* (2006) concluded that the use of *shoreline proxies* is justified under many circumstances, as the errors due to datum offsets are small relative to the change rates. As recently pointed out by DAVIDSON *et al.* (2006), video-derived Coastal State Indicators have several advantages over similar parameters obtained using conventional image sources, like air or satellite imagery. The position of the Mean Sea Level (MSL) contour, worked out using "virtual" topographic surveys using rectified video images, probably provides an unbiased indicator, as this is normally obtained from sophisticated image processing techniques, which may include numerical models to account for wave set-up processes (AARNINKHOF *et al.*, 2003). On the other hand, video-monitoring only covers small areas. Thus, airplane-based LIDAR survey can augment topographic knowledge and work towards identification of the MSL contour.

The absence of wave data for a particular region can be compensated by the use of wind-driven models. However, the use of single-point wind observations for local forecasting is problematic, while the use of locally calibrated, high-resolution circulation models provides a meaningful source for predictions. The present paper initially describes the occurrence of high-energy events along the RER coastline from the records available either as direct measurements or as archived wave forecasts. The paper then studies in detail the impact of storms occurred in the winter 2004-05 on a system of coastal dunes south of Ravenna and the associated shoreline changes. Finally, the effectiveness of a replenishment to counteract dune erosion is assessed.

METHODS

Wave Data

Buoy observations in Italy are provided by APAT through the RON (Rete Ondametrica Nazionale) network. Along the northern Italian coast of the Adriatic Sea there are two buoys which have collected data in recent years, one located near Ancona (43.83 N; 13.71 E) and one near the Po Delta (44.97 N; 12.63 E). The former has the longest wave record (1999-2006), but is located 130 km from the study area (Figure 1).

It was decided to prepare a review on the occurrence of storms over the period September, 2000-March, 2004. The lack of long-term buoy records from the upper Adriatic made it impossible to evaluate these extreme events from observations. It was therefore decided to use sea state forecasts from the WAM model operationally run by ARPA-SIM. For this purpose, model runs were extracted at a point with geographical coordinates of 44.5 N and 12.33 E, ideally located in a water depth of 9 m just south of Ravenna.

The third generation Wave Model (The WAMDI GROUP, 1988; KOMEN *et al.*, 1994) was used for wave prediction. The considered domain was the whole Adriatic Sea area, with an 8 km horizontal resolution (1/12°). WAM was forced by the wind computed at 10 m above sea level by the meteorological model LAMBO, the Limited Area Model Bologna. This was the ARPA-SIM limited area, numerical weather prediction model that was operational until March, 2004. It is a finite difference, split-explicit, primitive equation hydrostatic model, based on an early version of the NCEP Eta Model (MESINGER *et al.*, 1988). LAMBO was operationally integrated twice a day, nested on ECMWF operational runs of 00 and 12 UTC, the forecast length being 72 and 84 hours, respectively. Verification of WAM wave forecasts against observations at Ancona indicates that it was possible to use the [+24,+48 hours] forecast data provided by the WAM model for the isolation and evaluation of extreme events like sea storms. Further details can be found in the final report of the CADSEALAND Project (2006).

Many methods can be applied to isolate an extreme storm event from a set of samples, each method differing from the others for the considered variables and their combination (e.g. MENDOZA and JIMÉNEZ, 2004). The threshold for storms conditions was taken as a significant wave height of a 1.5 m and minimum event duration of 6 hours both for forecast data and observations.

Field Site and Morphological Datasets

The case study site (Lido di Dante) is characterised by a beach stretching 3 km from the edge of coastal protection structures to the Bevano river mouth (Figure 1). In front of the urbanised area there is a breakwater (770 m long) and its edge effects generated by the southern end of the breakwater are felt as far as 900 m from the structures, especially during NE storms (ARMAROLI *et al.*, 2005). There is some debate about the net direction of long-shore drift at the site. Unpublished numerical simulations (HYDROSOIL, 2004) predict for the area immediately south of the structures a southward drift of 49,000 m^3/yr, computed for the whole profile down to the estimated depth of closure (7 m). The area south of the village is instead free from coastal structures, with a pine forest and an eroding dune field. The dune system is single-ridged,

Figure 1. Location of Lido di Dante, Ravenna (1996).

with crest elevation of 1-1.5 m above MSL on the northern part and up to 5 m above MSL at the southern margin. In February, 2003 an ARGUS video-system was installed at the site (Figure 1). The system consists of four cameras mounted on a 18 m-high tower: three looking at the beach behind the breakwater and one looking at the natural sector. In this study the shoreline was extracted using the IBM (Intertidal Beach Mapper) tool of AARNINKHOF *et al.* (2003). Short-term (hours) shoreline surveys were carried out by ARMAROLI *et al.* (2006) to compare the DGPS data with ARGUS using a GIS. The study revealed that ARGUS and DGPS shorelines are identified with comparable precision (4-6 m), considering that the latter method is influenced by swash oscillations.

Two topographic LIDAR flights were undertaken at an interval of approximately one year (July, 2003-September, 2004). The first flight was provided courtesy of ENI, while the second one was carried out by the SGSS of the RER. The second flight took place after a major storm which occurred on 24th September, 2004. The morphology of the beach and the dunes was also monitored in 2004/2005 along cross-shore profiles regularly spaced (150 m), starting from the dune crest down to a depth of -1/-1.5 m below MSL. The dune crest elevation was also measured walking on the foredune ridge with an RTK-DGPS in dynamic mode. Particular attention was put on measuring the extension of overwash areas and their elevation.

RESULTS AND DISCUSSION

Storm Climatology

The four year WAM dataset shows that storms mostly occur in the autumn and winter seasons (Figure 2). The main direction of incoming waves during storms is the north-east in winter and the east in autumn. The frequency of occurrence seems to have increased during the winter period of the last three considered years, whereas it has remained more or less constant for the autumn period. Spring storms are less frequent and smaller, but
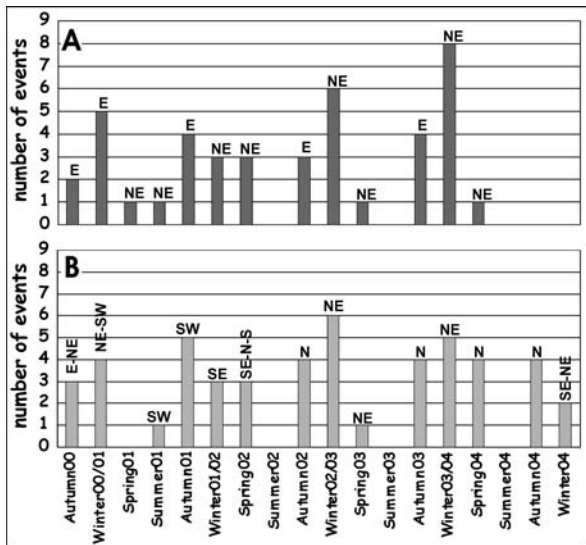
Figure 2. Seasonal number and direction of sea storms: A- forecasted by WAM; B- observed by the Ancona buoy.

they show less directional variability than autumn events, being all concentrated around the north-east.

These results are partially confirmed by the analysis of buoys observations, taking into account the distance of Ancona and Punta della Maestra buoys from the Emilia Romagna coastline and the different water depths of the buoys compared to the extrapolated point of the regional domain where simulation has been carried out. The Ancona buoy (depth of 75 m) has a long and consistent record of data but it is also further away from the domain of interest. The other buoy of Punta della Maestra (depth of 30 m) is closer but, on the other hand, it has a short and discontinuous dataset. For this reason in Figure 2 only a comparison between WAM and Ancona is presented. Notice that the forecast database only covered the period up to the spring of 2004. Thereafter a major model re-organisation took place and for consistency was not considered for further use.

The Storms of September 2004

Between 18:30 GMT of 24th Sept and 00:30 GMT of 27th Sept the buoy at Ancona registered an H_s of more than 5.5 m. If one uses a storm threshold for the wave height of 1.5 m, this was exceeded for 73 hours between 24th and 27th Sept (Figure 3). During the event there was also a maximum storm surge of 0.7 m measured by the tide gauge of Porto Corsini, near Ravenna (20 km away). The value of the surge was computed comparing the astronomical tide prediction with the tide gauge record. The surge was not particularly high, below the level of the 1-yr event indicated in YU et al. (1998). Offshore wave data identify a first storm occurring between 24-25 Sept and a second one between 26-27 Sept. The maximum energy was reached during the first event. Transposition of the wave offshore climate to the study site predicts a wave height of 5.65 m, which exceeded the 25-yr return event, being the largest measured event on record.

Notice in Figure 3 that the maximum water level registered by the tide gauge in Ravenna did not correspond to the storm peak. Wave direction changed during the storm from SE to NNE. The SE winds caused the surge because they were combined with low

barometric pressure. The effect of the storm on the coast could have been worse if the surge and the maximum tidal level reached on 24th September, 2004 were simultaneous with the storm peak.

The Morphological Record of Storminess

From the analyses of storminess presented above, it is clear that the winter of 2003/2004 was an exceptional year for the number of storms from NE with good agreement between the wave forecasts and the buoys. On the other hand, the autumn of 2004 was characterised by the concomitant action of exceptional high tides and storm clustering from the north. The winter of 2002/2003 also followed a similar pattern. Two issues were investigated: a) the response of the beach at Lido di Dante following this "exceptional" clustering of events that occurred in Sept 2004; b) to assess if there was a trend of continuous erosion that was onset by the frequent storms of the previous years.

To evaluate the erosion caused by storms in autumn 2004 and whether or not the beach recovered its equilibrium state, the shoreline evolution was assessed from video images, using the MSL contour. This was calculated on selected days by mapping shorelines using the IBM tool and then choosing that with elevation zero (referred to local MSL datum). Days with spring tides under calm conditions were chosen, selecting images of the area before the storm (2nd Sept, 2004-13 images) and after the event (30th Sept, 2004-10 images). The two datasets were collected under comparable spring tidal ranges.

The results (Figure 4) show that the area is divided into two parts: the one close to the structures was dramatically eroding; the central and southern areas were oscillating or stable. The video images also showed that the dunes were touched by run-up and overtopped by waves. The analysis of video images confirmed that rhythmic features were moving alongshore in the central and southern parts of the beach, according to the dominant wave direction, as proposed by ARMAROLI et al. (2005).
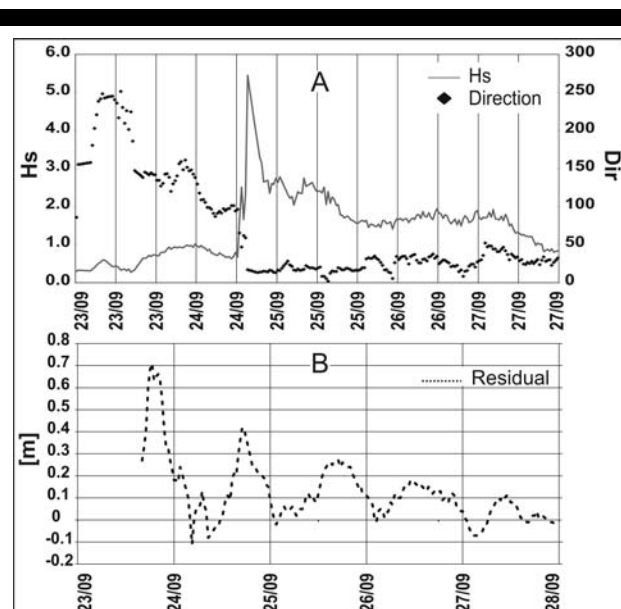

Figure 3. A- Significative wave height (Hs) and wave directions (Dir) registered by the Ancona buoy between 23 and 28th Sept, 2004; B- Residuals between measured tides at Ravenna and astronomical predictions.
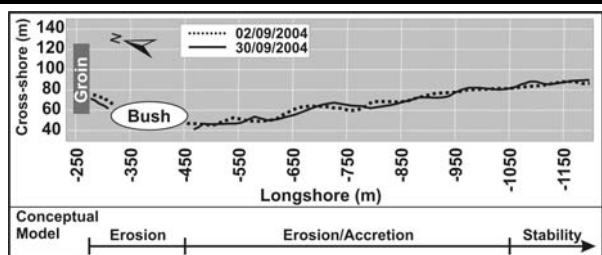
Figure 4. Comparison between MSL identified using ARGUS imagery on 02/0904 and on 30/09/04. The interruption in the interpretation is due to the presence of a large bush which covers part of the beach.

The rhythmic features are strictly related to the formation and migration of intertidal bars, which are common at the site (BALOUIN *et al.*, 2006). The analysis of the shoreline position revealed that the southern part of the beach is wide and stable. Regarding the dune foot, retreat in the central area was observed, while in the area close to the structures the dunes were almost completely eroded.

The analysis of the topographic datasets collected during 2003/2004 proved that an increase in the erosion rate of the dunes was caused by overwash and overtopping events that however had started during storms in the winter of 2003/2004. A comparison between the dune profiles measured in the surveys before and after the storm occurred in September, 2004 (Figure 5), revealed a variable behaviour of the area up to about 1 km from the structures, where it was actually achieved a peak in retreat (14 m), during that single storm event. Profiles showed that there were localised sediment inputs due to dune erosion during the storms, with many points of overwashing observed in the field.

The dunes that suffered most from overtopping were those close to the structures in an area with consistent beach erosion (ARMAROLI *et al.*, 2005). Figure 5 shows the strong retreat of the beach and the destruction of the first line of dunes. It is important to note how the areas with healthy dunes (over 4 m high) were not affected at all by the exceptional event of September, 2004. Where the dune system is stable and the beach slope mild the beach tended to be wider. It is striking how the dune undercutting rate, measured during the DGPS surveys, dropped passed the 1 km boundary from the structures, which also corresponded to a general stability of the intertidal beach observed from the video imagery and the topographic surveys.

A conceptual model of the morphological behaviour of this beach when hit by storms was produced dividing the area into three zones. A first one located between the edge of the groin and a boundary at -450 m to the south, with high erosion rates. The issue to be considered in this case is the influence of the breakwater. When north-easterlies generate storm waves, diffraction by the barrier's edge may generate a concentration of wave energy on this coastal stretch. The beach slope was indeed generally steep in the area immediately to the south of the barrier. Modelling by HYDROSOIL (2004) predicts for this beach a net southward drift of 49,000 m^3/yr. A second intermediate coastal segment, extended up to -1050 m southwards of the tower, had variable erosion/accretion tendencies. The modelling studies cited above identify here a net long-shore transport to the south of 30,000 m^3/yr. On the other hand, the southernmost area, which extended to the edge of the coverage by ARGUS (-1200 m), was instead essentially stable, even under extreme forcing conditions with combined occurrence of high waves and surge levels. To note that this area receives consistent sediment input from lateral erosion of dunes at the Bevano river mouth, due to northward migration of the inlet and subsequent sand removal from the mouth by long-shore drift directed northwards (BALOUIN *et al.*, 2006).

Beach Recovery Potential

A replenishment scheme was carried out in spring 2005 with the placement of 33,000 m^3 along the beach south of the structures, along a distance of 800 m from the breakwater.

To assess the effectiveness of the replenishment, two DGPS surveys were undertaken before the beginning of the works (27th February, 2005) and after completion (7th May, 2005). The survey consisted of 20 profiles closely spaced every 50 m (Figure 6), extended from the dune crest to the low tide limit. The same profiles were then extracted from the DTM of the LIDAR Survey undertaken in September, 2004 after the storms that eroded the dunes. The aim of the study was to evaluate the evolution of the beach during the winter, the effectiveness of the replenishment and the displacement of the sediment dumped during operations. As can be seen in Figure 6, the beach had not recovered from the erosion of the storms of September, 2004 and just few weeks after replenishment most of the sand had been removed from the dumping site (northern profiles, e.g. P20).

It seemed however that the sand was displaced southward and re-arranged on the intertidal beach in the form of swash/bars and low tide terraces, which are typical of the area. A volumetric comparison between the surveys before and after the works confirms a discontinuous pattern of erosion/deposition around
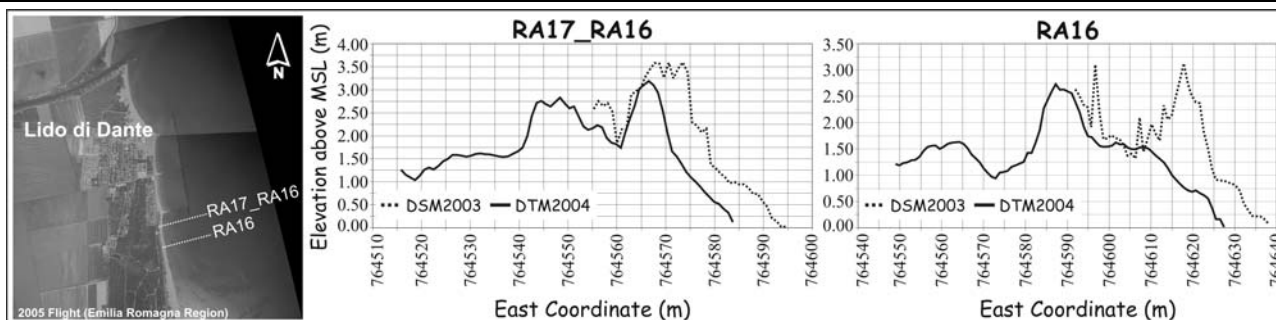

Figure 5. Comparison between 2003-2004 LIDAR data of two profiles that are immediately to the south from the protected area. Note the destruction of the first line of dunes.
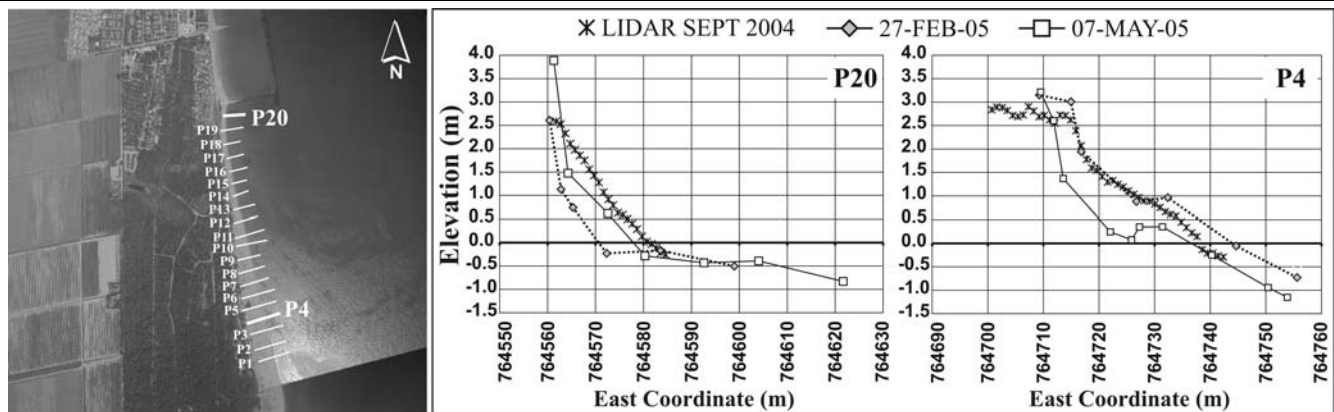
Figure 6. Comparison between beach profiles surveyed after major storm (Sept 04), winter 2005 and after beach replenishment (May 05).

MSL. Clearly the sand volume injected into the littoral budget was not large enough to produce tangible results.

CONCLUSIONS

The frequency of storm events has grown during the winter period of the last three years of the studied period (2002-2004), whereas it has been more or less constant for the autumn period. The maximum number of storms occurred during the 2003-2004 winter period. During September, 2004 a group of strong sea storms caused hazards for open sea and harbour activities, damage to seaside tourist facilities and severe erosion of the RER coastline. The work on the case study site of Lido di Dante has quantified the impact of these storms on one of the few remaining areas in the Region with coastal dunes. The work identified a variable pattern of erosion according to the distance from coastal structures.

The storms generated beach loss mainly in the area close to the structures. Emergency replenishment schemes (33,000 m^3) undertaken after the storms were not successful, only providing a "placebo" effect on the sediment budget. Comparing the beach profile response with estimates of annual long-shore transport, we conclude that replenishments should be larger of about one order of magnitude and spread over a longer segment of coastline.

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