Integrated Coastal Zone Management (ICZM) –

The Global Challenge

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- List of finalized chapters
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Evaluation of maximum storm wave run-up and surges along the Emilia-Romagna coastline (NE Italy): A step towards a risk zonation in support of local CZM strategies

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The coastal zone of the Emilia-Romagna region is exposed to risk from coastal flooding during storms. The vulnerability of this coastline is a topic of interest for future coastal planning as this area provides large revenue for coastal communities and the whole region. High-resolution air-borne laser detection technology (LIDAR) has permitted 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. Following a period of exceptional events occurred in September 2004, with a return period of ~~100~~ years, the whole coastal system is in a state of weakness. A risk evaluation was therefore undertaken for combined events of storm waves and surges, with return periods of 1, 10 and 100 years. A methodology for the characterisation of dune erosion is proposed.

Introduction

The years 2004 and 2005 were characterised by a large number of coastal disasters around the world. We all remember the sad days following the tsunami in East Asia and the landing of Hurricane Katrina on the coast of Louisiana in the USA. Unfortunately in both cases the control of the processes that generated the events is beyond human power. However, if adequate mitigation policies had been in place at a planning level, many lives would have been saved.

In the Editorial Preface to the November 2005 issue of the Journal of Coastal Research, Pilkey and Young (2005) present some thoughts on the impact of Hurricane Katrina, playing on the double meaning that the word “impact” can have in the current usage of the English language. If one considers the “physical” impact of the running water on people and properties, we tend to consider the event exceptional, because of the huge damage to the city of New Orleans. On the other hand, the “political” impact of the event was considerable, with large space on the mass media around the world, the resignation of top US officials and a general belief that nothing could be done against this "act of god". We forget that, after all, New Orleans is a town built on reclaimed Mississipi levees, which by definition (Oxford Dictionary of Earth Sciences, 1990 Edition) are subjected to periodic overbank flooding. In the public outcry that followed the disaster, nobody reminded us that coastal Louisiana was already badly damaged by passage of Hurricane Camille in 1969. Following that disaster^ construction criteria were introduced to mitigate future flooding but still this was not enough to avoid that the points of major damage by Katrina were exactly the same ones observed after Camille.

The coast of Emilia-Romagna is only occasionally exposed to catastrophic events like tsunamis (Tinti *et al.*, 2004) and it is not exposed to hurricanes. However, there is evidence that in recent years a change in meteorological conditions is taking place in the northern Adriatic Sea (Trigo and Davies, 2002; Pirazzoli and Tomasin, 2003). Although some of these authors suggest an implication of this variation in wind regime on the occurrence of storm surges, the forecasting of changes in wave climate is difficult, since it is linked to larger-scale climatic circulation.

Regarding the impact of storms on the nearshore, in order to carry out meaningful simulations of processes like surges and wave run-up, it is necessary to have access to a detailed Digital Terrain Model. For the Emilia-Romagna coastline the task of obtaining a detailed landscape characterisation is not simple, due to the high degree of urbanization of the coastal stretch. Further difficulties are created by the interplay of wide-scale processes like natural subsidence in the Po area and further losses of elevation generated by gas exploration and production in the Ravenna area (Gambolati *et al.*, 1998). Recent studies have shown that at present the rate of subsidence around Ravenna is stable and is no longer increasing. However, there are areas that still have ground lowering rates of 10 mm/yr (Teatini *et al.*, 2005). The development of the coastal zone reached the current level of exploitation in the 1970's, when out of 107 km of coastline 77 km were providing revenue for the local economy through tourism (Preti, 1993). Therefore, the competent authorities for planning at a regional level are considering the production of a risk cartography.

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. Dune ridges represent a natural form of coastal protection against the action of waves and storm surges. Many numerical models have been developed to predict profile response and sediment exchange between the beach and the foredune (e.g. Vellinga, 1982; Larson and Kraus, 1989; Kriebel and Dean, 1993). However, a limitation of all numerical models up-to date is a meaningful reproduction of the role of dune vegetation in dissipating the energy of the overtopping seawater.

The use of Lidar technology for the study of coastal changes has become widespread in the last 10 years. In the USA a repetitive monitoring programme is active since 1996, and aims at the evaluation of storm risks, involving several agencies such as NOOA, NASA and USGS (http://coastal.er.usgs.gov/lidar/).

To create a storm risk cartography using numerical simulations, the U.S. Army Corps of Engineers has been using data obtained with air-borne laser technology. In particular, they have combined data for the subaerial beach with surveys obtained using the *Shoals* bathymetric Lidar (http://shoals.sam.usace.army.mil/). Bathymetric Lidar has also been proved to be a useful tool for the study of sea bed morphodynamics, for example in Florida, where a penetration of 70 m was obtained (Finkl *et al.*, 2005). The Lidar technique provides a quick method for the assessment of the impact of extreme events like hurricanes (Zhang *et al.*, 2005) when it becomes necessary to cover large areas of the coastal zone within a short time span.

The current paper describes the impact of storms occurred in 2004 on a system of coastal dunes in the area of Ravenna (Lido di Dante area). The source of the work was the comparison between two Lidar flights undertaken at an interval of approximately one year (July 2003–September 2004) with the second flight carried out after a major storm. An assessment of coastal vulnerability using statistically significant wave parameters was then undertaken.

The case study site: the dunes of Lido di Dante

This beach stretches along a coastal segment that is 3 km long, extending from the Lido di Dante settlement to the Bevano river mouth (Fig. 1). In front of the urbanised area there is a submerged breakwater (770 m long) with a design crest elevation of -0.5 m below MSL (Lamberti and Zanuttigh, 2005). The area south of the village is instead free from coastal structures, with a pine forest and an eroding dune field.

The maximum tidal range is about 0.9 m at spring tides, while it decreases down to 0.3 m at neap tides. The wave climate is usually mild, with significant wave heights lower than 1 m, mainly from the East (65% of occurrences) (Gambolati *et al.*, 1998). Two different storm directions prevail in the Adriatic Sea: the Scirocco from SE and the Bora from NE. Storms with one-year return period, with direction NE-E-SE, have wave heights around 3 m and periods of 7.5 s (IDROSER, 1996).

Recent studies based on interpretation of aerial photography and GIS mapping (Ciavola *et al.*, 2004) identified that the erosion process started in the late 1970s and that the construction of groins and of the breakwater did not produce any positive results on the nearby beaches. The integration between morphological surveys of the dune-beach system (Balouin *et al.*, in press) and video-monitoring (Argus technology) of coastline and bathymetric changes (Armaroli *et al.*, in press) suggests that edge effects generated by the southern end of the breakwater are felt as far as 900 m from the structures, especially during NE storms.

The authors (Balouin *et al.*, in press) have been monitoring the area since 2001 with a Total Station and DGPS RTK. Results show that the dune system is single-ridged, with crest elevation of 1–1.5 m above MSL on the northern part of this coastline and up to 5 m above MSL at its southern margin. At this point the northward migration of the river outlet generates lateral dune erosion, so that local authorities carried out an artificial diversion of the river in the early

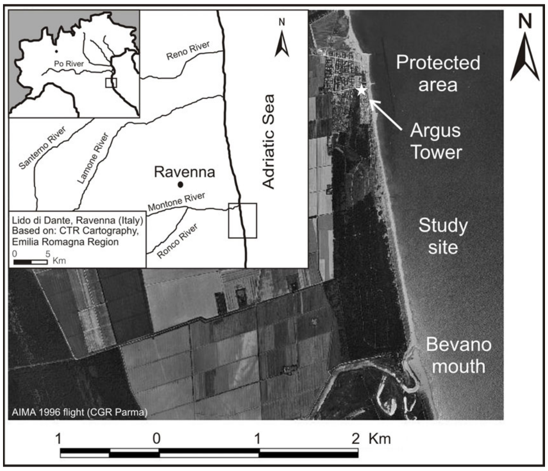

Figure 1. Site location map.

Spring 2006. The whole area has a high natural value, as it is included in the Po Delta National Park and is considered a site of special ecological value at a national and international level (European Union legislation and Ramsar Convention).

Dunes are covered by vegetation that changes in diversity and density moving from north to south. Thus vegetation can be considered an indicator of the state of healthiness of the dune system (Armaroli *et al.*, 2005). In fact, foredune vegetation (e.g. *Ammophila sp.*) disappears in the northern sector due to the effect of storm waves that physically remove the dune front.

Wave transformation models run by Zanuttigh and Lamberti (2005) show that the presence of the breakwater generates erosion of the sea floor outside the protected area (mainly in the southern part as scour-holes) and that NE (Bora) storms create very strong currents around the southern end-part of the breakwater.

Considering the submerged part of the beach, the area close to the breakwater does not present submerged features, while close to the river it is characterised by the presence of a well-developed system of bars that is extremely stable and preserves the beach from erosion (Armaroli *et al.*, 2005).

Methods and datasets

Wave data

Offshore waves in Italy are available on the website (http://151.38.159.87:5556/ron/ron_web/default.asp) of APAT (Agency for Environmental Protection and Technical Assistance), which maintains the RON (National Wave Measurement Network). Data is available as Significative Wave Height $(\mathrm{H_s})$, Mean Wave Period $(\mathrm{T_m})$, Mean Wave Direction (D) and water temperature. The closest buoy to the site is the Punta della Maestra buoy, in front of the Po Delta (44.972 N;12.833 E) at a water depth of 30 m. The buoy was installed in 2003 but unfortunately it always presented a discontinuous record and it was retrieved in 2005. A second buoy is located near Ancona (44.830 N; 13.715 E) at a water depth of 70 m and generally works without interruptions. One must notice that, considering the distance between the buoys and the shape of the Adriatic basin, local events are on some occasions contrasting on the two wave records.

In order to check the reliability of the two wave records, extreme storm events were reconstructed for the offshore area near Ravenna using the wave transposition method, based on the relationship between effective and measured fetches.

Lidar data

The survey was undertaken on 27 September 2004 and covered a coastal corridor about 800 m wide, equivalent to 9524 hectares (Fig. 2). The Lidar acquired data using a 25 KHz source, with a beam opening of 10°, flying at an altitude of 2300 m. Acquisition accuracy provided a density of 0.5 points per square meter, a horizontal precision of 1 m and a vertical one of 0.2 m. Data was later post-processed to obtain a Digital Terrain Model (DTM) and a Digital Surface Model (DSM) with a regular grid size of 1×1 m.

A second Lidar dataset was provided by the Ente Nazionale Idrocarburi (ENI), collected during a flight in July 2003. Unfortunately in this case the data available is only in Digital Surface Model (DSM) format, but with a grid size comparable to the former dataset. Testing of the comparable accuracy of the two flights was undertaken using fixed structures (e.g. jetties and buildings) as benchmarks.

Figure 2. Area covered by flight lines. The background is a QuickBird image captured in 2003.

The impact of storms

The airplane flew over the area after a period of strong storms incoming from the NE-E sector, occurred between 18:30 GMT of 24 September 2004 and 00:30 GMT of 27 September 2004 (Fig. 3). The buoy at Ancona registered a maximum H_s of about 5.5 m. If one uses a storm threshold for the wave height of 1.5 m, this was exceeded for 73 hours between 24 and 27 September 2004. Offshore wave data identify a first storm occurring between 24–25 September and a second one between 26–27 September. The maximum energy was reached during the first event: a transposition of the wave climate to the study site predicts an offshore significative wave height of 5.65 m, with a significative wave period of 7.7 s, which exceeded the 25-yr return event.

During the event there was also a maximum storm surge of 0.7 m measured by the tide gauge of Porto Corsini, near Ravenna (Fig. 3). The value of the surge was computed comparing the astronomical tide prediction using the WxTide Software (www.wxtide32.com), calibrated by the authors for Ravenna and the tide gauge record. The surge was not particularly high, below the level of the 1-yr event indicated in Yu *et al.* (1998).

In Fig. 3 it is possible to notice that the maximum water level registered by the tide gauge in Ravenna did not correspond with 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 24 September 2004 were simultaneous with the storm peak.

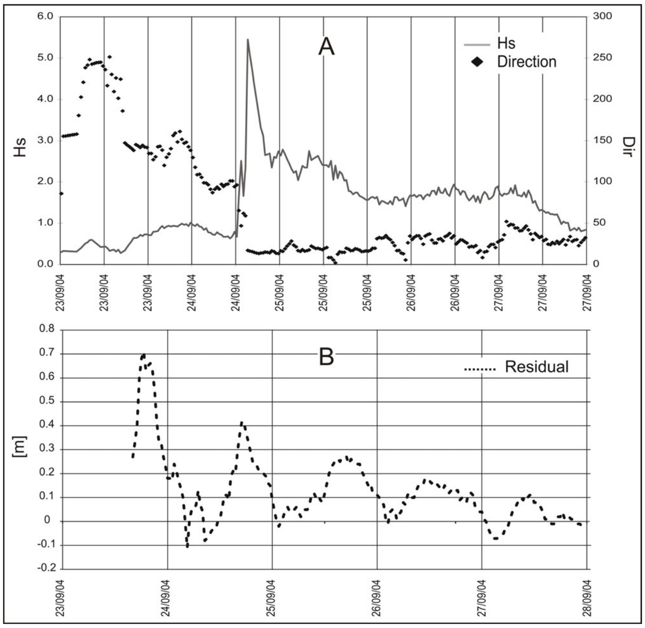

Figure 3. A Significative wave height (Hs) and wave directions (Dir) registered by the Ancona buoy between 23 and 28 September 2004; B- Residuals between measured tides at Porto Corsini (Ravenna) and astronomical predictions.

To test the significance of the observed event it was decided to carry out a risk assessment exercise, considering the worst scenarios, using a joint probability of a storm occurring at the same time as an atmospheric surge and with the maximum spring tidal level of $+0.45$ m above MSL (IDROSER, 1996). The parameterisation was obtained from the literature using the statistical analysis of Yu *et al.* (1998), who calculated surge levels for events with return periods of 1, 10 and 100 years. The work of these authors is considered reliable as it used a wind circulation and barometric model for the whole northern Adriatic. Significative wave height (H_s) and significative wave period (T_s) are taken from IDROSER (1996) that statistically computed them using empirical relationships that were calibrated with long-term wave data recorded by gauges mounted on oil platforms in front of Lido di Dante. The characteristics of the events are presented in Table 1.

In order to assess the effect of storms with different return periods on the dune system and on the areas behind the beach, the level of water ingression was calculated using the beach slope of different profiles measured on the 2004-DTM. It was decided to calculate the beach slope along profiles spaced every 500 m that have been monitored by the Emilia Romagna Regional Authorities since 1993 (ARPA, 2000) and to increase the number of profiles by computing intermediate

Table 1. Characteristics of storm events. The surge value only considers atmospheric effects.

Return Period (years)	H_s (m)	T_s (s)	Storm Surge (m)
T1	3.3	7.7	0.85
T10	4.7	8.9	1.04
T100	5.9	9.9	1.28

cross-sections (17 profiles in total). The location of these profiles is presented in the risk maps presented below.

The slope of the beach was calculated starting from the high water spring tidal level ($+0.45$ m above MSL, IDROSER 1996) to the dune foot, as this is the area where run-up would act during storm conditions. Where the dunes are not present, the limit used to evaluate the beach slope was the boundary between the beach itself and fixed beach infrastructures (e.g. beach huts, protection walls, fences, etc.). The formula proposed by Holman (1986) was used to calculate run-up, considering as still water level (SWL) the mean sea level plus the maximum spring tide. After the run-up computation, for each profile the maximum water elevation (run-up+surge+tide) was prolonged onto the beach surface to identify the point of maximum water ingression, to create a storm risk cartography for dunes, beaches and infrastructures.

For the dune risk it was decided to use the guidelines of the Eurosion Project (http://www.eurosion.org), which produced a classification of the different types of dune damage after a storm. The Eurosion Project defines a "Frontal Dune Reservoir" described as the area between the dune top and the dune foot, calculated on a beach cross-section. A boundary of 160 m^2 is fixed to distinguish between "dune removal" and "duneface retreat". The results presented here do not derive from a cross-sectional area computation. The authors decided to create a specific terminology considering only the comparison between water elevation for the worst scenarios and the maximum profile elevation (Fig. 4). The effect of the storm is discriminated between natural and built-up areas. The risk is defined as "foredune erosion" (or base undercutting), "dune overtopping" and "flooding" (Fig. 4). The last two definitions correspond to a risk of water ingression (flooding) behind the dunes or across human infrastructures. To notice that both in the case of dunes and structures, overtopping is considered to happen, but the limit of inland ingression of the water table is not considered, as this would imply the use of a numerical model to account for discharge values, surface roughness, losses for infiltration, etc.

The distinction between the two categories (natural or anthropogenic) comes from the need of representing the different effects of storms on sections that have different characteristics and usages. This implies that for a coastal manager it is important to consider the "flooding" process in different ways. If a coastal flood occurs where there is a dune system, in a completely natural area, it means that it will damage and/or destroy the dunes, with an important ecological and morphological impact, but with no economical losses or risk for lives. In this particular case two subcategories of dune erosion, e.g. complete removal or frontal erosion, were considered to accurately describe all the possible morphological configurations, taking also into account that in many cases dunes act as the first line of defence, since the inland territory has elevations around or below sea-level.

If the flooding takes place in an area without dunes and with human infrastructures, the damage will be mainly on human activities, people and buildings, with possible impacts on the local economy. In reality even dune overtopping and removal, as well as partial erosion, could be considered to have a cost to society, as the penetration of salt water inland may affect agricultural practices. In both cases mitigation strategies will need some financing from the Regional government. On the short-term, the response to flooding behind infrastructures is mitigated using sand bags, while on the long-term beach replenishments have become standard practice.

The results were put inside a GIS to produce risk maps for the three scenarios (Fig. 5). The GIS contains 2005 colour air photography supplied by the Emilia Romagna Regional Authorities for the entire coast, shapefiles of the beach profiles monitored since 1993, the new profiles calculated by the authors using the Lidar DTM and the T1, T10 and T100 symbols that describe the risk of damage/flooding of each section. If an operator clicks on the symbols (see legend

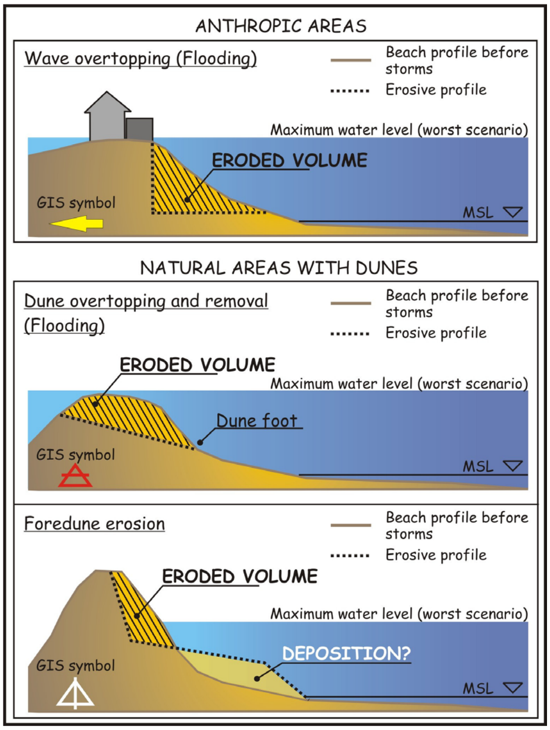

Figure ~~5.~~ Scheme of the effects of storms (and relative terminology) on the coast for the worst scenario. Note that the water level drawn in the figure is only indicative of the possible scenarios.

inside Fig. 5) within the GIS program, it is possible to visualise attributes associated with each profile such as:

- Profile name
- Short description of the profile (if it is natural with or without dunes, if it crosses anthropogenic areas, etc.)
- Storm return period
- Maximum level reached by the water (run up+tide+storm surge)
- Maximum elevation above MSL of the beach or dunes along the profile
- The impact of the storm on the profile (foredune erosion, dune overtopping or flooding)

GIS is an ideal tool for risk evaluation in the coastal zone, because it allows to have a large-scale perspective of the coastal dynamics of littoral cells. Therefore, the identification of high-risk zones is immediate.

It was decided to use two different symbols to identify profiles that suffer from flooding/overtopping because, as described above, the coastal manager needs to know without hesitation which are the real risks and what is at risk. If the profile is natural with dunes, the symbol is a red triangle, if the area is natural without dunes or not natural (with human infrastructures) it is a yellow arrow. The designed GIS could help managers to have an overall view of littoral cells, to quantify the damage in different ways and to plan different interventions considering which are the priorities, if one of these events should occur. It is also easy to use and gives the necessary information at a first glimpse.

Scenario for the 1-year storm (T1)

There are 9 profiles that suffer from flooding (Fig. 5). Three are with dunes (dune overtopping), three on the Bevano spit and the last three are in the area in front of the Lido di Dante village. In the latter case the damage is on infrastructures. It is important to remember that the effect of the breakwater on incident waves was not considered in the run-up computation, because the formula of Holman (1986) uses the wave height in deep water. The profiles at risk from dune overtopping are close to the structures in an area that suffers from strong beach erosion (Armaroli *et al.* 2004). Comparing in Fig. 6 the LIDAR survey done in 2003 (DSM) with the one undertaken in 2004 (DTM)~~,~~ it is possible to notice the strong retreat of the beach and the destruction of the first line of dunes. Field observations undertaken immediately after the storm of September 2004 confirm dune overtopping and flooding.

Scenario for the 10 and 100-year storms (T10, T100)

It is important to notice how the areas with healthy dunes are safe even from the T100 event (Fig. 7). Where the dune system is stable and the beach slope mild, run-up levels tend to be lower as wave dissipation takes place. In Fig. 7 it is clear that between the 2003 and the 2004 surveys the beach and the dunes did not change significantly. Between the T10 and the T100 scenarios there is only one profile that changes from foredune erosion to dune overtopping: it is located north of the structures (Fig. ~~6~~). Here there is a small (less than 500 m) stretch of dunes that have variable crest height moving from north to south. Indeed the dunes that are close to the Fiumi Uniti river are at risk even from the T1 event, while 250 m to the south they are safe even from the T10 event.

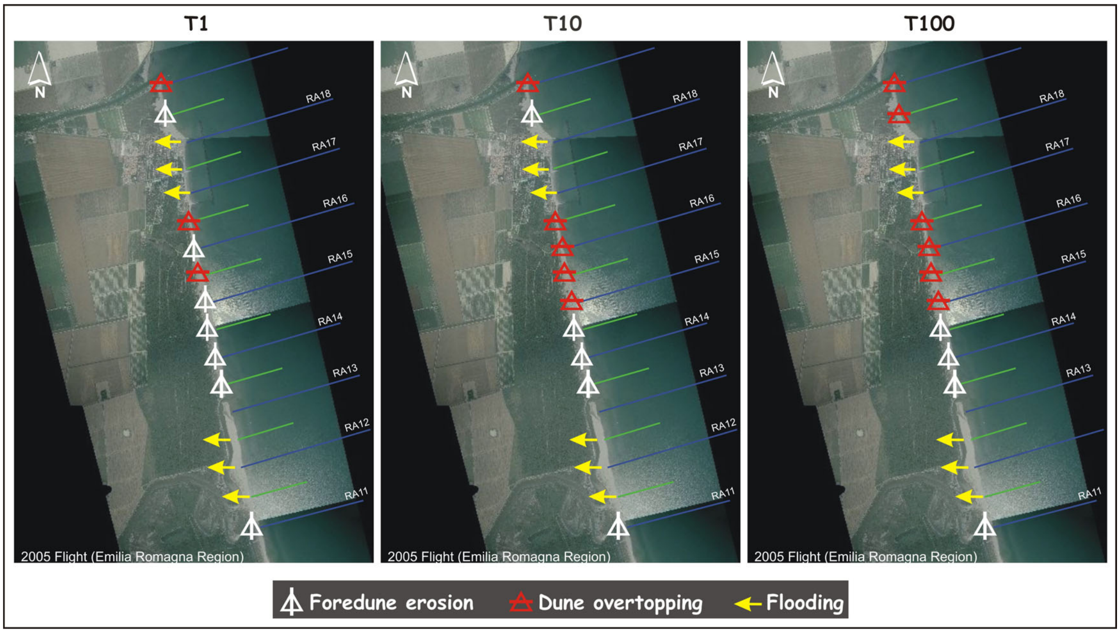

Figure 6. Risk map for the T1, T10 and T100 scenarios. The blue profiles are part of the Regional Monitoring Network of ARPA, while the green ones were measured on the Lidar 2004 DTM.

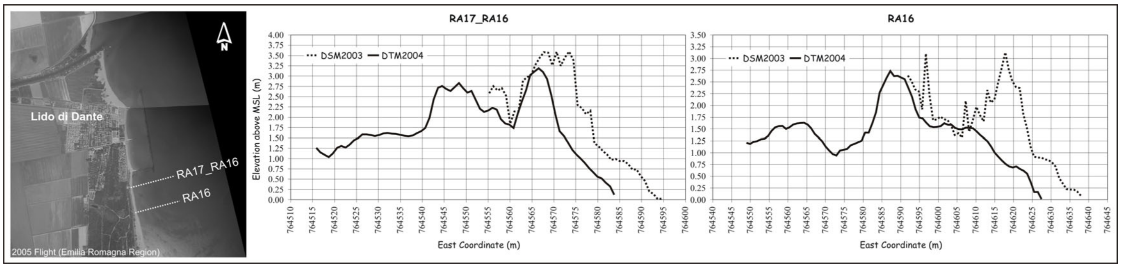

Figure ~~7~~. Comparison between DSM 2003 and DTM 2004 Lidar data of two profiles that are immediately to the south of the protected area. Notice the destruction of the first line of dunes.

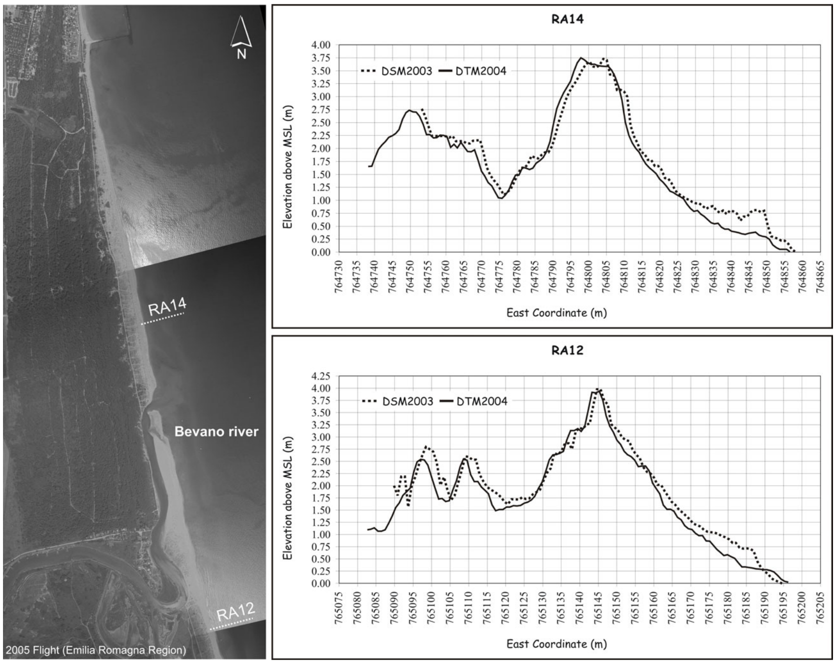

Figure ~~8~~. Comparison between DSM 2003 and DTM 2004 Lidar data of two profiles located immediately to the north and to the south of the Bevano mouth. Notice the stability of the dunes and the beach.

Considering the length of studied coast (almost 4 km) used for the risk evaluation, it is possible to produce a table with the percentage of occurrence for each risk category (Table 2). There is a 6% left out to reach a total percentage of 100%, as one section was not considered in the computation (RA13, Fig. 5). This is too close to the Bevano mouth, that rapidly migrates northwards (Ciavola *et al*., 2005), so that this profile changes rapidly both in slope and elevation.

From Table 2 it is immediately clear that as the events increase in energy, the percentage of foredune erosion decreases in favour of dune overtopping, The percentage of flooding for the anthropic areas and for the Bevano spit remains the same for the three scenarios. The area in the northern part of the study sector, with infrastructures, is at risk even for the 1 year event, and the Bevano spit is not well developed, so that embryo-foredunes here are not yet high enough to avoid flooding. If we consider the sum between the two "flooding" scenarios, it is immediately

Table 2. Percentage of each risk class for the three scenarios.

	Foredune erosion (%)	Dune overtopping and flooding – natural areas with dunes (%)	Wave overtopping and flooding – build-up areas and natural areas without dunes (%)	Total of areas interested by flooding (%)
T1	42	15	36	51
T10	30	27	36	63
T100	24	33	36	69

noticeable the small difference between the impact of the T10 and T100 events, meaning that the risk high even for events which do not necessarily have low return periods.

Conclusions and recommendations

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 risk evaluation for exceptional events has proved that a wide beach can be considered a symptom of safety.

The Regional Authorities, following the publication of their Integrated Coastal Zone Management Plan on 15 February 2005 have officially chosen beach replenishment as the preferred strategy for coastal protection, especially where infrastructures are present. However, despite a wide beach is a good measure for counteracting erosion, there is no guarantee that buildings and people living behind it are safe.

It becomes imperative to extend the approach used for this case study to the whole coastline, using high-resolution topographic data. The final aim will be the production of a comprehensive evaluation of risk from storms for the whole coastal region, considering the value of what is at risk. Unlike simple forecasting of sea-level rise by overlaying the current topography with inundation surfaces, the approach presented in this paper is physically based on hydraulic formulations of run-up.

Finally, if this information system could be linked to a wave and surge model like the one maintained by the Meteorological Service of the Emilia-Romagna Region (Arpa-~~SMR~~), a forecasting of flooding points and levels could be undertaken in a similar way as it is already done for river flooding, acting as an essential starting point for evacuation and rescue procedures.

Dunes along the Emilia-Romagna coastline are now rare and at risk in many places. There is a lot of discussion of implementing design procedures and methods of recovery. We believe that crest elevation and the beach slope in front of the dune remain the most critical parameters to evaluate. In this sense the type of work presented in this paper can act as a supporting tool to intervention strategies.

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