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Integrated and interdisciplinary scientific approach to coastal management

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ABSTRACT

Coastal zones and beach management practices, regulatory decisions, and land use planning activities along coastal zones have historically been made with insufficient information concerning the dynamic coastal environment. In this study we address and integrate an interdisciplinary scientific approach to Coastal Management in a scenario where lack of this information has resulted in the alteration of the natural dune system of the beach of Cala Millor (Mallorca, Balearic Islands, Spain), and also in the perception of the beach retreat and in a parallel way, a risk for the tourism resources. In this work the detailed studies on beach morphodynamics have been developed as a basis for integrating proper beach management, beach natural dynamics and local users and economic agent interests. From this point of view a set of solutions are considered as the basis for a management policy that links beach science and beach use as a tourism resort resource.

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1. Introduction

There is an increasing concern about the implications of present and future environmental changes for nature conservation and the welfare of human communities. The importance of an integrated, predictive and adaptive approach to ecosystem management has been already highlighted [1,2]. In this sense there is a general consensus about the three types of information and/or actions needed to address emerging and current issues. First, reliable site specific baseline information on ecosystems; second, knowledge of how the production of goods and services in specific ecosystems will respond to biophysical changes and third, the development of integrated regional models that incorporate biophysical, economic and technological changes to provide policy-makers with better understanding of the consequences of different management options. These data, including the interactions among them, must be aggregated at relevant spatial and temporal scales [1,3]. Essentially, conceptual ecological frameworks are needed and the downscaling of these frameworks into scales representative of specific systems, such as the coastal zones, are necessary for effective coastal management [4–6].

Specific, well identified results have been obtained from a number of research studies related to coastal management in recent years [7–9]. An important, often neglected second step is to transform these results into new methodologies and practical applications necessary to achieve management of the coastal environments that is based on viable scientific research, thus resulting in more integrated and sustainable solutions to coastal problems. This is the classical path of innovation, which begins with scientific research and ends with the identification of new products and/or services requested by society and, at a final stage, introduced in the market. The transfer of appropriate, usable scientific knowledge to society and the introduction of practical, innovative science-based management options in coastal areas are necessary at a global scale and are particularly relevant in the coastal zone because it is a public domain that has crucial socio-economic, cultural and environmental functions [2].

Despite widespread recognition of the needs outlined in the previous paragraph, the relationship between coastal science and coastal management is far from linear mostly because of a lack of comprehension between coastal scientists and end-users [10,11]. Other problems also arise from the divergence of perceptions related to the explicit identification of the information that is needed to deal effectively with a given coastal problem [12,13]. Essentially, there is a gap between coastal management at the conceptual level and the practical applications: for example, beach management in the Balearic Islands, as almost everywhere [14–16], has traditionally involved either nourishment of beaches or the construction of groins. Recent debates over beach management options in the Balearic Islands have highlighted the need for a long-term management strategy which incorporates a full understanding of beach dynamics and economic and leisure-based activities in beach environments [17].

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In March 2004, local and regional authorities, coastal managers, representatives of the tourism sector and additional stakeholders from Cala Millor, one of the most important tourist resorts in Mallorca (Balearic Islands, Spain), requested a scientific study that would i) asses beach evolution from an interdisciplinary perspective and ii) develop new integrated and interdisciplinary coastal management strategies that would reflect the most recent advances in scientific knowledge. Against this background, this article describes the response to this request and, in doing so, illustrates the important role of science for sustainable development and coastal management and the need to conduct research that bridges the gap between conceptual models and specific application thus representing what we believe to be a truly integrated and interdisciplinary approach to science-based integrated coastal zone management. The methodological approach that was used to conduct the study follows Ayensu's integrated model [1], which implies i) an assessment and overall acceptance of the complexity of the system to be studied and the need for interdisciplinary, integrated approaches; ii) the identification of conceptual models and the interacting sub-systems and, iii) an analysis of existing interactions and conflicts, and potential management options needed to achieve integrated, science-based sustainable management of the coastal zone.

In other words, the goal of this approach is to develop innovative procedures of sustainable management of the coastal zone that are not only based on the most recent scientific and technological advances, but that are both usable and acceptable to local decision-makers and administrations. In that sense Cala Millor is an ideal location for this purpose because there is a conflict between natural dynamics and socio-economic issues. From an ecological or environmental perspective the goal was to establish and to understand the conceptual functional model of Cala Millor beach, from the quantification of the system response to the physical inputs, e.g., wave patterns, shoreline evolution, sediment transport, dunes modifications and conservation of *Posidonia oceanica* meadows (a protected marine habitat from European Directive 92/43/CEE). From a socio-economical point of view, our research provides an up-to-date inventory of human and economic resources and their relationships with the beach, seeing as the natural ecosystem from which all the social and economic results are based upon.

The paper is composed of six main parts. First, an introduction to science based coastal management concerning with the topics and current developments on coastal management. Second a description of the environmental conditions and the historical background of Cala Millor beach management actions. The third section describes the results obtained from a quantitative study of the beach dynamics and *P. oceanica* meadows characterization on the basis of topographical surveys, bathymetries and hydrodynamic numerical simulations, as well as the related sociodemographic and economic issues. The fourth part states the benchmark and describes the different the potential management solutions that can be proposed according to results obtained and the conceptual model established. The fifth section discusses the role of science on coastal and beach management from the experience at Cala Millor. Finally, the sixth part relates to a general overview where conclusions highlight both the potential solutions for the case study conflicts and the role of science on sustainable beach management.

2. Study site

The Balearic Islands are located in Western Mediterranean, being Mallorca the main island of the archipelago. The socio-economic structure of the Balearic Islands is based on a service economy. Therefore the tertiary sector occupies 80% of the economy, while industrial activities and construction 18% and the primary sector 2%. Tourism is the main economic activity of the islands with a contribution of 75% of its 22 billion euros GPD in 2006 [4]. The tourist sector is based on the "sun and beach" tourist model that has resulted in a substantial increase in urbanization, resulting in a drastic transformation of the landscape, especially in coastal areas [17–20]. The implementation of an economic model based on tourism gave rise to a change in the territorial organization around the leisure industry, transforming large areas and coastal zones (rural and natural landscapes) into urban spaces of primary and secondary residences and tourist sites with associated services.

2.1. Environmental conditions

The study area is a seaside tourist resort located in the eastern coast of Mallorca, at the Bay of Son Servera (Fig. 1). The Bay is characterized by a maximum depth of around 25 m at 7 km from the coastline which reduces to 8 m at 300 m from the coastline. Water clarity is high around the Balearic ramp because there is virtually no fluvial input from the island and continental sedimentation is minimal [21]. Waves approaching from NE and ESE come into the bay through northern and southern mouths, respectively. Meteorological and wave observations from Puertos del Estado (http://www.puertos.es) show that waves with significant height over 1 m act on the beach just during the 2% of the days of a year. Forcing by tides is almost negligible in the Mediterranean with a spring tidal range of less than 0.25 m, although combined changes between tides, atmospheric pressure and wind setup can account for sea level elevations close to 1 m [22].

Cala Millor is a beach backed by a boulevard, hotels and residential houses, and bounded by two rocky headlands, Cap Pinar northwards and Punta de n'Amer Southwards (Fig. 1). It is a sandy beach near 1700 m long with a concave shape. From a morphodynamic point of view, Cala Millor is an intermediate beach [23] with a configuration of transverse and crescentic bars. The sediment consists of medium carbonate bioclastic sands, being the median sediment size (D_{50}) on the beach around 0.34 mm. *P. oceanica* meadows appear at 8 m in depth nearly a hundred meters from the shoreline.

2.2. Historical sand nourishments and beach management

The development of the zone started in the late 50s at the north of the bay with an inland farmer and fisherman settlement. During the seventies developments grew southward, impacting a lagoon and field of dunes. More recently, many hotels and a coastal boulevard were built bordering the beach. Today, Cala Millor is an urban beach with more than 600,000 users during summer season and reaching 1 million users year-round with a high degree of fidelity. The importance of the beach for the tourism sector and the problems related with its sediment balance has resulted in the implementation of at least five beach nourishment projects and the construction of in the 90s of peers normal to the shore. The use of nourishments, as "soft" remedial measures, have increased significantly everywhere since the 1980s [15,24]. The last nourishment at Cala Millor was carried out during spring 2002 in response to the extreme storms that had affected the northeastern beaches of Mallorca in November 2001, incorporating around 40,000 m^3 of sand to the beach. Successive beach nourishments incorporated sand volumes lower than 10,000 m^3. It is interesting to note that the accumulated amount of sand used for the nourishment is similar to the volume of sand of the aerial beach which is estimated as 60,000 m^3 (Table 1). In spite of these actions, stakeholders and local administration perceived in 2004 that erosion was a problem and requested the suggestion of further interventions, developed as a result of this project.

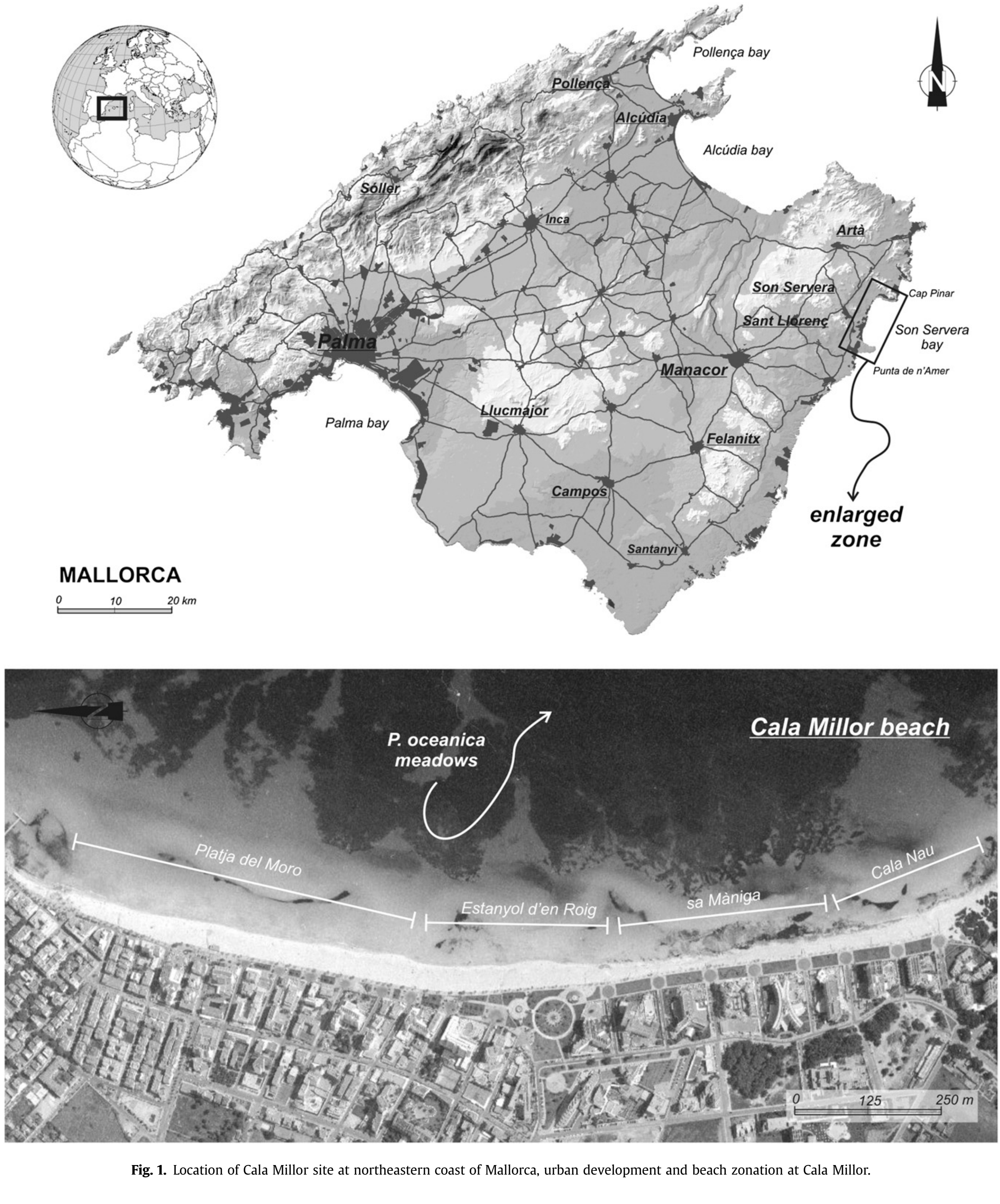

Fig. 1. Location of Cala Millor site at northeastern coast of Mallorca, urban development and beach zonation at Cala Millor.

3. Interdisciplinary quantitative study and evolution of a Mediterranean beach

3.1. Emerged historical beach evolution and inter-annual variability (1956–2004)

An historical evolution of the emerged beach has been developed from the superposition of aerial photography previously digitalized and georeferenced corresponding to images from 1956 to 2004. Differences in aerial beach surface have been calculated through GIS technique (Table 2). In 1956 the area of the emerged aerial beach was of 44,260 m^2, corresponding to the original scenario when the beach, the lagoon and the field dunes in the southern part were not disturbed (see Fig. 2). The mean width was 33 m, which corresponds with the naturally narrow configuration of Mediterranean beaches [25]. In 1968 the beach surface increased

Table 1
Sand nourishment works at Cala Millor and sand budget involved.

Year	Volume (m^3)
1989	?
1990	8000
1993	5400
1996	4759
2002	±40,000
Total	>58,159

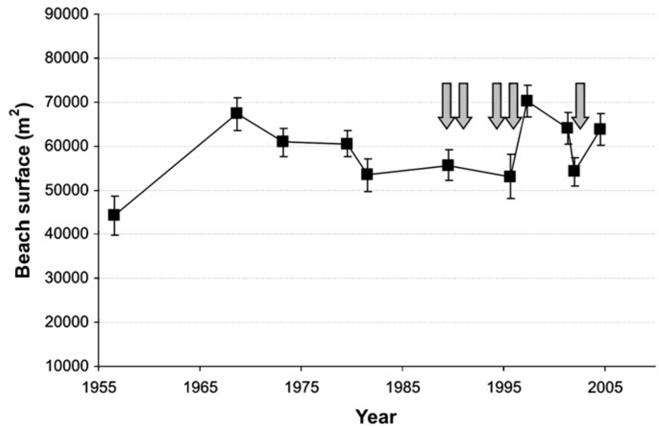

Fig. 2. Dry surface beach historical evolution. Arrows indicate nourishment works.

significantly (+25,568 m^2) because the urban development affected the dune field and sand was removed from dunes and brought to the beach. This is the reason by which in 1968 Cala Millor beach register one of maximums beach surface between 1956 and 2004. Since then, aerial beach extension experienced a continuous retreat just disrupted by nourishment works. At the same time that nourishment works punctually increased the beach surface (e.g. 17,147 m^2 between 1995 and 1997), they resulted in the retreat of the upper limit of the *P. oceanica* meadows.

The study of the spatial variability shows that the beach behaviour differs in the three sectors analysed, north, central and south (Fig. 3). If data corresponding to 1968 are excluded (since they are of clear anthropogenic origin), then the standard deviation of the southern sector is ±3 m and therefore is more stable than the northern one with values of ±7 m. To obtain a useful quantitative reference value for comparison, we recomputed the mean beach surface (excluding anomalous years as 1968 and 1973 because they correspond with intense urbanization of the area) obtaining $59{,}346 \pm 7724\ m^2$. Therefore, in May 2004, when local actors subjectively indicated that the beach was suffering an important erosion process, the beach surface was around 7% bigger than its mean reference value and was actually also higher than the original, undisturbed natural beach surface.

3.2. *Beach morphodynamics and* P. oceanica *meadows*

In order to characterize the aerial and submerged beach evolution an intensive sampling program was carried out from May to December 2004, including bathymetries and survey profiles. Seven bathymetries were obtained monthly (except for November) using a BioSonics DE 4000 echosounder. A set of eighteen cross profiles separated at 250 m were surveyed monthly from the boulevard path to *P. oceanica* seaweed meadows.

In order to study the evolution of the beach, several beach survey profiles were conducted and compared with prior beach studies. In 2004 a study of beach topography showed that the beach surface was 60,159 m^2, it decreased 2622 m^2 respect of the 2002 surveys. The results highlight that beach evolution is a response to wave climate conditions. During the summer, the beach increased in surface area (5297 m^2) and during the winter, the beach suffered erosion in both the central and the southern sectors (1443 m^2). Therefore the 2004 annual balance resulted in an increasing in beach surface of 4712 m^2 (Fig. 4).

Beach basement depth was assessed by coring along the emerged beach. Results show that, in the northern sector, the beach surface rose between 1.5 and 1.7 m above the mean sea level and the mean sand thickness was of 0.85 ± 0.35 m. In s'Estanyol, the central beach sector, sand surface rose to 1.9 m and sand thickness overcame 1.5 m in depth. Southward, despite achieving the beach surface topographical positions of 2.4 m above m.s.l, the sand thickness was of 0.2 m because basement has higher spot heights than in other beach locations.

Beach bottom is smooth without any important accident. Shallow sectors are arranged with a configuration of bars and troughs which evolve temporally (Fig. 5). The type of bottom is related to the bathymetric gradient. From m.s.l. to 2 m, bottom is sandy although there are some rock outcrops in the central and southward sectors of the beach which also crops up in the emerged beach, especially in the southern sector close to the Punta de n'Amer cape. Between bars and to depths between 6 and 8 m the ground is also sandy. From this point a crust of *P. oceanica* rhizomes appears separating sandy bottom and seaweed reef meadows

Table 2
Dry beach characterization from historical analysis.

Year	Dry beach surface (m^2)	Surface variation (m^2)	Max. width (m)	Min. width (m)	Mean width (m)
July 1956	44,260 ± 4306	–	59	13	33
August 1968	67,274 ± 3704	+23,012	69	16	44
March 1973	60,819 ± 3452	−6452	70	15	42
June 1979	60,541 ± 2976	−278	55	22	39
June 1981	53,423 ± 3744	−7117	51	17	34
June 1989	55,625 ± 3424	+2202	53	23	37
July 1995	53,041 ± 5120	−2584	49	19	34
March 1997	70,188 ± 3744	+17,147	62	34	48
March 2001	63,994 ± 3744	−6194	58	24	42
January 2002	54,209 ± 2400	−9785	55	–	–
June 2004	63,749 ± 3680	9540	58	21	40

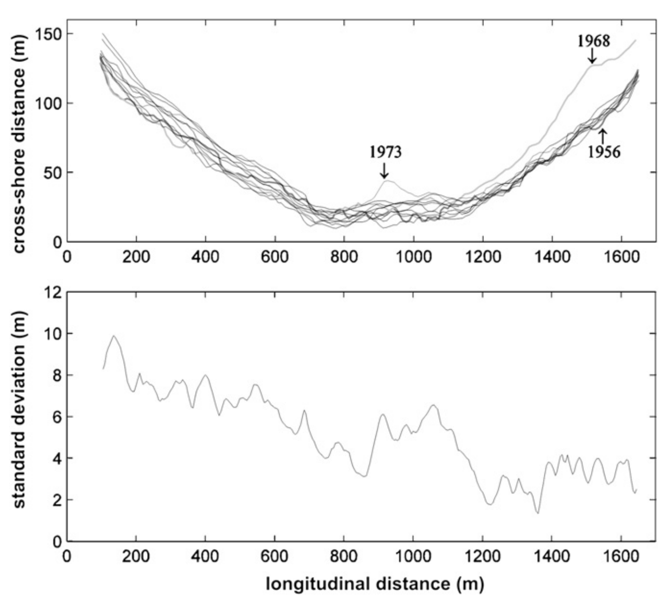

Fig. 3. Temporal evolution and spatial variability of the coastline at Cala Millor.

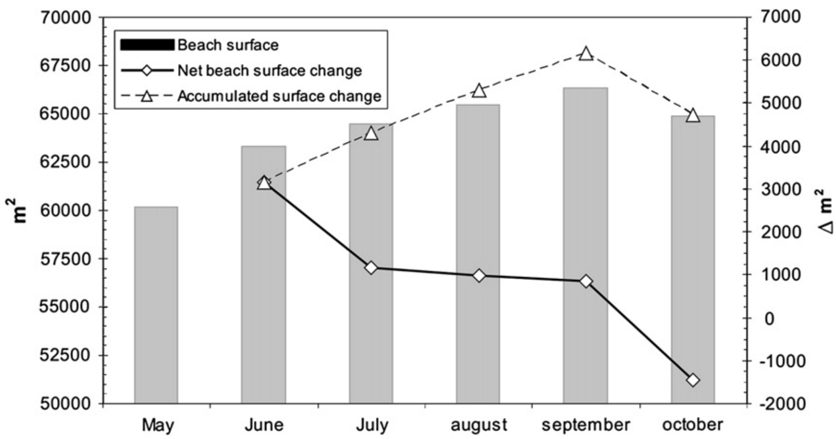

Fig. 4. Beach surface temporal variations during 2004 surveys.

evidencing the meadow regression. One of Cala Millor characteristic features is that the nearshore sandy bottoms are colonized by the endemic reef-building seagrass *P. oceanica* (Fig. 6) which is known to affect near coast sediment dynamics [26]. Seagrasses and other vegetation attenuate wave and current energy, therefore diminishing sediment resuspension, erosion and transport [27–29]. The upper growth limit of *P. oceanica* is conditioned, among other factors, by sediment stability and thereby this plant rarely grows in the very nearshore (less than 3 o r 4 m depth) where the vertical growth rate of the plant, around 1.5 cm y^{-1} [30–32], cannot cope with the intense sedimentary dynamics. The slow horizontal growth rate of the seagrass, 5 cm y^{-1} [33], precludes the rapid shoreward advance of the meadow. On longer time scale, the meadow plays an active role in sedimentary balance of the beach both supplying biogenic sand and/or trapping sediments in the eventual offshore migration. There is evidence that *P. oceanica* beds can produce 60–70 g m^{-2} y^{-1} of calcium carbonate [34]. Sand beach is composed by medium and fine sands with a large percentage (more than 70%) of bioclastic sediments most of which derive from organism associated with the *P. oceanica* meadow ecosystem [21].

Intense variations in bathymetry related to bars movement take place in a range of depths between 0.5 and 4.5 m and can achieve bathymetry rates of change of 1 m. These situations are the results of the shift between the dominant summer mild wave conditions which drives the onshore sand bar migration change and the intense storms of the end of summer with a strong mean current which drives the bar offshore. Monthly changes on submerged beach imply an amount of sediment transport of 31,000 m^3 $month^{-1}$ (Table 3), with maximums of 64,000 m^3 $month^{-1}$ and minimums of 11,319 m^3 $month^{-1}$. The global balance for the period of assessment, 3570 m^3 $month^{-1}$, is lower than the error of the calculus method. Thus the beach system can be assumed to be in equilibrium.

3.3. Waves and currents modeling

The effect of strong winds on currents is of particular relevance in shallow areas where fine sediment is re-suspended in a zone much wider than the breaker zone which, in the Balearic Islands, frequently extends 500 m or even 1000 m from the shoreline (depths of the order of 20–30 m). The effects of different wind conditions have been assessed using a 3-dimensional finite element coastal model [35,36]. The characterization of waves, currents and sediment transport have been calculated by means of open sea wave conditions –WANA point 2076,037; (39.63°N/3.5°E) offer daily wave forecast outputs from the WAM wave model [37] and consist of significant spectral wave height (H_s), spectral peak or wave period (T_p) and mean wave direction (θ) reported every 3 h.– and the wave propagation to the shore using a mild slope parabolic model (OLUCA-SP). Wave breaking currents are finally obtained from the radiation stresses and computed with a depth integrated Navier Stokes model (COPLA-SP) [38].

Typical wind currents induced by winds blowing from NE and SE and with velocities of 6 m/s, push waters towards the SW following the coastline. Because the flux on the platform is weak ($<$10 cm s^{-1}) increasing close to the coast, there is an enforcement of 5 cm s^{-1} in surface from North to South along the beach and of 2 cm s^{-1} in depth (Fig. 7). Sea waves have a significant height lower than 1.3 m and account during the 50% of the sea states, usually from NNE and NE. Extreme wave values have been calculated from hourly wave data comprising the period from 1998 to 2001. The recurrence interval is of two years for wave height of 5.7 or 5.8 m related with sea states from the second quadrant and they are more frequent between November and February. The wave height related to the recurrence interval of 5 years is of 5.7 m and for 10 years it achieves wave heights close to 8 m (Table 4). The wave pattern corresponding to the NE and SE directions present the refractions of the wave parallel of the coast, as well as the disruption of waves approach according to shoaling and the position and the type of bars. During NE storm conditions the wave height in the beach is close to 2 m. The associated currents are directed towards the North in the southward zone of the beach and they act as a longitudinal current with a South direction in the rest of the beach. Where these currents concur, a transversal current (rip current) with an offshore direction is generated playing the role of a sediment output of the system (Fig. 8). During SE storm conditions, because beach is sheltered by Punta de n'Amer cape, that also generates wave diffraction, there is an alongshore current along the coastline with a North direction (Fig. 8). The mean conditions, with prevalent wave directions from NE, E and SE, are not energetic enough for generating transversal currents. Thus, in this kind of conditions the beach suffers soft longshore currents and configurations related with bars, troughs and rip currents (Fig. 8).

3.4. Social and economic issues

Cala Millor is a tourist resort located on the borderline of the municipalities of Sant Llorenç des Cardessar and Son Servera. Cala Millor has a population of 6072 inhabitants censed but during summer it can increase up to 17,046 inhabitants more with the

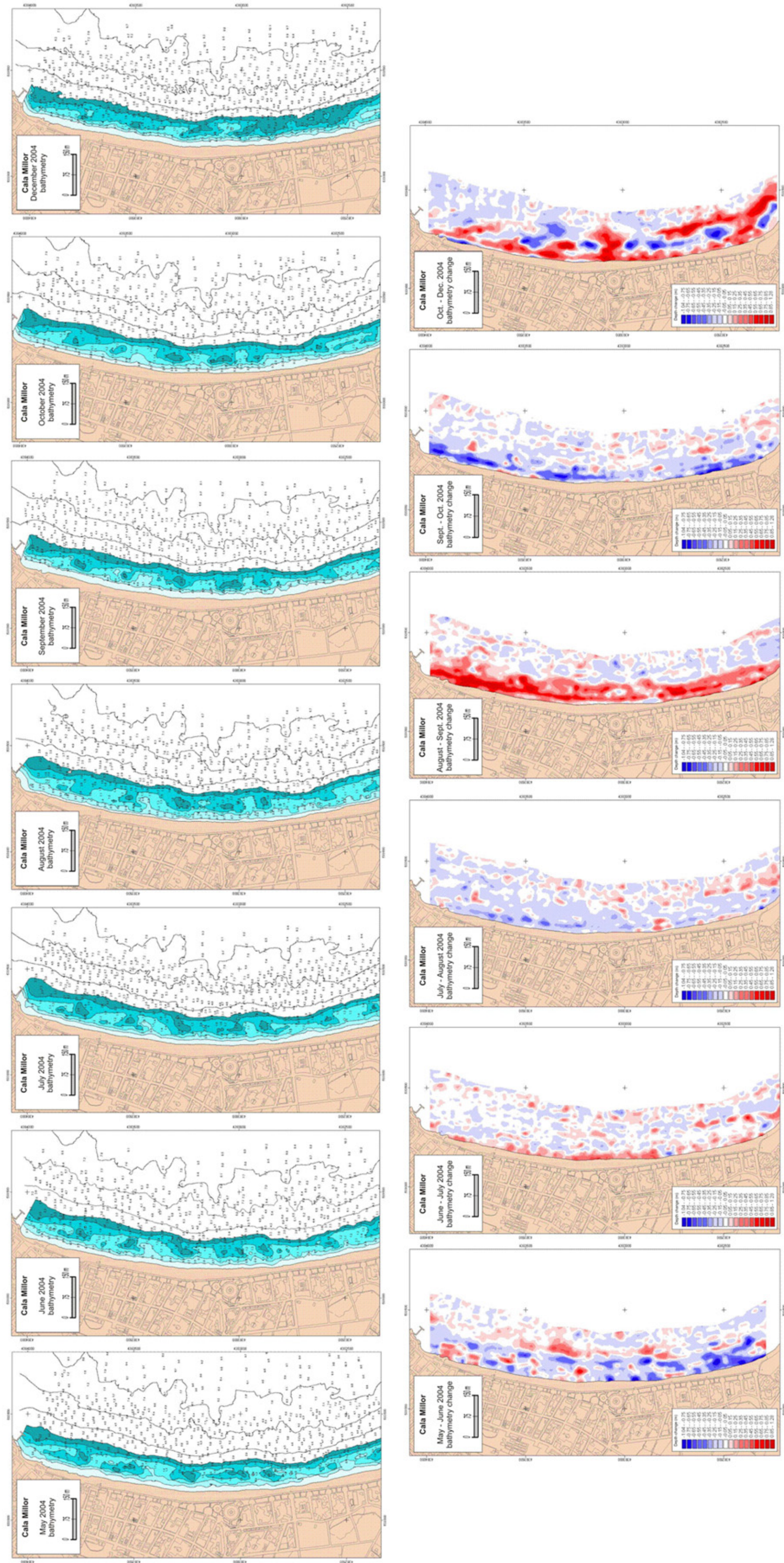

Fig. 5. Cala Millor bathymetry and morphological change between May–December 2004.

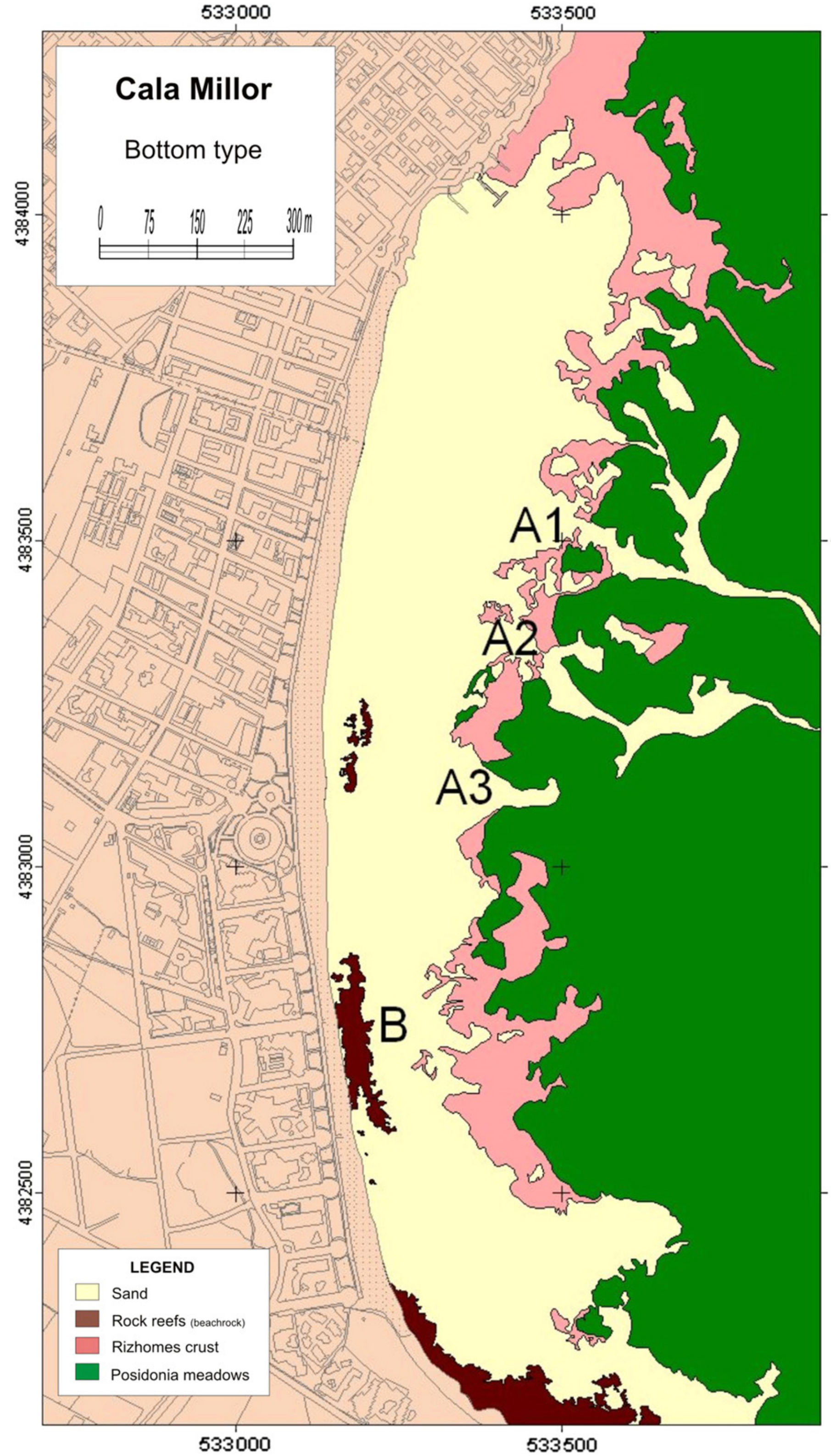

Fig. 6. Spatial distribution of *Posidonia oceanica* meadows and bottom type at Cala Millor.

touristic places. The tourist occupancy takes values between 74.6% and 91.3% of the hotel bed places during summer season. This means that the Cala Millor real population achieves the value of 20,263 inhabitants; three times more people than the rest of the year. Mean daily number of beach users fluctuates from 6400 to 6800 users, at the end of the tourist season these rates mean that at least 500,000 individuals have engaged in recreational activities at Cala Millor beach.

At Cala Millor there are 330 commercial establishments related to tourism activities (Table 5); 221 of these establishments are

Table 3
Submerged beach sediment budget evolution computed from bathymetric surveys during 2004 in terms of volume change (m^3month^{-1}) and volume change related to beach length ($m^3lm^{-1}month^{-1}$).

	Accretion (m^3/month)	Accretion (m^3/lm/month)	Erosion (m^3/month)	Erosion (m^3/lm/month)	Balance (m^3/month)
May–June	20,530	12	44,152	26	−23,622
June–July	25,121	15	13,802	8	11,319
July–August	12,604	7	34,141	20	−21,537
Aug.–Sept.	75,329	44	11,352	7	63,977
Sept.–October	11,027	6	44,734	26	−33,707
TOTAL	144,611		148,181		3570

hotels, restaurants and coffee shops. 74% of inhabitants living in Cala Millor work in the service sector [39]. The rest of the workers are related to the construction sector that is closely related to tourism economy.

Tourist expenditure is estimated at 57.32 € day^{-1} from which 4.49 € corresponds to transport costs, 18.29 € to hotel accommodation and 34.54 € for other expenses [39]. Taking into account summer tourist hotel occupation, the total daily expense achieves values ranging from 21 to 28 million of Euros. Thus, the economic activity of Cala Millor tourist resort at the end of summer season achieves gains of 75 millions of Euros. This highlights the important role of tourist activity at Cala Millor and also the importance of the beach as an environmental resource in a classical tourism destination of sun, sand and sea [4].

3.5. Legal and administrative issues

In Spain coastal areas fall under the jurisdiction of the Spanish Coastal Law 22/1988 [4] and their main goals are: (a) guaranteeing coast public use and access, (b) protect and restore coastal areas and (c) contribute to satisfactory levels of water quality. Under the coastal law framework, coastal management activities suffer from the division of competencies between the different administrative units at the local (municipalities), regional (autonomous regional governments), and national levels (Spain Government). Each one of these entities tends to address partially aspects related to the coastline. For instance, local authorities manage the exploitation and cleaning of the beaches; regional authorities can plane major uses and criteria and executive projects and actions relates with Coastal General Directorate under the Spanish Ministry of Environment. This multi-tiered, overlapping jurisdictional framework is confusing and often leads to ineffective management, communication and coordination in the coastal zone [6]. Recently the Ministry of Environment have been merged with the Ministry of Agriculture and Fisheries, resulting in the creation of the *Dirección General de Sostenibilidad de la Costa y del Mar* that many consider will hamper coastal and environmental conservation at the national level.

4. Basis for a benchmark and potential solutions

The analysis of the morphodynamic state of the Cala Millor beach shows that, despite human and economic impacts, the beach remains a dynamic system in an equilibrium state. In fact, beach surface at this time is larger than it was before the urban development. The erosion dynamics identified by local beach-users, hotel owners and administration is related to the inter-annual variability in wave energy and direction, as well as to the natural transport of sediments in the beach. These are intrinsic characteristics of the Mediterranean beach environment [25]. Current and wave simulations associated with this research show that during mean wave conditions the beach sediment is transported from one place to another of the beach rather than removed from the system entirely. It is only during energetic gales from the NE and SE that beach erosion actually occurs. However, despite the fact that the beach is wider than it was before urbanization, development of the zone has affected the beach in its capacity for recuperation. The backwards dune system was destroyed for hotel construction and a boulevard path was built up without considering the shape of the coastline, which means that the beach can no longer use these natural mechanisms for beach recuperations. This is particularly evident in the central section where the beach is more dynamic and variable in width due to its orientation and wave incidence angle. Consequently, this is also the section where the coastline and the boulevard path are less parallel. So, during energetic storms, which are the responsible of beach erosion, the diffraction related with the boulevard walls enhances the process of beach erosion and the exit of sediment from the system.

As the beach is very important for tourism, it is necessary to achieve an equilibrium between natural conservation of the beach and social or economic benefits of the area. In this context, some of the important considerations for integrated coastal management in Cala Millor are:

a) That, contrary to popular belief, there has been no significant erosion or retreat of the beach at Cala Millor. In fact, the current beach is wider than it was prior to human settlement, and perceived erosion is related to beach sediment transport and interannual balances.
b) Beach retreat should be avoided because the system has become artificial and by itself it does not have the capacity of recuperate previous conditions.
c) Current conditions should be maintained because loss of beach surface area can affect the number of users of the beach and the number of tourists visiting the local hotels.
d) *P. oceanica* meadows are included in priority conservation habitats list from the European Directive 92/43/CEE.

The results presented so far outline unexpected relationships among socio-economic interests, perceptions of beach erosion, real beach dynamics and evolution, hydrodynamics and *P. oceanica* ecosystem protection. These potentially conflictive interactions illustrate the importance of adopting an integrated management approach where economic development and respect for the natural running of the beach system and the conservation of the ecosystem need to be taken into account. Based on the results of this study and this consideration, five management options have been developed, ranging from no action to the construction of breakwaters and groins. They include:

a) No action: This management option consists on maintaining the actual state of the beach driven by natural processes and rhythms.
b) Sediment budget balance and conservation of the beach: This policy implies the reconstruction of the beach areas moving

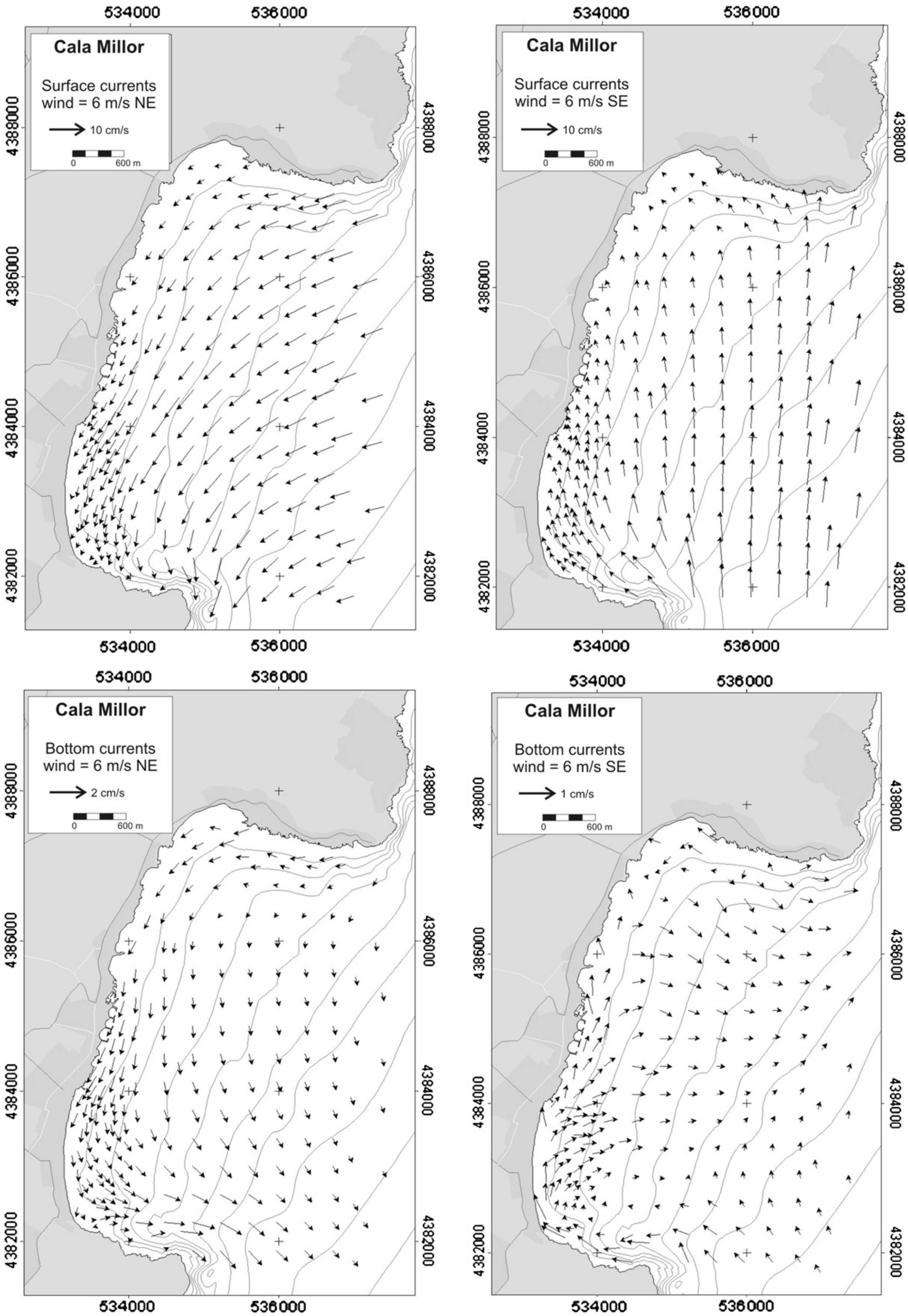

Fig. 7. Currents induced by typical winds conditions corresponding to winds from NE and SE.

Table 4
Extreme wave height and associated recurrence interval at Cala Millor (1996–2004).

Shape parameter (Weibull distribution)	FT-I	$k = 0{,}75$	$k = 1{,}00$	$k = 1{,}40$	$k = 2{,}0$
Correlation	0.95	0.99	0.98	0.95	0.91
Square of residuals	0.35	0.18	0.19	0.36	0.50
2 years recurrence interval	5.66	5.78	5.83	5.73	5.57
5 years recurrence interval	6.41	7.02	6.82	6.47	6.12
10 years recurrence interval	6.98	8.04	7.57	6.99	6.48

sand from the lateral sectors of the beach, where the volume of sediment is bigger, to the central sector.

c) Dune system reconstruction and design of the boulevard path: The design of the boulevard path does not correspond to the coastline curvature, especially between s'Estanyol and Cala Nau, where the beach is narrower and deficit of sediment accounts. The reconstruction of the boulevard, 15 or 20 m backwards, will reduce the wave reflection during storms and wave run-up extreme water levels with associated loss of sediment in the central zone of the beach. In the area gained to the boulevard, a dune system can be reconstructed in order to recuperate the natural mechanisms of adjustment of the beach-dune system. Tracking paths and beach access as well as educational information should be implemented related to dune system restoration.
d) Sand Nourishment: This alternative implies the artificial reconstruction of the central sector of the beach incorporating sand from another place.
e) Construction of groins and dikes

To address the potential environmental and socio-economics costs and benefits of each management option based on scientific results is a key step for an integrated and sustainable management of coastal environments and also for public administration panel decisions. Therefore advantages and disadvantages emerge from the spectrum of solutions considered to address the Cala Millor management situation (Table 6).

There are some risks related to the no action management option because the beach system has lost its recuperation capacity against extreme phenomena due to the urban development and the disconnection of the dune system from the beach. The no action could result in the degradation of the beach from a socio-economic point of view because the beach surface could decrease, which could result in fewer beach users and tourists, resulting in economic costs to the tourism resorts of the area. The sediment budget balances option is a short-term solution because according to morphodynamic studies, the sediment will be redistributed briefly. This option implies some risks because the natural profile of the beach can be altered. Also, a continuous monitoring of the beach is needed to assess the amount of sand to be displaced without disturbing the natural equilibrium of the beach and the response to the extreme storm conditions. Taking the previous considerations into account, it was decided that the dune system reconstruction with the redesign of the boulevard path option is the best management option from both environmental and socio-economic perspectives In this management scenario, the sediment problems and natural readjustment of the beach are solved naturally. At the same time, there is a major beach surface and a new natural recreation resource, the dune system that enhances the quality of the tourist resort and in this way the economic and social benefits. Despite the fact that nourishment is considered a soft action from an engineering point of view, it is not the best solution from the point of view of sustainability. Nourishment is a short-term solution which in the past has been demonstrated that not

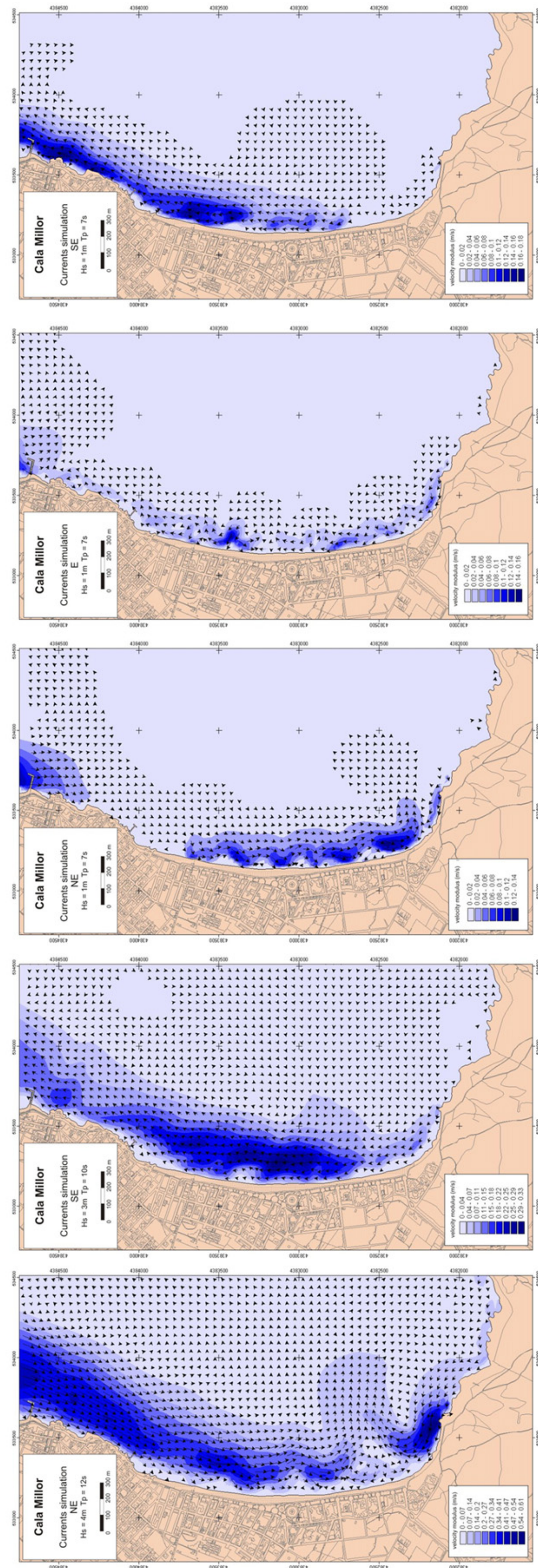

Fig. 8. Mean and storm simulated waves and currents intensities according to the most usual sea scenarios that work at Cala Millor.

Table 5
Cala Millor socio-economic indicators.

Indicator	
Number of inhabitants	6072
Number of hotel beds	17,046
Beach users (July to September)	600,000
Number of service establishments	330
Mean expense by tourist and day	57.32 €
Third sector employed population (2002)	2496

always is effective. On the other hand it demands a non-renewable resource because the production of bioclastic sand is very slow. In addition, there are secondary effects on the beach system due to the way in which nourishment affects the role of *P. oceanica* meadows [39,40], that have an important role as reef protection of the beach. Finally, the construction of groins perpendicular to the coast was developed many years ago with poor results. It is well known that the installation of groins has local effects and transfers the problems to other sectors of the beach

5. Benefits of an integrated science based approach

The current results illustrate some theoretical considerations related to studies of biophysical beach attributes study, socio-cultural and economic systems and beach management. In terms of diagnosis, prior to this research, stakeholders and scientists identified problems and solutions related to Cala Millor based on very different information, interests and perspectives. Each of them generated a proposal for beach management. This type of scenario could occur in any number of coastal management environments. In the case of Cala Millor, the socio economic sector required a wider beach because it was the main resource for hotel users. Nourishment of the beach represented an immediate response to this need. On the other hand, coastal engineers knew that the beach was not undergoing a clear erosive process and that nourishment, from a physical point of view, was not necessary because this policy was applied in different previous occasions without positive results. Also from the beach evolution it has been highlighted that nourishments by themself are not a key solution. Oceanographers and biologists identified the regression of *P. oceanica* meadows as an important consideration for water quality and beach morphodynamics [40–43]. Hence, their solution was to protect this habitat. Each sector concerned with beach derived an acceptable or tolerable partial solution. As it was presented in previous sections, management responses may cause changes to the natural systems of beach environments directly or indirectly, but it is obvious that the many interactions among and within the components of the beach environments operate concurrently and result in a feedback loop effects on natural and socio-cultural systems. In light of this fact, scientific research that takes into accounts the interests and concerns of the various stakeholders without compromising the natural environment in the long-term is necessity. Without this approach, interferences and feedbacks between beach agents, processes and actions generate different sets of positive and negative feedbacks. The interdisciplinary and integral knowledge of each one of them allows for the prediction frequency, directions and magnitude of the different interactions. For example it is probable that without a scientific integrated approach there would have been yet another beach nourishment project. This action would have resulted in more *P. oceanica* meadow regression, which would most likely result in problems with nutrients, microalgal booms, water quality, wave attenuation, sediment production, etc. Eventually, this would have a negative impact on the number of beach users and on hotel occupancy. In this example, science helped to identify the pieces of the puzzle and how they fit as well as what to do if some of them have to be moved (not sure about this sentence). It provided a long-term solution that could not have been considered without the input of scientific data on beach dynamics.

The main contribution of integrated and interdisciplinary approach to beach management is that it contributes to maximizing the benefits minimizing the costs, both in biophysical and socio-economic terms. Although the link may not be evident to all stakeholders in the short-term, the long-term health of the socio-economic environment is merged with the health of the

Table 6
Benefits and risks related to potential solutions proposal and agents involved in Cala Millor beach management.

Management proposal	Beach stability Physical system	Biological system *Posidonia oceanica*	Water quality	Socio-economic system
1. No action	+	+ + +	-	-
2. Sediment budget balance	-	+	-	+
3. Dune system reconstruction	+ + +	+ +	+ +	+ +
4. Sand nourishment	-	- - -	+	+
5. Construction of groins and dikes	-	-	-	+

■ very high risk; ■ high risk; ■ medium risk; ■ low risk; ■ null risk.
+ + + very high benefeits, + + high benefeits, + low benefeits, - low loss, – high loss, — very high loss.

natural environment. Science can provide justification and proof that a long-term, integrated vision is necessary for achieving sustainability as opposed the short-term, sector solutions that so often preside. The integrated science approach is the key for transfer of information among the physical, ecological and human-use perspectives on beach management. From this point several potential management actions can be developed, but with a solid scientific knowledge that allows incorporating socio-economic benefits and bio-physical equilibrium. In this way since this study was done, local authorities have not nourished the beach and the reconstruction of the boulevard backwards and also the restoration of the dunes are on the time schedule of coastal managers.

6. Conclusion

The case of Cala Millor is an example of the complex interactions between scientific knowledge, stakeholder perceptions and economic interests and associated solutions for beach management. Despite public opinion to the contrary, there is no a significant erosion or retreat of the beach at Cala Millor. However, beach retreat, which can occur from extreme weather events, should be avoided because the system has become artificial and by itself it does not have the capacity to restore. Loss of beach surface are can affect the number of beach users and the number of people using tourist resort, thus having negative socio-economic impacts. The reconstruction of the boulevard, 15 or 20 m backwards, will reduce the wave reflection during storms and for this reason the loss of sediment in the central zone. In the area gained to the boulevard, a dune system can be reconstructed in order to recuperate the natural mechanisms of adjustment of the beach-dune system. Tracking paths and beach access as well as educational information should be implemented related to dune system restoration. This option is the best management option related to the morphodynamic characterization of the beach and the socio-economic interests. Nevertheless the main conclusion of this paper is not the study case results for a particular beach. The main message of this work is that a science based interdisciplinary and integral approach is a key issue for sustainable and successful beach management.

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