Research Article

Coastal management risk analysis of an embayed beach in Majorca island

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Abstract
Coastal erosion affects many coastlines around the world. This is a serious problem for the Balearic Islands, located at the western Mediterranean Sea, since the economy of the region largely relies on tourist activities along the sandy coastline. Therefore, coastal management strategies are required, particularly, in anthropized coasts as it is the case of Cala Millor beach (north-eastern Mallorca). A risk analysis for this micro-tidal sandy beach is performed in this paper. It is recognized that the beach suffers a persistent loss of sediments since its natural balance was changed due to anthropic activities that took place in that Spanish coast in the 1960s. Some solutions can be adopted to solve this problem, but it is important to be aware that, close to the shore, the seabed is covered by a native vegetation known as Posidonia Oceanica. This seagrass meadow plays an important role in this coastal system, being responsible by the lamination of the waves through energy dissipation, which are inextricably linked to coastal morphology. Therefore, any solution needs to address local specificities, and its consequent potential impact must be incorporated into the coastal risk management process. This study analyzes the failure modes identified according to the failure modes and effects analysis/failure mode, effects and criticality analysis, proposing a set of recommendations, in order to mitigate the occurrence of failure modes and to minimize risks.

Keywords Coastal management · Environmental impacts · Morphodynamics · Risk analysis · Urban beach

1 Introduction

Coastal erosion is one of the main problems of coastlines around the world. Many parameters can be associated to coastline retreat (e.g., maritime climate, sediment transport, sea level rise, etc.), but it is unclear to what extent these factors influence coastal erosion [1, 2]. Particularly, in densely populated coastal regions with high urban development, besides important environmental impacts, there is an increasing socio-economic concern related to erosive processes because they affect population, nearshore infrastructures and assets. This is the case for many Mediterranean regions, whose economies, largely rely on tourist activities along the sandy coastline [3].

In this paper, an anthropized micro-tidal sandy beach located in Mallorca (Balearic Islands, western Mediterranean Sea) is analyzed. Cala Millor beach (north-eastern Mallorca) is a typical "sun and sand" tourist destination in urban environments of the Mediterranean region, characterized by an elevated seasonal turnover. However, the beach suffers a persistent loss of sediments since its natural balance was changed due to anthropic activities that took place in that Spanish coast in the 1960s, leading to the disruption of the natural mechanisms of protection against high-energy events.

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According to Tintoré et al. [4], in 1956, the area of the emerged beach was of 44,260 m^2. This comprises the original natural scenario when the beach, the lagoon and the field dunes in the southern part of the beach were not disturbed by anthropic modifications. In 1968, due to the urbanization works and tourism development, the beach surface increased significantly (+25 568 m^2) because the urban development affected the dune field and sand was removed and brought to the beach. The destruction of the original system and the absence of appropriate management led to a continuous retreat associated with the sand redistribution and beach equilibrium adjustment [5].

New monitoring technologies were required for Cala Millor and by 2007 the IMEDEA (Mediterranean Institute for Advanced Studies) developed a coastal video monitoring system that operated temporally [6]. Since 2011, the beach monitoring program of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) covers Cala Millor beach. This program includes topobathymetric surveys, video monitoring and in situ measurements of nearshore waves and currents, among others [7, 8].

The observations confirm that the natural equilibrium beach state was modified, making the beach more reflective and vulnerable than before. Morphodynamic modeling of the beach seems to support an observed problem resulting from an imbalance of sediment transport due to the drift from north to south during storm situations, which can significantly affect the future use of the beach [9]. It is necessary to correct the problem, or at least mitigate it, by means of sustainable and economic solutions. Some solutions can be adopted to solve this problem, but it is important to be aware that, close to the shore, the seabed is covered by a native vegetation known as Posidonia Oceanica [10]. Indeed, the Balearic Islands are located at the transition area Atlantic/Mediterranean and possess its own biodiversity in the world's oceans. This Posidonia meadow has an important role in the system [11]. This kind of vegetation is responsible for the lamination of the waves through energy dissipation inextricably linked to coastal morphology [12, 13]. Thus, any solution needs to address local specificities, and its consequent potential impact must be incorporated into coastal risk management.

In this study, a risk analysis is performed for Cala Millor beach in order to assess its current situation. Different solutions are discussed, envisaging a sustainable coastal management and meeting the local societal needs where preservation of the environment is essential to assure both residents' welfare and the competitiveness of the tourist sector.

The paper is organized as follows. Section 2 is devoted to the description of the study site, providing information of the beach, wave climate and local specificities. Section 3 focuses on the risk management process. Section 4 describes different solutions for short- and long-term coastal management, identifying and analyzing its risks. Finally, the conclusions are drawn in Sect. 5.

2 Study site

2.1 Cala Millor beach

Cala Millor beach is situated on the north-eastern coast of the Spanish Mallorca island in the western Mediterranean Sea, near the eastern coast of the Iberian Peninsula (Fig. 1). It belongs to the municipalities of Sant Llorenç and Son Servera, located at about 60 km from the capital of Mallorca, Palma de Mallorca.

Offering a fine and clean sand, Cala Millor beach is also called "Arenal de Son Servera" and it is located in the south bay area of Son Servera. The economy of Son Servera was primarily based on a rich agriculture, livestock and fishing. Nevertheless, in the past decades, a strong economic expansion, in which has been immersed Cala Millor, associated the beach to a popular summer tourist area. The beach and its municipalities offer many opportunities for leisure and entertainment and, nowadays, tourist activities are the actual main source of income.

Cala Millor is a micro-tidal sandy beach located in a large natural bay, where the beach is embedded in 1600 m length and 35 m wide, being orientated NNE-SSW. The coastal area is characterized by low ground bounded by cliffs. As shown in Fig. 1, the bay of Son Servera is bounded on the north by the "Cape des Pinar" and south of "Punta de n' Amer." Although beneath the cliffs there are steep slopes, the bathymetry in the central part of the bay is different, following the same topography pattern with regular and shallow slopes covered by Posidonia Oceanica (Fig. 2). The dry beach contains a small layer of fine sand, which rests on a rocky stratum which is frequently exposed after large storms. The sand essentially consists of bioclastic sand. The coarse fraction does not exist and the average of the particle size is uniform, with a median grain size $d_{50} = 0.33 \pm 0.3$ mm [14].

2.2 Wave climate

The offshore wave conditions at Cala Millor beach are recorded by the Capdepera buoy. This buoy is part of Puertos del Estado (the Spanish holding of harbors) buoys network and it is located 36.45 km northeast of Cala Millor at 48 m depth (3.49° E, 39.65° N). Providing hourly hydrodynamic data, the buoy has been operative during the period 1989–2014.

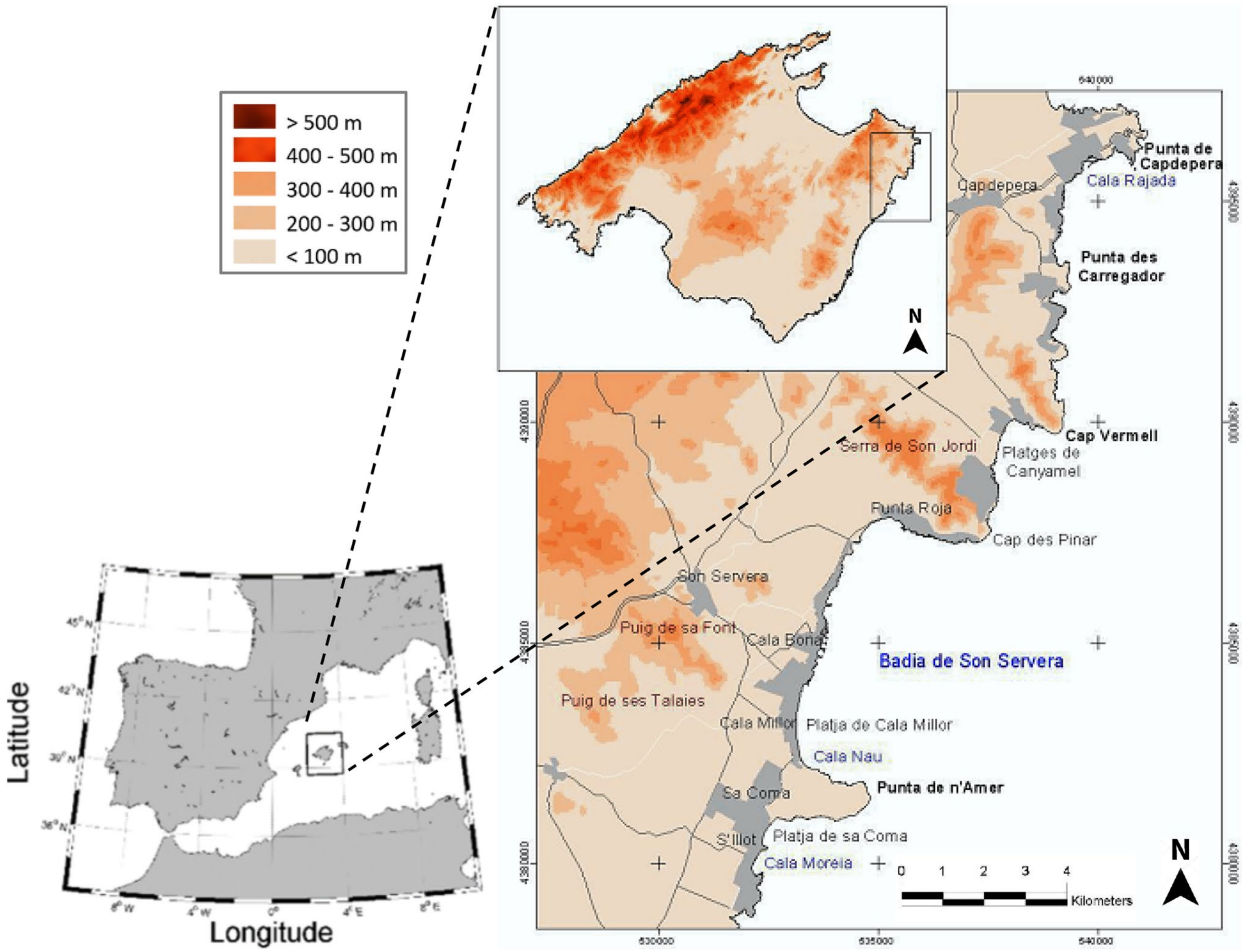

Fig. 1 Location of Son Servera's bay in Mallorca island in the western Mediterranean basin

Over the past decade, the buoy mainly registered waves coming from the first and second quadrants, where swells from the first quadrant possess a higher frequency and present an average direction of 18° (N18E). The second quadrant presents lower frequencies with an average direction of approximately 117° (S63E).

Figure 3 shows the annual/seasonal variability in terms of significant wave height (H_s) and wave peak period (T_p) over the past three decades. This buoy data analysis allows the characterization of the wave climate, revealing the usual variability associated with the Mediterranean climate (defined by hot, dry summers and rainy winters). The figure presents the average values as well as their fluctuations regarding the standard deviation around the average. During summer months (June–August), the wave height and the peak period are smaller in comparison to colder months (December–February). The maximum wave height values are about 1.2 m, while the average is 1.0 m. The longer peak periods are up to 7 s and an average of 8.7 s, averaging 6.2 s.

Considering the Capdepera buoy data, Abreu et al. [9] studied the morphodynamics of the beach, considering representative wave regimes for Calla Millor beach. The simulations were performed with the SMC program (System of Coastal Modeling), which integrates a series of numerical models and allows to model the study site. The results enabled a better understanding of Cala Millor beach morphology, taking into consideration the wave climate and, also, the roughness effects caused by Posidonia Oceanica meadow. The analysis revealed a clear imbalance of the sediment transport for different wave directions, reflecting the differences between the waves originated in the first or second quadrants. This difference enhanced the sediment transport to the south. This imbalance between north and south may be responsible for an annual net loss of sediments in the bay, resulting in the disappearance of the sand substrates of the southern dry beach area.

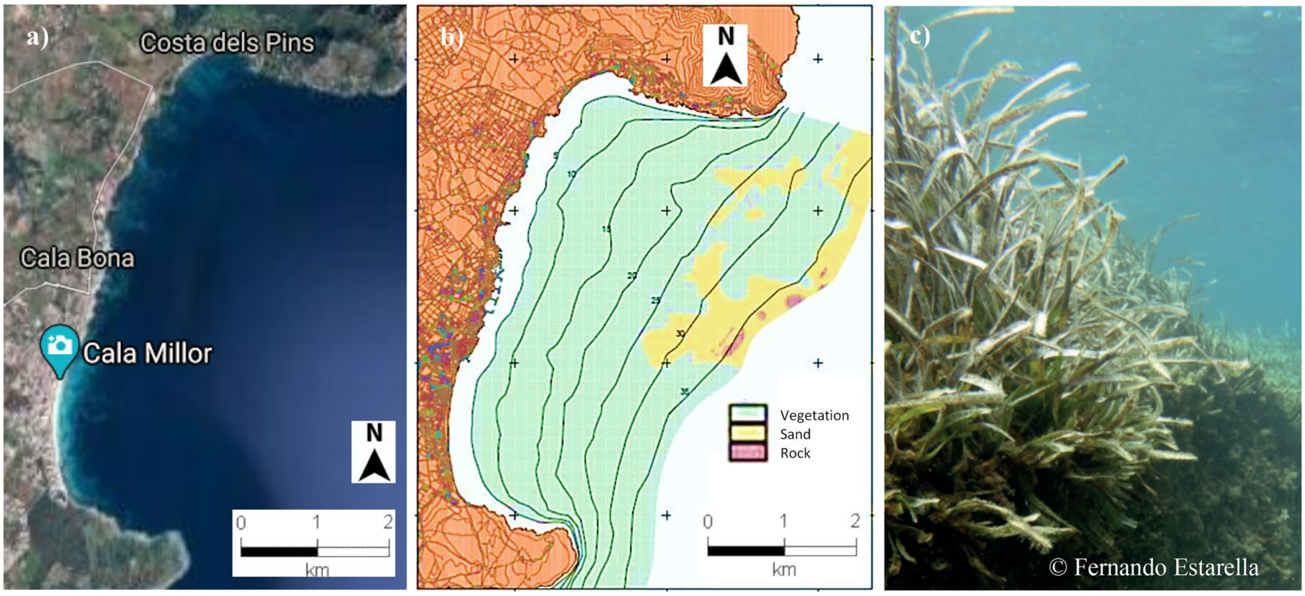

Fig. 2 **a** Aerial view of Son Servera's bay; **b** morphology (sand, rock, sea bottom flora) and their bathymetrical location; **c** native vegetation—Posidonia Oceanica

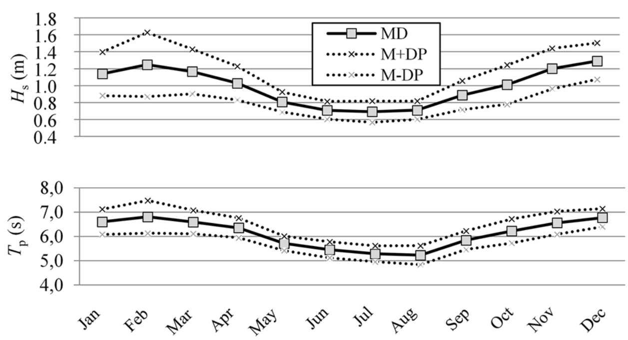

Fig. 3 Capdepera buoy: H_s and T_p over the past three decades. The solid lines represent average values. The dotted lines add and subtract the standard deviation

Abreu et al.'s [9] simulations also addressed the roughness effects associated with the Posidonia Oceanica meadow covering part of the seabed. The seagrass is extended from 5 to 30 m depth, reaching in some areas up to 35 m. The results support the idea that the morphological changes can be significantly attenuated in the presence of Posidonia Oceanica because the vegetation induces a reduction of the wave height. This expected natural energy dissipation [11] is relevant for coastal management, since the influence of the vegetation directly affects coastal morphology. Therefore, any intervention on that coastal system needs to take into account the existence of this vegetation.

3 Risk management process

According to the ISO 31000:2018 [14], all activities involve risk, and these risks are managed through their identification and analysis. With the implementation of a risk assessment, the need to impose some type of treatment to satisfy their risk criteria is defined. Risk management of this coastal stretch needs to consider the external and internal contexts, setting a strategy and achieving objectives and making informed decisions.

Figure 4 highlights how the risk management process involves the systematic application of policies, procedures and practices to the activities of communicating and consulting, establishing the context and assessing, treating, monitoring, reviewing, recording and reporting risks.

The risk assessment process is interpreted as the overall risk identification, analysis, and assessment process. This process should be implemented in a systematic, iterative and collaborative way, based on the knowledge and points of view of the stakeholders.

The identification of the risk is based on a process of research, recognition and description of risks, which can contribute to achieve, or prevent, its objectives. It involves identifying the risk sources, events, respective causes and potential consequences, which may involve the use of historical data, theoretical analysis, well-informed and expert opinions, and also takes into account the needs of the stakeholders.

Risk analysis is the process to understand the nature and determine the level of risks. It provides the basis

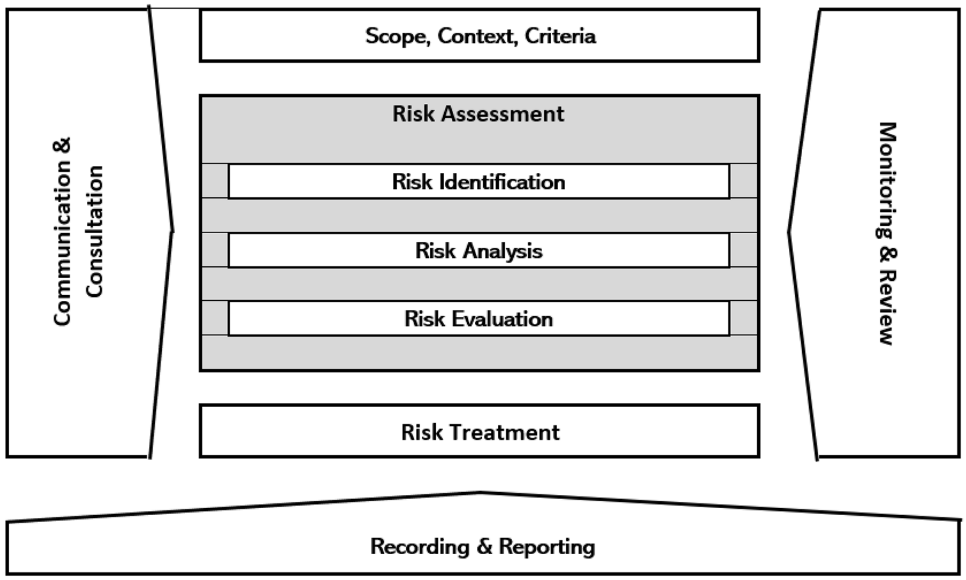

Fig. 4 Process risk management (based on ISO 31000:2018 [15])

for risk assessment and risk treatment decisions. It also includes risk estimation. The risk analysis can be influenced by divergences, or biases, opinions, perceptions, and judgments of risks. Events with a high degree of uncertainty can bring additional difficulty in their quantification, which can be a problem in the analysis of events with severe consequences, and it may be necessary to combine different techniques.

Risk analysis provides input to risk evaluation, for decision-making on whether the risk should be treated and for the definition of the most appropriate strategy and methods for dealing with risks. Depending on the circumstances of the analysis, the risk can be qualitative, semi-quantitative or quantitative, or a combination of these.

The failure modes and effects analysis (FMEA) and its semi-quantitative extension, based on the criticality analysis called Failure Mode, Effects and Criticality Analysis (FMECA), are a methodology that is applicable to any organization and process, allowing to view risk management as a global process. A FMEA/FMECA is an inductive risk analysis process, designed to identify possible failure problems before they occur, assessing the associated legal effects associated with these failure modes, and identifying and applying measures to mitigate their consequences [16].

According to Ben-Daya et al. [17], in the application of the FMEA, a series of questions should be asked: "What are the failures that can arise?," "How likely are these failures to occur?," "How severe are they, in the case of occurrence?" and yet, if not the most important, "How can these failures be avoided?."

The advantages that the use of this process can bring to its users are based on the systematization and methodical character of analysis of the various subsystems, respective operating states, failure modes and sequence of effects, allowing a reasoned reflection on the means of detecting and preventing failure modes and mitigating their effects [18].

The present study intends to name and analyze the failure modes identified in this case study, to collect as much information as possible about causes, effects, degrees of qualification of severity, occurrence, and detection, for the failure modes, according to the FMEA/FMECA and to present and propose a set of recommendations, in order to mitigate the occurrence of failure modes and to minimize risks.

The most frequently used method is the Risk Priority Number (RPN):

$$\text{RPN} = S \times L \times D \tag{1}$$

where S represents the severity, L is the likelihood and D is the detection. Normally, the severity of the failure mode is assessed on an ordinal scale from 1 (no effect) to 10 (dangerous effect). The likelihood is associated to the probability of occurrence and is classified from 1 to 10, where 1 means a remote probability of occurrence and 10 and a very high probability of occurrence. The possibility of detecting the potential first level of failure rates from 1 to 10, where 1 means that detection is likely (certain) and 10 means that detection is impossible.

With the potential failures listed, we can classify the failures according to the Severity, Likelihood and Detection indexes in order to calculate the risk. Respectively, the Severity (or severity of the failure and its effect) and Likelihood (occurrence) values can be obtained from Tables 1 and 2.

In addition, to calculate the risk, it is necessary to obtain the detection level for the failures and their effects. Note

Table 1 FMEA/FMECA—severity index

Index	Criterion
1	Undetectable effect on the system
2	Low severity causing mild annoyance in the stakeholder
3	
4	Moderate severity: dissatisfied stakeholder with noticeable loss of performance
5	
6	
7	High severity with high stakeholder dissatisfaction
8	
9	Very high severity: potential security risk and serious problems on the beach
10	

Table 2 FMEA/FMECA—likelihood index

Index	Criterion
1	Remote possibility of occurrence
2	Very low frequency: 1 time every 10 years
3	Uncommon: 1 time every 5 years
4	Low frequency: 1 time every 2 years
5	Occasional attendance: once a year
6	Moderate attendance: 1 time per semester
7	Frequent: 3 times per semester
8	High frequency: once a month
9	Very high frequency: once a week
10	Maximum frequency: 1 time per day

Table 3 FMEA/FMECA—detection index

Index	Criterion
1	Almost certain failure mode detection
2	
3	Very high probability of failure mode detection
4	
5	High probability of failure mode detection
6	
7	Low probability of detecting failure mode
8	
9	Remote probability of failure mode detection
10	

that detection is a value that shows the efficiency of the fault detection controls (failure mode). Table 3 lists the criteria associated to it, evidencing the higher the value assigned to the detection index, the greater the difficulty in detecting the failure.

FMEA is not a specific requirement of ISO 31000:2018, but it does satisfy the criteria by providing a process for managing risk. Here, a different form is presented than the one normally seen in the state of the art of FMEA/FMECA. All the characteristics of the indicators are maintained, and an analysis is created for each failure mode, according to the template shown in Table 4.

Each table, by failure mode, will have a comment section resulting from the knowledge obtained from other case studies, or from researchers and specialists in this area, contributing to the assessment of the failure mode that the Risk Analysis Team needs to develop.

4 Calla Millor coastal management

4.1 The use of FMEA/FMECA

In the absence of any action to protect the beach, since part of the natural beach recovery was destroyed with the construction of the seafront, nature will continue its natural rhythm, leaving natural processes to erode the beach. The problem of the recreational use of the beach in the south area will be aggravated. The loss of sand, even if temporary, will affect the quality of the beach, decreasing the number of users or moving them to other parts of the beach affecting the capacity of the beach. Ultimately, the incomes associated with the local tourism will diminish. Therefore, in the long-term, if any concrete action is taken, this leads to an untenable situation at the economic and social levels.

Considering the implementation of technical solutions, two different perspectives can be considered regarding sand management in a beach with these characteristics. A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline.

Nevertheless, any solution needs to take into account the existence of the *Posidonia Oceanica* meadow. This is a natural protection in the Balearic marine ecosystem, contributing to the protection of the coast. It stabilizes the submerged beach and tends to form reefs, reducing the energy of the swell that reaches the active zone of the

Table 4 FMEA/FMECA—adapted table for the risk matrix [16]

1.	**Group / Subgroup**	**A.** (Failure Modes Group)					**a)** (Failure Modes subgroup)					**[x]**
2.	**Failure Modes**											
3.	**Effects**											
4.	**Causes**											
5.	**Responsibility Control**											
6.	**Severity**		**7.**	**Likelihood**		**8.**	**Detection**		**9.**	**RPN**		
10.	**Recommended Actions**											
11.	**Current Process Controls**											
	Comments	….										

beach profile. Therefore, they act like natural submerged detached breakwaters. For this reason, its protection should be mandatory in zones where it exists, as it is the case of the Cala Millor beach.

Therefore, any actions that could suppose an aggression to *Posidonia Oceanica* must be avoided (e.g., discharges to the sea that could produce biochemical changes or induce changes in the water quality, affecting the photosynthesis of this vegetation). In addition, the persistent erosive coastal processes that could take off the plants in its upper limits during big storms and the free anchoring of boats with anchors that can hurt the plants need to be considered.

For Cala Millor beach, the Ministry of Agriculture, Fish, Food and Environment (MAGRAMA), advised by IMEDEA, for example, can be designated as the Spanish entity responsible for coastal management. Nevertheless, several stakeholders can be identified, directly and indirectly, associated with the expected quality of the beach, whether by economic interests, such as commercial and tourist associations representing the various companies in the sector, or by environmental associations, or by coastal municipalities given management policies which, in this case, would be Sant Llorenç and Son Servera municipalities.

The identification of risks was based on a bibliographic research process mentioned above. The events that could occur at Cala Millor beach were identified. The objectives for the management of this beach needs to consider: (1) financial aspects—revenues that tourism brings to the region, (2) coastal security—protection of the urban seafront (3) and environmental features—maintenance of *Posidonia Oceanica*, as well as of other coastal ecosystems given its own biodiversity.

The process of analyzing the identified risks, which basically consist of the sand loss and the destruction of the native vegetation, seeks to understand the nature of the risk. Tables 5, 6, 7 and 8 make use of the FMEA/FMECA risk analysis process. The recommended actions presented in each table are summarized in both short- and long-term coastal management perspectives and these solutions are presented and discussed in more detail the following sections.

The calculation of RPN in the traditional FMEA/FMECA formulation can induce decision-making strongly influenced by the Detection index, so the analysis should focus on the first two indices, Severity and Likelihood, according to the new approach.

Palady [19] proposes the elaboration of a matrix, using the indices of Severity and Likelihood assessment, with identical scale, being the first placed on the abscissa axis and the second on the ordinate axis (Fig. 5). The graph is divided into regions, where they stand out high risk (red), medium risk (yellow) and low risk (green) failure modes. The team to coastal management process may define the border points of the priority regions, in accordance with the policy of the organization's quality and procedures. In this case, Fig. 5 indicates that any of the failure modes are identified as "high risk."

4.2 Short-term sand management

In order to maintain a suitable thickness of the sandy stratum on the rocky substratum, annual interventions should be programmed to mobilize the sand inside the beach. Such interventions should be made in the end of April, before the beginning of the tourist period. This should be

Table 5 FMEA/FMECA—adapted table—{1} "coastal erosion—continuous sand loss"

<table>
<tr><td>1.</td><td>Group / Subgroup</td><td colspan="5">A. Coastal erosion</td><td colspan="4">a) Continuous sand loss</td><td rowspan="2">[1]</td></tr>
<tr><td>2.</td><td>Failure Modes</td><td colspan="9">Natural sediment transport of the bay</td></tr>
<tr><td>3.</td><td>Effects</td><td colspan="10">The loss of sand will affect the quality of the beach, decreasing the number of users or moving them to other parts of the beach, affecting the capacity of the beach and its recreational use.

In the long-term, if any concrete action is taken, this leads to an untenable situation at the economic and social levels, since the incomes associated with local tourism will diminish.</td></tr>
<tr><td>4.</td><td>Causes</td><td colspan="10">There is an imbalance of sediment transport due to the drift from north to south, reflecting the differences between the waves originated in the first or second quadrants. This may be responsible for an annual net loss of sediments in the bay, resulting in the disappearance of the sand substrates of the southern dry beach area.

The beach suffers a persistent loss of sediments since its natural balance was changed due to anthropic activities that took place in that Spanish coast in the 60s, leading to the disruption of the natural mechanisms of protection against high-energy events.</td></tr>
<tr><td>5.</td><td>Responsibility Control</td><td colspan="10">IMEDEA (Mediterranean Institute for Advanced Studies), with a coastal videomonitoring system</td></tr>
<tr><td>6.</td><td>Severity</td><td>5</td><td>7.</td><td>Likelihood</td><td>8</td><td>8.</td><td>Detection</td><td>8</td><td>9.</td><td>RPN</td><td>320</td></tr>
<tr><td>10.</td><td>Recommended Actions</td><td colspan="10">A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline.

Annual interventions (end of April) should be programmed to mobilize the sand inside the beach (short-term sand management).

Creation of dunes with small artificial nourishments.

Installation of detached modular breakwaters of low crest levels.

Artificial beach nourishments coming from external sources.

Retreat of the current seafront and the reconstructing of the ancient field of sand dunes, restoring the beach to its initial natural situation or, in alternative, replace the seafront by another with non-reflective characteristics.</td></tr>
<tr><td>11.</td><td>Current Process Controls</td><td colspan="10">Monitoring technologies. By 2007 the IMEDEA (Mediterranean Institute for Advanced Studies) developed a coastal videomonitoring system that operated temporally. Since 2011, the beach monitoring programme of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) covers Cala Millor beach.

Annual interventions (end of April) should be programmed to mobilize the sand inside the beach (short-term sand management).</td></tr>
<tr><td></td><td>Comments</td><td colspan="10">…</td></tr>
</table>

agreed with the local businessmen to avoid social problems at the time of the interventions.

A possibility for repairing and maintaining the beach could be obtained through the replacement of sediments on the dry beach area in the South area for a certain length. This can be achieved by moving sand from adjacent areas of the beach where the thickness of this type of sediment is higher, bearing in mind the different seasonal profiles of the beach. The main risk associated with this solution is that it is expected to have a loss of these sediments in the coastline due to the action of the swell. Therefore, it would be convenient to make sure that

Table 6 FMEA/FMECA—adapted table—{2} "coastal erosion—cyclical and seasonal sand loss"

1.	**Group / Subgroup**	**A. Coastal erosion**				**a) Cyclical and seasonal sand loss**				**[2]**
2.	**Failure Modes**	**Natural sediment transport of the bay**								
3.	**Effects**	The loss of sand will affect the quality of the beach, decreasing the number of users or moving them to other parts of the beach, affecting the capacity of the beach and its recreational use. In the long-term, if any concrete action is taken, this leads to an untenable situation at the economic and social levels, since the incomes associated with local tourism will diminish.								
4.	**Causes**	The annual/seasonal variability in terms of significant wave height associated with the Mediterranean climate (defined by hot, dry summers and rainy winters) affects Cala Millor beach morphology along the year. The local wave climate influences the shoreface profile of the beach. The cross-shore profile is affected by the seasonal differences between the waves originated in the first or second quadrants, resulting in the disappearance of the sand substrates of the southern dry beach area.								
5.	**Responsibility Control**	IMEDEA (Mediterranean Institute for Advanced Studies), with a coastal videomonitoring system								
6.	**Severity**	5	**7.**	**Likelihood**	7	**8.**	**Detection**	8	**9.**	**RPN** 280
10.	**Recommended Actions**	A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline. Annual interventions (end of April) should be programmed to mobilize the sand inside the beach (short-term sand management). The creation of dunes with small artificial nourishments. Such sediment deposits can cover small annual deficits of sand.								
11.	**Current Process Controls**	Monitoring technologies. By 2007 the IMEDEA (Mediterranean Institute for Advanced Studies) developed a coastal videomonitoring system that operated temporally. Since 2011, the beach monitoring programme of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) covers Cala Millor beach.								
	Comments	….								

the natural profile of the beach is not significantly modified because otherwise, it could promote erosion. In particular, the excessive modification of the elevations and slopes of the cross-shore profile might suppose the loss of a big part of sediments after a possible storm.

Considering the loss of sediments, it would be necessary for the creation of dunes with small artificial nourishments. This consists of artificial deposits that can be created during the long-term regenerations and it is supposed that such sediment deposits can cover small annual deficits of sand. For a correct redistribution of the sand on the beach it is necessary to define the thickness of the sandy stratum in all points of the beach, as well as loan areas of sand, thicknesses to be mobilized, etc.

It is also noticed the *Posidonia Oceanica* dead leaves appear on the beach. These remnants are not considered a residue and they can remain on the beach during the off-season period. That supposes a natural protection, increasing the percentage of organic matter on the sand and producing a higher connection between the grains, reducing the sediment transport. However, during the bathing season, it is necessary to clean the beach for the comfort of the users. Such mobilization of sands should be small and the operations should be carried out in seasons with little beach occupation.

There are sand losses produced by cleaning works on the beach when the *Posidonia Oceanica* is withdrawn accelerating erosion processes at the beach-dune system

Table 7 FMEA/FMECA—adapted table—{3} "Posidonia Oceanica dead leaves—continuous sand loss"

1.	**Group / Subgroup**	**A. Aggression to *Posidonia Oceanica***				**a) Continuous sand loss**				**[3]**
2.	**Failure Modes**	**Sediment transport associated to the seagrass**								
3.	**Effects**	*Posidonia Oceanica* dead leaves accumulated throughout the winter at the beach. During the bathing season, it is necessary to clean the beach for the comfort of the users. There is an associated loss of volume of sands associated to cleaning operations transported outside the beach-dune environment, not being restored afterwards. Ultimately, with the loss of sand, the incomes associated with local tourism will diminish. Therefore, in the long-term, if any concrete action is taken, this leads to an untenable situation at the economic and social levels.								
4.	**Causes**	The Cala Millor beach morphology takes into consideration the roughness effects caused by *Posidonia Oceanica* meadow. The imbalance of sediment transport between north and south may be responsible for an annual net loss of sediments in the bay, resulting in the disappearance of the sand substrates of the southern dry beach area.								
5.	**Responsibility Control**	IMEDEA (Mediterranean Institute for Advanced Studies), with a coastal videomonitoring system								
6.	**Severity**	4	**7.**	**Likelihood**	8	**8.**	**Detection**	7	**9.**	**RPN** 224
10.	**Recommended Actions**	The morphological changes can be significantly attenuated in the presence of Posidonia Oceanica because the vegetation induces a reduction of the wave height. This expected natural energy dissipation is relevant for coastal management since the influence of the vegetation directly affects coastal morphology. A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline. Any solution needs to consider the existence of the *Posidonia Oceanica* meadow. The manual collection the *Posidonia Oceanica* dead leaves can be an option, but it is a time-consuming job. Conventional machinery can be used in such operations. The creation of dunes with small artificial nourishments. Such sediment deposits can cover small annual deficits of sand.								
11.	**Current Process Controls**	Monitoring technologies. By 2007 the IMEDEA (Mediterranean Institute for Advanced Studies) developed a coastal videomonitoring system that operated temporally. Since 2011, the beach monitoring programme of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) covers Cala Millor beach.								
	Comments	…								

[20]. Therefore, there is an associated loss of volume of sands, as the material accumulated contains a great amount of sand which is usually transported outside the beach-dune environment, not being restored afterward [21]. Better methods could be applied and the frequency of the operations could be reduced. The manual collection can be an option, but it is a time-consuming job. Conventional machinery can be used in such operations moving sporadically the sand or taking advantage of cleaning beach machinery, moving the sand in order to obtain adequate volumes of sand, but restrictions on mechanical cleaning are important concerning the recovery of the first dune ridges [22]. A sand recovery system needs to be established during beach cleaning works and in the collection of remains of *Posidonia Oceanica* to avoid the continued loss of sediments.

Table 8 FMEA/FMECA—adapted table—{4} "Aggression to Posidonia Oceanica—continuous sand loss"

1.	**Group / Subgroup**	**A. Aggression to *Posidonia Oceanica***				**a)** Continuous sand loss					**[4]**
2.	**Failure Modes**	**Sediment transport associated to the seagrass**									
3.	**Effects**	*Posidonia Oceanica* meadow is responsible by the lamination of the waves through energy dissipation inextricably linked to coastal morphology. Its disappearance or reduction would aggravate the loss of sand, affecting the quality and capacity of the beach. Ultimately, the incomes associated with local tourism will diminish. Therefore, in the long-term, if any concrete action is taken, this leads to an untenable situation at the economic and social levels.									
4.	**Causes**	Aggressive actions to Posidonia oceanic, like discharges into the sea that could produce biochemical changes or induce changes in the water quality, could affect the photosynthesis of this vegetation and the existence of the seagrass. The persistent erosive coastal processes may remove the plants in its upper limits during big storms and the free anchoring of boats with anchors can hurt the plants, aggravating sand losses.									
5.	**Responsibility Control**	IMEDEA (Mediterranean Institute for Advanced Studies), with a coastal videomonitoring system									
6.	**Severity**	6	**7.**	**Likelihood**	8	**8.**	**Detection**	7	**9.**	**RPN**	336
10.	**Recommended Actions**	The morphological changes can be significantly attenuated in the presence of Posidonia Oceanica because the vegetation induces a reduction of the wave height. This expected natural energy dissipation is relevant for coastal management since the influence of the vegetation directly affects coastal morphology. A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline. Any solution needs to consider the existence of the *Posidonia Oceanica* meadow. Any actions that could suppose an aggression to *Posidonia Oceanica* must be avoided. In addition, the persistent erosive coastal processes that could take off the plants in its upper limits during big storms and the free anchoring of boats with anchors that may remove the plants need to be considered.									
11.	**Current Process Controls**	Monitoring technologies. By 2007 the IMEDEA (Mediterranean Institute for Advanced Studies) developed a coastal videomonitoring system that operated temporally. Since 2011, the beach monitoring programme of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) covers Cala Millor beach.									
	Comments	…									

4.3 Long-term sand management

The set of swells that affect Cala Millor beach is highly asymmetric. The swells coming from the first quadrant present more frequency when compared to the swells from the second quadrant. This fact results in a higher sediment transport from the north to the south [9]. Nowadays, during storms, the amount of sediments leaving from the dry beach toward the *Posidonia Oceanica* meadow is continuously increasing. Therefore, the short-term actions should be complemented by the establishment of a few long-term measures to correct the problem.

The installation of detached modular breakwaters of low crest levels could be an option. If they are oriented correctly, they could reduce the energy of the swells coming from the north and this would diminish the sediment

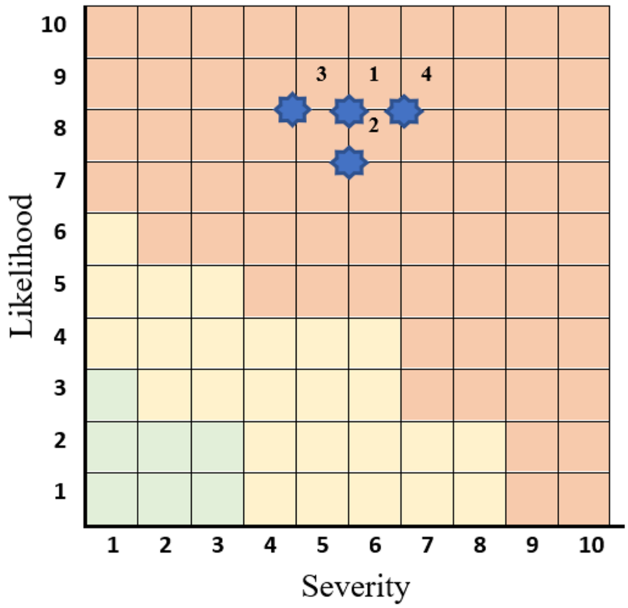

Fig. 5 Graphical representation of the RPN matrix (*S*, *L*)—simulation for failure modes {1} to {4}

fluxes in the north–south direction. In addition to the reduction effect of the swell toward the coast, this solution has the advantage to be easy to implement and, if necessary, also easy to be removed if the produced effect becomes unwanted. Furthermore, for its modular design, different compositions can be explored (elevation and length of the crest, etc.).

Artificial beach nourishments coming from external sources, contributing to big volumes of sediment is necessary to correct long-term losses. There are many options to obtain sediments for beach regeneration by replenishment of sand from outside of the system [23]. Possible loan areas in the Balearic Islands propose the use of marine deposits placed in the Balearic continental shelf. Several nourishment works were performed at Cala Millor since the 1980s. These works were done exclusively for tourism and leisure use and not due to any problem of beach retreat and erosion [5]. However, an important artificial nourishment was performed in Cala Millor beach, after the energetic storm of 2001, causing the loss of a significant amount of sediments. This was made in 2002 with sediments from the Banyalbufar area, located in the NW of the Mallorca island. After this nourishment, up until 2014, the beach remained stable [24].

The artificial nourishments should be done with low frequency and one should study in detail loan areas, its characteristics and the expected consequences due to the extraction of sand. The knowledge concerning coastal dynamics is still limited due to the complexity of the involved processes and one can find several negative experiences all around. Special care in the minimization of any social or political conflict related to nourishments should be considered, to make the community aware for the need of this type of action. It is recognized that artificial nourishments contribute to stabilize beaches (e.g., take advantage for the creation of dunes and to increase the existing ones), but this is done on a temporary basis since the origin of the problem causing erosion continues to exist.

The construction of the current seafront on the beach, constituted by a vertical ornament highly reflective, has led to the disruption of the natural mechanisms of protection against high-energy events during storms. It produces an increase of the agitation on the beach, causing the creation of a few transverse currents that throw the sediment toward the sea. Consequently, a non-recoverable loss of sand is observed. The retreat of the current seafront and the reconstructing of the ancient field of sand dunes, restoring the beach to its initial natural situation, would be a good option to consider. However, nowadays, the demolition of the seafront turns out to be extremely difficult to carry out since many installations are placed along with it. This option would conflict with the interests of local businessmen and people, and a likely scenario is that it would not be possible to carry it out due to legal determinants (private ownership). Therefore, to minimize such problem, the seafront could be replaced by another with non-reflective characteristics. This option would help to receive and store the sediments transported during the storms, approaching to a more natural beach-dune system.

5 Conclusions

This paper performs a coastal management risk analysis for a small sandy beach located in Mallorca Island. Cala Millor beach is embedded in a rocky bay and is a popular summer tourist area. However, the beach suffers a persistent loss of sediments since its natural balance was changed due to anthropic activities that took place in the 1960s. This resulted in the disruption of the natural mechanisms of protection against high-energy events.

There is an imbalance of sediment transport due to the drift from north to south, reflecting the differences between the waves originated in the first or second quadrants. This may be responsible for an annual net loss of sediments in the bay, resulting in the disappearance of the sand substrates of the southern dry beach area. If no appropriate measures are taken, the loss of sand will affect the quality of the beach, decreasing the number of users or moving them to other parts of the beach, affecting the capacity of the beach and its recreational use, diminishing the incomes related to local tourism.

Solutions for the short- and long-term coastal management are required, but they need to account for the existence of a native vegetation that is covering the seabed close to the shore. This seagrass meadow is responsible for the lamination of the waves through energy dissipation, being important to the coastal morphology. Therefore, any solution needs to address these local specificities and its consequent potential impact must be incorporated into a coastal risk management process.

This study presents a risk analysis process where the failure modes are identified according to FMEA/FMECA. Two different perspectives in the short- and long-term are considered regarding sand management on a beach with these characteristics. A short-term intervention would allow the use of the beach during touristic periods, whereas a long-term intervention aims to correct the instability of the coastline. A set of recommendations are proposed, in order to mitigate the occurrence of failure modes and to minimize risks. This risk methodology analysis aims to contribute to an effective and sustainable coastal management process.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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