Ocean & Coastal Management 54 (2011) 907–918

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Managing erosion-induced problems in NW Mediterranean urban beaches

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ARTICLE INFO

Article history:
Available online 15 June 2011

ABSTRACT

The applicability of recommendations of the Eurosion project to define a policy to manage coastal erosion has been tested at the "beach" scale in the Mediterranean coast. Thus, a favourable sediment status has been defined for these beaches taking into account their main functions: recreation and protection. Because they act at two different seasons, this status needs to be seasonally defined. For the protection function, the favourable sediment status depends on the level of safety fixed by the manager taking into account the importance of existing infrastructures and, for recreation it depends on the use density of the beach. The concept has been formalized for beach management within a framework where benchmarking plays a crucial role to determine the need of intervention. This has been illustrated for open cell beaches where one of its boundaries can permit variations in the sediment budget and for pocket beaches that act as closed sediment cells.

1. Introduction

1.1. The context

The recently signed "Protocol on Integrated Coastal Zone Management in the Mediterranean" (PAP/RAC, 2007) specifies that (sic) "the Parties, with a view to preventing and mitigating the negative impact of coastal erosion more effectively, will undertake to adopt the necessary measures to maintain or restore the natural capacity of the coast to adapt to changes, including those caused by the rise in sea levels. The Parties shall endeavour to anticipate the impacts of coastal erosion through the integrated management of activities, including adoption of special measures for coastal sediments and coastal works. The Parties undertake to share scientific data that may improve knowledge on the state, development and impacts of coastal erosion".

This follows the findings of the Eurosion project (European Commission, 2004) funded by the European Commission with the aim to provide quantified evidence on coastal erosion in Europe, on the problems caused by it and on the successes and failures of mitigation measures. It recommends four main elements to define a policy to combat coastal erosion:

- Increase coastal resilience by restoring the sediment balance and providing space for coastal processes.
- Incorporating coastal erosion costs and risks in existing planning and policy instruments.
- Make responses to coastal erosion accountable.
- Strengthening the knowledge base of coastal erosion management and planning.

However, these elements have not yet been formalized in a framework to be applicable by coastal managers nor their applicability to European coasts have been validated. To solve this gap and to adapt such strategy to the reality of the European coasts, the Conscience research project (Marchand et al., 2011, in this issue) was launched with the main strategic objective of developing and testing concepts, guidelines and tools for the sustainable management of erosion along the European coastline. In this work we analyze the applicability of these concepts and the proposed approach to a coastal typology very common along the European Mediterranean coastline, the urban beaches.

1.2. Mediterranean urban beaches

Urban beaches have been selected as a case study because they represent a large percentage of the Mediterranean coastline and are

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doi:10.1016/j.ocecoaman.2011.05.003

the main resource for coastal tourism, i.e., they are common and they are important in social and economical terms. Thus, they are the most frequented and exploited coastal types and they can be represented by beaches with the following characteristics: (i) relatively narrow beaches backed by waterfronts and (ii) heavily used during the bathing season and, in consequence, they support (or have to) services for beach users (see, e.g., Valdemoro and Jiménez, 2006). The typical length scale of these beaches varies from 100s of meters to a few kilometers with one or two lateral obstacles (semi-enclosed and pocket beaches, respectively).

These beaches play two main functions: protection and recreation. *Protection* refers to the function played by the beach to protect the hinterland (usually occupied by a promenade/waterfront) from wave action during storms. On the other hand, *recreation* makes reference to the function played by the beach to properly offer an environment for leisure (e.g., beach surface to accommodate users).

Regional climatic conditions determine the intensity of the interaction between coastal dynamics and beach functions. Under typical Mediterranean weather conditions, the season with the highest beach occupation (originally the summer, but now extending from Easter –April– to September) is the period with the lowest wave energy, while the period with the highest wave energy usually occurs during periods of very low beach use. In consequence, if the main management priority is to ensure the protection and safety of the hinterland, the beach should be at its optimum during the months with the highest wave energy content. However, if the target of the management is to promote/enhance the recreational function, the beach has to be at its optimum during the summer, since this is the period of highest use.

To illustrate how important management of coastal erosion in these beaches is, it has to be considered that about 72% of the Catalan beaches (NE Spanish Mediterranean) are subjected to erosion at an average retreat rate of 1.9 m yr^{-1} (CIIRC, 2010). If all the beaches are considered, the overall behaviour can be represented by an average erosion rate of 1 m yr^{-1} (CIIRC, 2010).

1.3. Objective and structure

Within this context, the main aim of this paper is to contribute to the implementation of the ICZM Protocol for the Mediterranean by analysing the applicability of recommendations of the Eurosion project (PAP/RAC, 2007) to define a policy to manage coastal erosion at the "beach" scale. In this case, we only focus on technical aspects which imply to define and apply the main concepts introduced in the Eurosion recommendations, i.e., coastal cell, favourable sediment status, coastal resilience and strategic sediment reservoir (Marchand et al., 2011, in this issue).

The work is structured as follows: (i) in the second section we discuss the applicability of the concept of coastal resilience at the studied scale, and of the concepts favourable sediment status and coastal cell, (ii) in the third section erosion processes and problems at the study site are presented to illustrate in real terms their magnitude along the Mediterranean coast, (iii) in the fourth section, the management of processes and problems are discussed by presenting the actual situation and how a sustainable approach could be implemented and, (iv) finally, the fifth section presents the main conclusions of the study.

2. Coastal resilience in the context of urban beaches

Coastal resilience has been defined in the framework of the Eurosion project (European Commission, 2004) as the inherent ability of the coast to accommodate changes induced by sea level rise, extreme events and occasional human impacts, whilst maintaining the functions fulfilled by the coastal system in the longer term. These three processes or agents can be easily associated to three different time scales: long-term (centuries), episodic (random) and medium-term (decades), respectively. In this study we focus on two scales: episodic (associated to the impact of coastal storms) and decadal (associated to the human impact plus background –natural– evolution) ones.

The first step consists in defining what "the inherent ability to accommodate changes" is. Thus, to define and assess beach resilience to the impact of extreme events we can use two main approaches: (i) by measuring the capability of the beach to recover (rebuild) after erosion due to the impact of the storm or, (ii) by measuring the ability of the beach to withstand changes induced by the storm.

In the first case, resilience would depend on the wave climate and beach characteristics, which will control the magnitude of post-storm onshore sediment transport rates and, thus, the velocity and intensity of natural beach reconstruction. We can denominate this as "basic resilience" because it is mainly controlled by the natural system and, in practical terms, the response associated with this resilience (beach recovery) is lagged with respect to the storm impact. The preferred beach management response making use of this resilience is indirect and it should consist in diminishing the erosion intensity in such a way that the ratio accretion/erosion increases although natural recovery processes will not vary. Other possible measure is shoreface nourishment, where an stock of sediment is placed in the submerged part of the beach profile to be transported shorewards by wave-induced dynamics enhancing the recovery of the beach (e.g., Hamm et al., 2002; Walstra et al., 2010).

In the second case, the resilience depends on beach characteristics (width and volume) that will control the resulting configuration after the impact of a storm. Thus, the wider the beach is, the larger the resilience will be. Here, the resilience is measured in terms of the remaining post-storm beach, which will continue playing the usual functions. The preferred beach management response making use of this resilience – in addition to acting on erosion intensity – is by increasing its width, which can be done by advancing the shoreline (e.g., by means of beach nourishment) or/and by retreating the landward beach limit (e.g., retreat or realignment). The efficiency of promoting this resilience is instantaneous, i.e., the storm impact verifies on a beach wide enough to accommodate the changes.

These two approaches are also applicable at the medium-term scale by replacing the erosion induced by the impact of a storm by, e.g., decadal-scale erosion due to the existence of a (natural or man-induced) longshore sediment transport gradient.

Finally, to support the objective of coastal resilience, Eurosion introduces the concept of a 'favourable sediment status' for coastal systems, which is defined as the situation of 'coastal sediments' that will permit or facilitate meeting such an objective in general and of preserving dynamic coastlines in particular. To properly apply it to management of erosion processes and problems in the considered beaches, the type of sediment cell as a function of the sediment budget needs to be considered. Here we analyze the case of a closed sediment cell for a pocket beach and the case of a non-closed sediment cell for an open beach. Its application in the study area is detailed in Section 4.

3. Costa Brava beach processes and problems

3.1. General description

The Costa Brava is located on the NE Spanish Mediterranean coast (Fig. 1). It is a highly indented coast with most of the coastline composed of cliffs, especially in the northernmost area. Bayed and pocket beaches are the dominant beach type, with most of them composed of coarse sands which are here represented by s'Abanell and Lloret de Mar beaches.

s'Abanell is a 2.5-km long sandy semi-enclosed beach located in Blanes (Fig. 1), which is bounded at its northern part by a small rocky headland, Sa Palomera, whereas its south end is dynamically supported by the Tordera delta. The beach can be zoned into two areas as a function of the urban development of its hinterland: (i) a *N* urban area, about 1.5 km long, with a promenade running along the back of the beach and (ii) a *S* semi-urban area, about 1 km long, where the hinterland is occupied by camping areas with the southernmost 500 m without any promenade in the backbeach. This southern part supports some small installations from a desalinization plant located upstream of the Tordera river. This spatial variation in the hinterland is also reflected in the degree of beach use, with the *N* area being intensively used whereas the *S* one presents a much lower density of use. The subaerial beach has an average width of 27 m (summer 2008) and it is composed by a sediment size of about 1.2 mm.

Lloret de Mar is a 1.3-km long and 50 m wide sandy bayed beach (Fig. 1) embedded between two low cliffs. The shoreline is almost linear with the exception of the areas surrounding the two ends, where it adopts a curved form due to the effects of wave diffraction at the cliffs. The beach is backed by a promenade with its crest level placed at approximately 4.5 m above the sea level and it is protected at the ends by a revetment of quarry stones. A total of 6 short groins, of about 30 m long, are placed along the beach at regular distances and are partially or totally covered by the sand when the beach presents its "normal" alongshore uniform plan shape configuration. The emerged area is characterized by a sediment size of 0.95 mm, very well sorted and without significant fine fractions.

3.2. Beach processes

3.2.1. s'Abanell beach medium-term behaviour

As mentioned before, s'Abanell is a semi-open beach at its south end that is delimited by the presence of the Tordera delta. Fig. 2 shows shoreline evolution rates of the beach calculated during the last 5 decades (from 1957 until present). As it can be seen the beach presents two different evolutive periods: (i) an accretive behaviour during the period 1957–1973 and (ii) an actual erosive one from the end of the 70s until present. During the first period the beach was accreting due to the supplies of the Tordera river. Although most of sediments were transported towards the south by the net longshore sediment transport pattern, part of the sediment was redistributed towards the beach by diffusion and by the action of secondary southern waves. At the end of this period the beach reached its maximum width.

During the second period, the evolution trend changed due to human action. In this case, the erosive behaviour is related to the sharp decrease in river sediment supplies (Jiménez et al., 1998). Several millions of m^3 of sediment were dredged for construction from the riverbed mainly from the end of the 60s to the end of the 70s (Rovira et al., 2005). This created a sink for new river supplies and, in consequence, the balance between riverine sediment supply and removal due to littoral dynamics determined the Tordera delta to be reshaped and eroded. This delta front erosion affected the beach stability since the delta was acting as a dynamical support at its southern end. As in the previous period, two differentiated parts can be distinguished in the beach: (i) a northern part where the beach is almost stable and (ii) a southern one extending along 1 km, where the beach is erosive with recession rates increasing towards the *S*. The southern end in the Tordera delta the area shows the largest retreat.

These shoreline changes were converted to sediment volumes by assuming the hypothesis usually applied in shoreline change models, i.e., associated beach profile changes extend down to the depth of closure and changes in the beach extends up to the berm height. The depth of closure in the area has been estimated to be 7 m using the Hallermeier (1981) formula fed by wave data recorded at a wave buoy off the Tordera delta during the period 1984/2007. With this, the averaged annual sediment loss resulting in the observed shoreline changes (beach erosion) has been calculated to be 30,000 $m^3\,yr^{-1}$ which should be removed from the coastal cell (the beach) by the southwards directed net longshore sediment transport. In order to estimate its potential annual variability, we have estimated the potential longshore sediment transport rate by using the CERC formula with the *K*-coefficient adjusted for the local sediment grain size following the dependence law proposed by (del Valle et al., 1993). Using wave data recorded in the area from 1984 up to date, we find an average annual net longshore sediment rate of 21,000 $m^3\,yr^{-1}$ directed southwards, with a standard deviation

Fig. 1. Area of study.

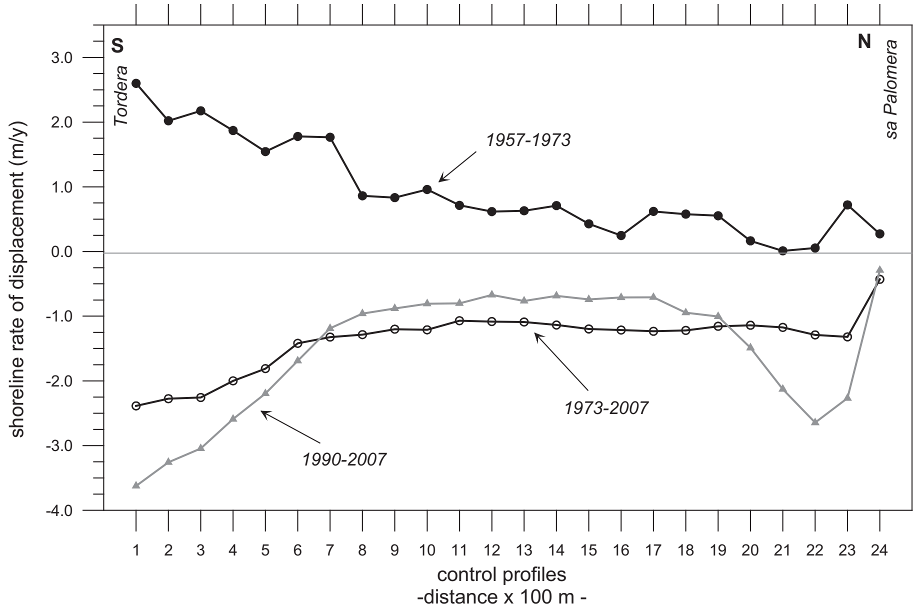

Fig. 2. Long-term shoreline rates of displacement along the s'Abanell beach.

of 21,000 $m^3 yr^{-1}$. Calculated transport rates varied between a maximum value of 69,000 $m^3 yr^{-1}$ and a minimum one of $-5{,}500$ $m^3 yr^{-1}$ (directed northwards). Assuming, that this computed climatic variability can be transferred to sediment budget estimations, the s'Abanell beach annual sediment budget can be approximated by an average loss of 30,000 $m^3 yr^{-1}$ varying between a maximum loss of 99,000 $m^3 yr^{-1}$ and a potential gain of 8000 $m^3 yr^{-1}$. This range of variation was obtained by applying the ratios obtained in the calculations of annual potential longshore sediment transport between the maximum and minimum rates with respect to the mean value to the calculated sediment budget from shoreline data.

3.2.2. Lloret de Mar beach medium-term behaviour

Opposite to the previous case, Lloret de Mar is a pocket beach with two headlands delimiting a closed sediment cell. Due to this, shoreline changes do not reflect a sediment volume change of the coastal cell, but volume changes around the waterline. The latter can be interpreted as coastline fluctuations around an equilibrium shape, depending on the direction of the incoming waves.

Fig. 3 shows the range of shoreline configurations that Lloret de Mar beach can present. The most frequent configuration corresponds to a shoreline exposed towards the SSE (May 2008 in Fig. 3) which corresponds to the direction of the integrated energy flux of effective waves in the area (Jiménez et al., 2003; Gracia et al., 2008), associated to the beach equilibrium shape. The other two configurations correspond to: (i) a situation generated by the cumulative action of Eastern storms during a long time without the action of secondary *S* waves resulting in an extreme reorientation towards the South (May 2004 in Fig. 3) and; (ii) a situation generated by the cumulative action of Southern storms without the action of *E* waves resulting in an extreme reorientation towards the North (May 2001 in Fig. 3). This beach configuration is not very frequent in the area because due to the coastal alignment (Fig. 1) the beach is protected from SW waves. An analysis of beach shoreline changes from 1986 until present has shown that net sediment losses from the beach zone are negligible and, in consequence, it can be considered as a closed sediment cell (Gracia et al., 2008).

3.2.3. Beach changes due to storm impacts

In addition to decadal scale processes, both beaches are also affected by the impact of storms which induce a series of sudden changes superimposed to the above described ones. Depending on the beach pre-storm configuration, resulting changes locally may involve the nearly total disappearance of the subaerial beach (Jiménez et al., 1998, 2003).

In order to estimate the potential magnitude of storm-induced changes, the beach profile erosion model SBEACH (Larson and Kraus, 1989) has been used. To do this, beach profiles typical of the analyzed beaches (they have similar reflective profile characteristics since they are composed by coarse sands) were used together with storm wave conditions typical of the area (Jiménez et al., 2002). Fig. 4 shows the calculated shoreline retreat induced by the impact of storms with different associated return periods. This has been obtained by using wave storm defining parameters (Hs, Tp and duration) associated to given return periods obtained from the extreme wave climate of the study area following the methodology outlined in (Sánchez-Arcilla et al., 2008, 2009). Thus calculated values represent an order of magnitude of the expected erosion due to cross-shore sediment transport under the condition that waves are not significantly modified by coastal morphology. In the case of Lloret de Mar, the northeastern part of the beach is sheltered from the action of *E* storms due to the diffraction on the headland, whereas the *S* part remains exposed. For *S* storms, the entire beach is homogeneously exposed (Jiménez et al., 2003). In the case of s'Abanell, almost the entire beach is equally exposed to the action of storm waves. However, it has to be mentioned that longshore sediment transport under the action of *S* storms feed the beach with sediment from the Tordera delta in such a way that after the action of these storms, the Northern part of the beach is usually recovered in terms of sediment volume.

3.3. Beach problems

In essence, a coastal problem can be defined as a situation where a given coastal process (or a set of them) negatively affects existing resources or uses, i.e., when a coastal function of interest is affected negatively. Due to the characteristics of the studied Mediterranean

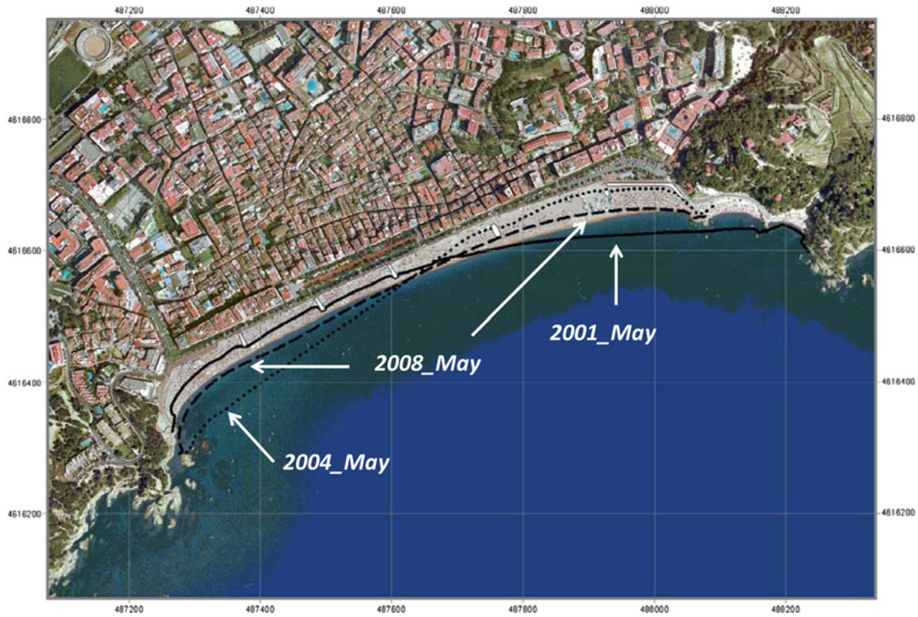

Fig. 3. Shoreline reorientations along the Lloret de Mar beach (after Gracia et al., 2008).

beaches, problems should mainly be related to beach malfunctions regarding protection and recreation.

3.3.1. *Protection function*

Fig. 5 illustrates different problems related to beach malfunction regarding the protection of the hinterland. These problems vary in typology and intensity depending on storm characteristics and beach morphology at the time of the impact.

Minor problems should occur when the beach is overtopped by waves during the storm and the promenade and the hinterland is overwashed by water and sediment removed from the beach (Fig. 5 top). These events usually occur when the total water level during the storm (storm surge + wave run-up) exceeds the beach crest level and the promenade. Under these conditions waves induce a temporal inundation of the hinterland resulting in a post-storm situation usually characterized by a promenade and adjacent areas full of sediment. This will cause small damages for instance to gardens and drains, with the municipality being the main affected stakeholder and suffering all the expenses incurred to clean the area and to put the sand back at the beach. When sand and water transported landwards during the storm arrive to private properties (Jiménez et al., 2003), part of the damages are transferred to the private sector.

When waves directly impact on the promenade, failure of the infrastructure frequently occurs (Fig. 5 middle). In most of the cases, this is due to the fact that most of the existing beach promenades along the Spanish Mediterranean coast were built in the 70s during the tourism boom. At that time, beaches were wide and promenades were generally built without considering the probability of suffering the expected wave action. As a consequence they were not designed as coastal structures but as architectural elements. As erosion has become dominant, beaches protecting these infrastructures got progressively narrower and storm waves started to directly impact on them. Depending on the structural design, this can result in major damages and the incurred costs are related to the reconstruction and further protection of the promenade.

If other infrastructures are present in the beach, they could be also affected. Fig. 5 (bottom) shows the damages on existing desalinization plant facilities (wells and a pumping station) at the S end of s'Abanell beach. Because these facilities were built in the most erosive stretch, few years after their construction they were severely affected by storm impacts. As a consequence of this, the station was protected by riprap and by emergency beach nourishment (see Section 4). Along this southern end, the limit of the existing campsite has also been affected by storm-induced erosion (Fig. 5 bottom). The storm-induced damages have forced the campsite to retreat since no hard protection to stop this beach retreat did exist (Fig. 5). As a result, the camp installations closest to the sea have been destroyed and abandoned.

All these problems occurring in the s'Abanell beach are a clear example of the synergetic action between storms and medium-term evolution. Thus, under original accretive-stable conditions only extreme storms were able to exceed the capacity of a wide beach to dissipate their energy. However, when medium-term erosion began to affect the beach, smaller storms became able to exceed the dissipation capacity of a narrower beach. This means that for a steady wave climate, the frequency of storm-induced problems became more frequent due to the progressive narrowing of the beach (Jiménez et al., 1998, 2002).

In the case of pocket beaches without background erosion, protection-related problems can be present even in the case when

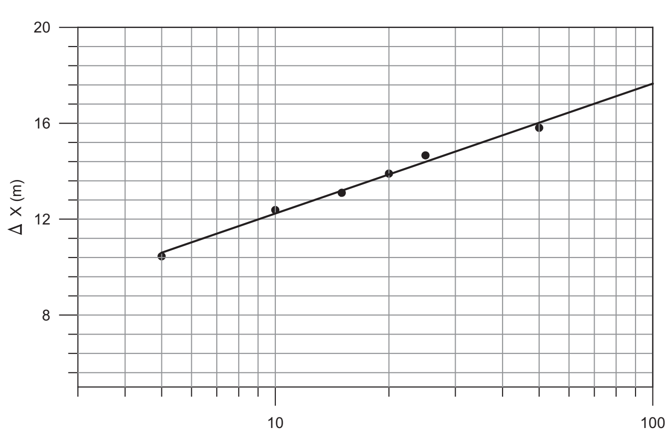

Fig. 4. Calculated storm-induced shoreline retreat for typical Costa Brava beach profile associated to given return periods.

Fig. 5. Coastal protection problems in s'Abanell beach. Top: minor problems due to beach and promenade overtopping. Middle: severe problems affecting promenade stability. Bottom: severe problems affecting infrastructures of a desalinization plant and the limit of campsites at the *S* part of the beach.

the average beach width exceeds the storm-induced retreat. This might occur when a storm impacts on a beach presenting an extreme shoreline reorientation (cf. Fig. 3). Under these conditions, the subaerial surface locally tends to be ill shaped, because the beach at one of its ends will be narrower than the storm-induced retreat. Thus, there will be a part of the beach very sensitive to the impact of a storm and, if infrastructures are not designed to resist wave action, they can be damaged in a similar way to that described above. Fig. 6 (top) shows the results of the impact of a *S* storm along the Lloret de Mar beach when it was re-orientated towards the *N* (configuration of May 2001 in Fig. 3).

3.3.2. Recreative function

Beach recreational malfunctioning is related to those processes and responses affecting the recreational carrying capacity. This would mainly occur due to (i) a decrease of the available beach surface per user and/or (ii) the loss of functionality of existing beach services for users (Fig. 7).

The decrease in the available beach subaerial surface for users will be mainly due to the existence of long-term erosion processes acting on open sediment cells. This will occur when long-term shoreline retreat determines the beach width to be narrower than the optimum recreational width, which is the part occupied by users (for the Spanish Mediterranean beaches assumed to be about 30–35 m (MOP, 1970)). Under this condition, the combination of a steady affluence of users with a progressive narrower beach results in a proportional increase in users' density that could affect the beach recreational carrying capacity. Thus, high quality beach tourism destinations are usually associated with large available surface per user whereas mass tourism accepts larger densities. Different threshold values recommended for users' density can be seen in (Roca et al., 2008). In extreme cases, the persistence and cumulative action of erosion processes can determine the increase of the occurrence of overcrowding events and/or the collapse of the beach due to the nearly full disappearance of space for leisure (Fig. 7).

In addition to the medium-term erosion processes, storm-induced erosion can also affect the beach recreational carrying capacity. Although as it was mentioned before, there is a time lag between the storm and the recreational seasons in Mediterranean beaches during "normal" climatic years, some exceptions could occur. This would happen for stormy seasons longer than usual and/or when late storms occur in April–May just before the start of the bath season. Under these conditions natural recovery processes would not have enough time to rebuild the beach (Valdemoro and Jiménez, 2006).

Regarding the loss of functionality of existing beach services, this will occur when shoreline retreat determines existing beach services to be exposed to wave action (Fig. 7). Within this category we can include the cases where existing accesses become useless due to the local disappearance of the beach. This can be the result of a long-term retreat in open sediment cells and/or extreme shoreline reorientations in pocket beaches (Fig. 7).

Fig. 6. Coastal protection problems in Lloret de Mar beach. Top: promenade stability problems at the *S* end due to direct wave impact under extreme shoreline reorientation. Bottom: full overtopped beach and promenade and massive overwash sand transport.

4. Management of erosion-induced problems

4.1. Introduction

Once the erosion-induced problems have been introduced, the different elements to be considered in a beach management process are presented in what follows. As for any coastal problem, different solutions can be formulated resulting in a series of alternatives that have to be comparatively evaluated according to some criteria (economic, environmental, social, etc.). It is not the objective of this work to make such an analysis of alternatives but to check whether the general EU recommendations for managing coastal erosion can be downscaled to be applicable at the scale of our study.

This has been done by using the Conscience Frame of Reference (Marchand et al., 2011, in this issue; Van Koningsveld and Mulder, 2004), which is an analysis framework that has been successfully

Fig. 7. Recreation malfunctions due to large erosion of the subaerial beach (top) and due to affectation of beach accesses and services due to extreme shoreline re-orientation (bottom).

applied to coastal management problems such as stability, recreation and navigation (Kroon et al., 2007; Jiménez et al., 2007; Medina et al., 2007). In what follows, first we introduce the approach implemented until today in the area to manage existing problems and, later we apply the Conscience approach (Marchand et al., 2011, in this issue) to the study area.

4.2. Present management

At present, the management implemented in these beaches to cope with erosion-induced problems has been purely reactive, i.e., any time when a problem appeared a practical solution to deal with the specific problem has been executed. This means that no medium/long term strategy has been defined for the beach and, implicitly, this is equivalent to have an action plan instead of a management plan.

In the case of s'Abanell beach, because most of the problems have been related to the failure of the beach regarding the protection function, actions taken until now categorized in two groups: (i) decreasing the need of protection by the beach and (ii) increasing the protective capacity of the beach.

Actions to decrease the need of protection by the beach have been aimed at increasing the structural strength of existing infrastructures. In the case of the beach promenade, broken or collapsed sections have been redesigned to behave as seawalls. For those sections not fully destroyed, the existing structure has been protected by placing riprap at the toe of the promenade and collapsed parts have been fully redesigned as a seawall with an inverted *T*-profile and a toe protection. At the south of the beach the auxiliary station associated with the desalinization plant has been protected by placing a riprap seawall surrounding the building to resist the direct wave impact.

Actions to increase the protective capacity of the beach consisted of occasional beach nourishment operations designed to instantaneously solve an emergency situation. During the last two years up to three different beach nourishments have been executed. The first one took place in December 2007 to protect the auxiliary station at the south of the beach because it was directly exposed to wave action. About 180,000 m^3 of sediment were dredged from the submerged part of the Tordera delta between 15 m and 20 m water depths and placed along the southernmost 600 m of the beach (Fig. 8). One month later about half of the placed sediment had disappeared from the area and the station was again at the waterline (Fig. 8).

In May 2008 the beach was nourished with about 144,000 m^3 of sediment along 700 m at the northernmost part. According to the project, these works were designed to enhance the safety of the promenade. The sediment was also obtained by dredging the submerged deposits in front of the Tordera river mouth. Six months later, almost all the sediment had disappeared from the area and the riprap protecting promenade was again exposed to wave action. Finally, during the summer of 2009, about 250,000 m^3 of sediment were supplied to the beach to recover it from the erosion induced by the impact of winter storms, one of them being the largest recorded in the area in the last 50 years. In this case, the sediment was obtained from a submerged deposit located about 20 km to the south.

In addition to this, along the southern part of the beach, which is the most eroded part, the owners of the campsites have been forced to retreat the outer limits of the installations due to the disappearance of the emerged beach and the exposure to direct wave action (Fig. 5).

In summary, present management of erosion-induced problems is based on emergency actions without any long-term perspective or planning, i.e., there is not a strategy to cope with processes but a collection of actions driven by problems.

4.3. Towards sustainable erosion management in Costa Brava beaches

4.3.1. Strategy

The application of the frame of reference to the study area for the considered beach functions (protection and recreation) is

Fig. 8. Emergency beach nourishment at South s'Abanell beach duringat December 2007. Top left by courtesy of Google Earth. The arrow in top photos indicates the relative position of station with respect to the shoreline just after the works. Bottom: beach just after the works (left) and one month later (right).

shown in Fig. 9. Once governing processes are determined behind a problem affecting the beach basic functions, the need of intervention should be justified (Ministry of Environment, 2008). At the top level, the strategic objective is set to get a sustainable beach properly maintaining protection and recreation functions. This objective is based on the fact that coastal tourism is the main economic activity in the area and, in consequence, beaches are the basic resource for economic development of coastal municipalities and, due to this, the beach carrying capacity must be preserved or enhanced. On the other hand, since all these beaches support different infrastructures, they need to provide protection and/or safety. The introduction of the term sustainable implies that any policy to be implemented must be efficient in environmental, economic and social terms. In this sense, it has to be stressed that the (local) social perception about the present management of the s'Abanell beach is quite bad, with continuous complaints from the different affected stakeholders.

4.3.2. Favourable sediment status

The strategic objective should be achieved by defining an optimum configuration able to permit the beach to support both functions, which is the core of what is called the tactical level in Fig. 9. In order to define this optimum configuration we make use of the concept of "favourable sediment status". This optimum beach status will seasonally vary because each target function needs a given configuration in order to be supported. Thus, there will be two main configurations:

- A winter (stormy period) favourable sediment status for enhancing/preserving the protection function that will be defined by the volume of sediment required to generate a beach wide enough to dissipate the energy supplied by a storm of a given return period.
- A summer (calm period) favourable sediment status for enhancing/preserving the recreation function that will be defined by the volume of sediment required to generate a beach wide enough to accommodate users and required services.

This favourable sediment status should be given by a beach configuration with a width equal to the required width in order to support the corresponding function plus an additional safe area. With respect to the protection-oriented status, the target beach configuration will depend on the level of safety required by the manager according to the importance of the hinterland. Thus, a risk level, R, will be selected and then, we shall estimate the corresponding critical return period, Tr, of the storm to induce beach erosion within a selected time period or beach "life", L. Following Borgman (1963) the relationship between risk, R and lifetime, L, can be expressed by

$$R = 1 - \left(1 - \frac{1}{\mathrm{Tr}}\right)^{L} \quad (1)$$

According to recommendations of the Spanish Ministry of Public Works (Puertos del Estado, 1990), the minimum time period of concern, L, for coastal protection and nourishment works should be 25 years. Because in most of Mediterranean beaches the failure of the protection capacity is not likely to cause human losses, it will have an economic repercussion ranging from low to medium; the maximum admissible risk, R, should range between 0.5 and 0.3, respectively, (Puertos del Estado, 1990). By substituting these values into (1), the critical return period of the storms to be analyzed varies between 37 and 71 years, respectively. These values are used to calculate the storm-induced beach retreat (Fig. 4), ΔW_{Tr}, and then, the minimum configuration to ensure the protection function of the beach can be defined, W_{prot}. Here we have selected this width to be 1.5 times the storm-induced beach retreat, ΔW_{Tr}, which implies to assume that after the impact of a storm of the selected return period, there must remain at least a beach width equal to the half of the induced erosion in order to let the beach to keep on being operative (to offer a partial protection).

With respect to the recreational status, the target configuration will depend on the density of use of the analyzed beach. If the starting point is a situation in which the density of use is low, beach surface losses are acceptable provided they do not determine an excessive increase in users' density, i.e., to remain below the

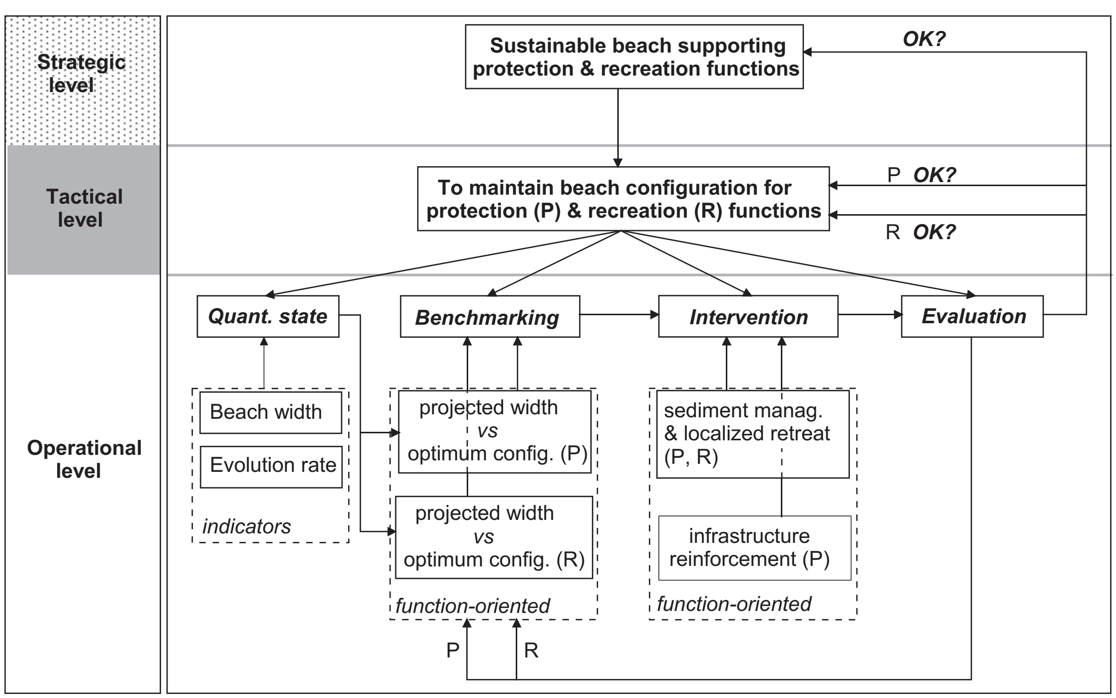

Fig. 9. Application of the Frame-of-Reference for protection- (P) and recreation- (R) oriented beach management.

saturation level (about 4–5 m^2/user in beaches of intensive use, see Roca et al. (2008)). In spite of this, here we establish the optimum beach width from the recreational standpoint, W_{recr}, in 30–35 m which is the value usually accepted for Spanish Mediterranean beaches (MOP, 1970; Yepes, 2002).

4.3.3. Implementation at the operational level

At the operational level, the first step consists in selecting a series of indicators to monitor the state of the beach. These indicators will be used in a benchmarking process by comparing the present beach status against the favourable sediment status to decide when intervening to maintain its functionality. This benchmarking is especially important because, in a coastal management process, there is a time lag between the identification of the need to do something and the doing itself. This lag includes all the time expended in the normal administrative procedure since the problem is identified up to the point when the solution is executed. It can have a duration of up to several years.

For open cell beaches, the selected state indicator is the "projected beach width". This is obtained by projecting the actual beach width (which is measured and updated at least at yearly basis) at time T taking into account the present evolution trend (rate of displacement obtained from shoreline data analysis). The minimum time frame to estimate beach evolution should be equal to that used in the risk analysis for beach protection (1), i.e., the time period of concern, L.

Fig. 10 shows the application of the benchmarking procedure for the protection function to different parts of the s'Abanell beach, which are characterized by a different beach width an evolution rates. Thus, if we just consider the storm-induced beach retreat, ΔW_{Tr}, the south part of the beach will be below the favourable sediment status since year 1, whereas this situation will happen in the central part at year 7 and in the north part at year 19. However, if the favourable sediment status is strictly applied by using the minimum width required for the protection function, $W_{prot}(=1.5\Delta W_{Tr})$, most of the present beach are below the required configuration at present. The only exception will be the north part that will reach this level at year 11. In any case, these results indicate that the present status of the s'Abanell beach, regarding the protection function, is quite delicate and, in consequence, existing infrastructures can be easily exposed to wave action. This is reflected in the present frequent occurrence of damages along the s'Abanell beach as reported in the previous section.

The application of the benchmarking procedure for beach recreation is illustrated in Fig. 11. In this case, instead of dividing the beach in different parts as it was done for protection, we have used an average beach width and user density because if one part of the beach is overcrowded, users would tend to move to other less used areas, i.e., spatial variations in users' density tend to smooth out. In this example, we have used the data on beach use reported by Roca et al. (2008) and the beach–users interaction model proposed by Valdemoro and Jiménez (2006) starting from the summer 2008 configuration. Thus, assuming that beach width changes will be directly transferred to users' density (when the actual width is narrower than the optimum value), the beach will experience a systematic decrease in its carrying capacity, reaching the saturation level (4 m^2/user) by year 8. Because this is an urban beach of intensive use, the favourable sediment status is fixed to a beach configuration supporting a density of use of 5 m^2/user and, this will occur (if evolution trend does not change) in about six years. In any case, obtained results indicate that present evolution is seriously affecting the beach carrying capacity.

4.3.4. Intervention

The main result of the benchmarking process is the identification of the need of intervention (and the moment to actually execute it) in the beach to enhance its functionality in terms of protection and/or recreation. This intervention implies to develop a strategy to maintain the required configuration corresponding to the favourable sediment status according to the type of beach and governing physical process. Although different options exist to cope with erosion, here we illustrate the application of the framework (Fig. 9) solving identified problems by sediment management based techniques. This should allow maintaining the beach functionality without significantly modified beach characteristics.

In the case of open-cell beaches showing an erosive behaviour, the main technique to be used is beach nourishment. Other possible action such as shoreface nourishment should not be an efficient option for the site and problem because we need to instantaneously increase the beach width. The design will be based on the definition of two volumes of sediment to be supplied to the

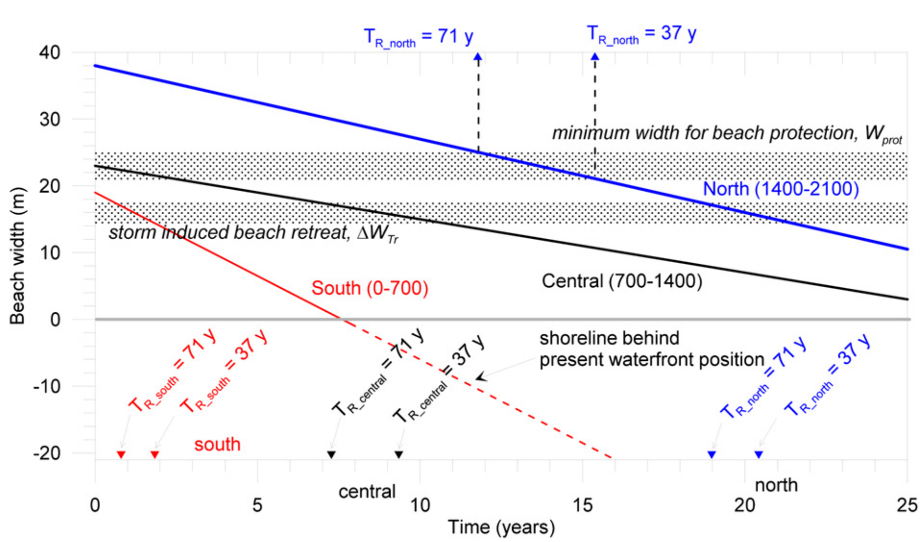

Fig. 10. Benchmarking process for protection in s'Abanell beach. The shown return periods indicate the time when the beach width at each part (south, central, north) will have the same value than the expected storm-induced beach retreat (bottom) and minimum value for beach protection (top).

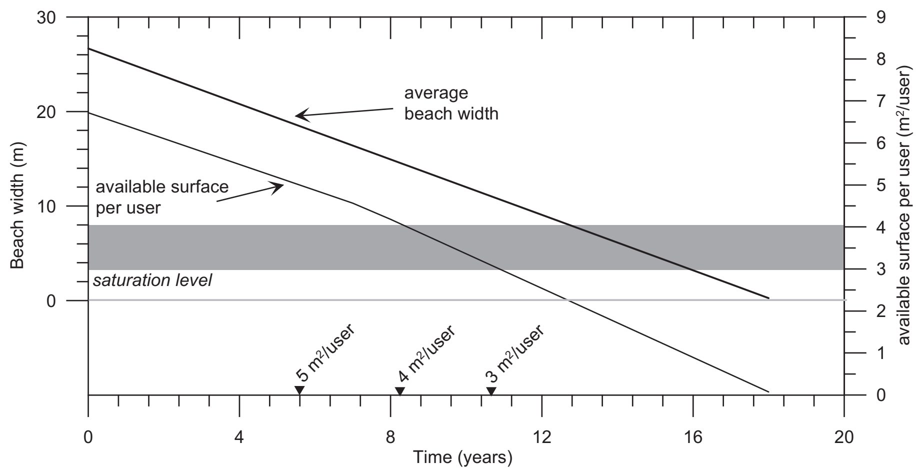

Fig. 11. Benchmarking process for recreation in s'Abanell beach.

beach: (i) the volume required to maintain beach functionality and (ii) the volume required to compensate medium-term losses.

Since the beach is going to be managed to support the two functions, the first task is to evaluate the volume required to maintain each function: (i) volume required to reach the favourable sediment status for protection, V_{prot}, and recreation, V_{recr}. These two volumes will not be the same because the optimal status for each function is different. The volume required to maintain beach functions, V_{func}, will be the maximum of the two volumes, $[V_{func} = \max (V_{prot}, V_{recr})]$.

In addition to this volume, in erosive beaches we have to add a volume of sediment to compensate expected losses, V_{ero}, due to the action of medium-term processes during a given life period, T_{lf}. This period will be selected according to two main criteria: (i) the manager decision about the durability of the solution and, (ii) the yearly variability in the estimated sediment losses. The first one is just a choice and it should be in order of 5–10 years (to avoid re-nourishing very frequently, at the same time maintaining the beach width within reasonable bounds). The influence of the second one will increase for beaches with higher variability. The idea is to compensate "unexpected" losses above the estimated value due to the presence of an energetic year. Thus, if variability is high, it is recommended to select life periods relatively large (in the order of 10). Table 1 shows the calculations done for designing a sediment-based solution for maintaining the s'Abanell beach functionality for protection and recreation. In this case, it has been assumed that the borrowed sediment will be fully compatible with the native one and it will respond to littoral dynamics in the same way as under present conditions. If this is not the case, the estimated volume must be corrected to account for the difference in sediment behaviour.

Table 1
Calculation of required sediment volumes for maintaining the protection and recreation functions at the s'Abanell beach.

Initial average width (2008)	$W_{ini} = 20$ m
Recreational optimum width	$W_{recr} = 35$ m
Storm return period	Tr = 71 years
Storm-induced erosion	$\Delta W_{Tr} = 17$ m
Protection optimum width	$W_{prot} = 25$ m
Averaged sediment loss	$V_{ero} = 30{,}000$ m^3 yr^{-1}
Life period	$T_{lf} = 10$ years
Volume for recreation	$V_{recr} = 375{,}000$ m^3
Volume for protection	$V_{prot} = 192{,}000$ m^3
Volume for beach functionality	$V_{func} = \max(V_{recr}, V_{prot}) = 375{,}000$ m^3
Volume for compensating erosion	$V_{ero} \cdot T_{lf} = 300{,}000$ m^3
Volume for beach nourishment	$V_{tot} = V_{func} + V_{ero} \cdot T_{lf} = 675{,}000$ m^3

In the case of bayed beaches with a closed sediment budget, the intervention should mainly consist in redistributing the existing sediment to re-shape the beach towards that associated with the favourable sediment status. This might be an instantaneous action generally based on the back-passing technique in which the sediment is artificially transported from the deposition area (the widest part of the beach) towards the erosive one (the narrowest part) without implying a variation in the sediment budget.

5. Summary and conclusions

In this paper we have analyzed the applicability of recommendations from the Eurosion project to define a policy to manage coastal erosion, tested at a number of "beach" scales in the Mediterranean coast. To do this, we have defined a favourable sediment status for these beaches taking into account their main functions: recreation and protection. Because these two functions are dominant in two different seasons, i.e., summer and winter, respectively, the favourable sediment status for Mediterranean beaches needs to be seasonally defined.

With respect to the protection function, the favourable sediment status depends on a given safety level, which is fixed by the manager taking into account the importance of existing infrastructures. On the other hand, the recreational favourable sediment status depends on the density of use of the beach that depends on the quality and type of tourism.

The concept has been formalized for beach management through the frame-of-reference in the benchmarking process by using the "projected width" as the main coastal state indicator. This projected width is calculated taking into account the type of sediment cell where the beach is. For open cells, where one of its boundaries can permit variations in the sediment budget, the beach width is projected at a given time horizon by applying the present evolutive trend to the actual width. The manager can act at this level of the management process by defining the time horizon of the projection. This projected width is then compared with the required value to achieve the favourable sediment status for the considered functions in order to detect the need to make any intervention.

For pocket beaches which act as closed sediment cells, the projected width is given by extreme shoreline reorientations within the bay with respect to the average (equilibrium) configuration. These maximum reorientations will represent the largest deviation with respect to the optimum beach state at both ends of the beach, which will locally affect the protection (local exposure of the infrastructures) and the recreation (local affectation of beach services and decreasing carrying capacity) functions.

In spite of the quasi-generalized erosive behaviour of Catalan beaches, the concept of favourable sediment status neither has been used, nor defined in the area. In most of the cases, the implemented management of erosive processes can be classified as purely reactive. Thus, instead of establishing a management process in which the required actions to maintain an operative beach are identified well in advance, they have been taken when problems have appeared. This reactive action has been based on the use of beach nourishment and, due to the lack of long-term policy, no estimations for the long-term sediment requirements have been done.

Due to the dominant recreational use of these beaches, the need of quality sediment is one of the cornerstones of any measure to manage erosion. At the regional level, this implies that a long-term erosion management plan should include the identification of strategic sediment reservoirs. They will be used as borrow sites with sediment of enough quality to be used in nourishment operations located in areas where such operations will not significantly affect the environmental status of surrounding areas.

Finally, it has to be mentioned that although here we have illustrated the management of erosive process by using beach nourishment, the other way to increase the beach resilience to erosion (i.e., by retreating the landward beach limit), could also be applied and, if done, will usually increase the durability of the solution. Thus, although apparently, basic design of beach nourishment is well known (e.g., Dean, 2002), in some cases, the post-nourishment beach behaviour is not the expected one. As an example, the s'Abanell beach has been nourished with about 580,000 m^3 in three operations from November 2007 to September 2009. However, this added sediment volume has disappeared from the beach and, this should be equivalent to a sediment loss of 290,000 m^3/a that is about 9 times the estimated annual average sediment loss.

Acknowledgements

This work has been done in the framework of the Conscience and VuCoMA research projects, funded by the EU (Contract No. 044122 SSPI) and the Spanish Ministry of Science and Innovation (CTM2008-05597/MAR), respectively. The authors would like to thank to Departament de Política Territorial i Obres Públiques of the Government of Catalonia for supplying some of the data used in this study. The authors also thank the two anonymous reviewers for their comments and suggestions on the original manuscript.

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