# Managing coastal erosion: from long-term coastal evolution to seasonal shoreline changes

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**Abstract** Erosion problems along the southern Brazilian coast are evaluated, taking into account the complex interactions of long- and short-term natural processes and socio-economic factors. Coastal evolution during the Holocene are considered, together with shoreline changes in the shorter term, to measure magnitudes of changes relevant to coastal management (using aerial photographs, DGPS mapping and beach profiles). This study focuses on specific sites to illustrate the importance of integrating processes acting at different spatial and temporal scales to define the best management practice to deal with coastal erosion. One of the case studies is the area of Hermenegildo, a small beach village built on top of the dunes, in a flat, low-lying coastal plain. The settlement is experiencing long-term coastal retreat and often is threatened by erosion during storms. As the local government does not have a policy to regulate construction of coastal defences, the Hermenegildo coastline is protected by a range of amateur schemes initiated by individual property owners. Due to a public action filed in 2005, the local government now is obliged by law to map and deal with illegal occupation in dune areas (which are protected by the Federal Constitution), and to establish a plan of coastal uses and regulations. Based on the available data, potential management approaches are evaluated in terms of long-term sustainability, and economic and technical viability.

**Key words** beach erosion; coastal protection; integrated coastal management; GIS; public perception; Brazil

## INTRODUCTION

In times of climate change, sustainable development and Agenda 21, governments worldwide are making efforts to follow the guidelines of international conventions (e.g. the United Nations Framework Convention on Climate Change) and to meet the targets of major international agreements (e.g. Kyoto Protocol, EU Habitats Directive). The rising sea levels, increasing storminess and extreme weather predicted by most climate change models urge coastal managers to adopt integrated coastal management principles, re-evaluate implemented policies and adapt to a changing environment. It is beyond doubt that the increasing public debate on global warming has provoked a considerable advance in scientific knowledge, including monitoring of the natural environment to assess types and rates of change, and their impacts on people's lives. However, the distribution of knowledge is uneven in space and time as few coastal environments have been extensively studied and even fewer locations and/or variables have been the subject of long-term monitoring. Nevertheless, it is expected that governments, policy makers and coastal managers, will consult with coastal scientists to find the best management practices to deal with the expected increase in coastal erosion and flooding. The importance of this task cannot be understated when considering that about 41% of the world's population live within 100 km from the coast and a good part of the world's economy is supported by coastal regions (Martínez *et al*., 2007).

This study focuses on management challenges faced by small coastal communities where scientific data is scarce, specialised expertise is rare, funding is limited, and local authorities are unprepared. Here, one study case from south Brazil is used to analyse potential management practices based on the best scientific knowledge available. Hermenegildo is a beach village built 12 km north of the Brazil–Uruguay border (Fig. 1), at the southern end of the Holocene barrier of the Rio Grande do Sul (RS) coastal plain. It has a permanent population of approx. 500 people. However, due to the number of second homes, the population increases 10 to 15 times in the summer months (Esteves & Santos, 2001). This section of the Holocene barrier has been subjected to long-term retreat, and often beachfront houses are destroyed during storms due to flooding and beach erosion. In the last few decades, property owners have built seawalls and revetments in an attempt to protect their houses (Fig. 2), resulting in 2.5 km of an uneven and discontinuous armoured

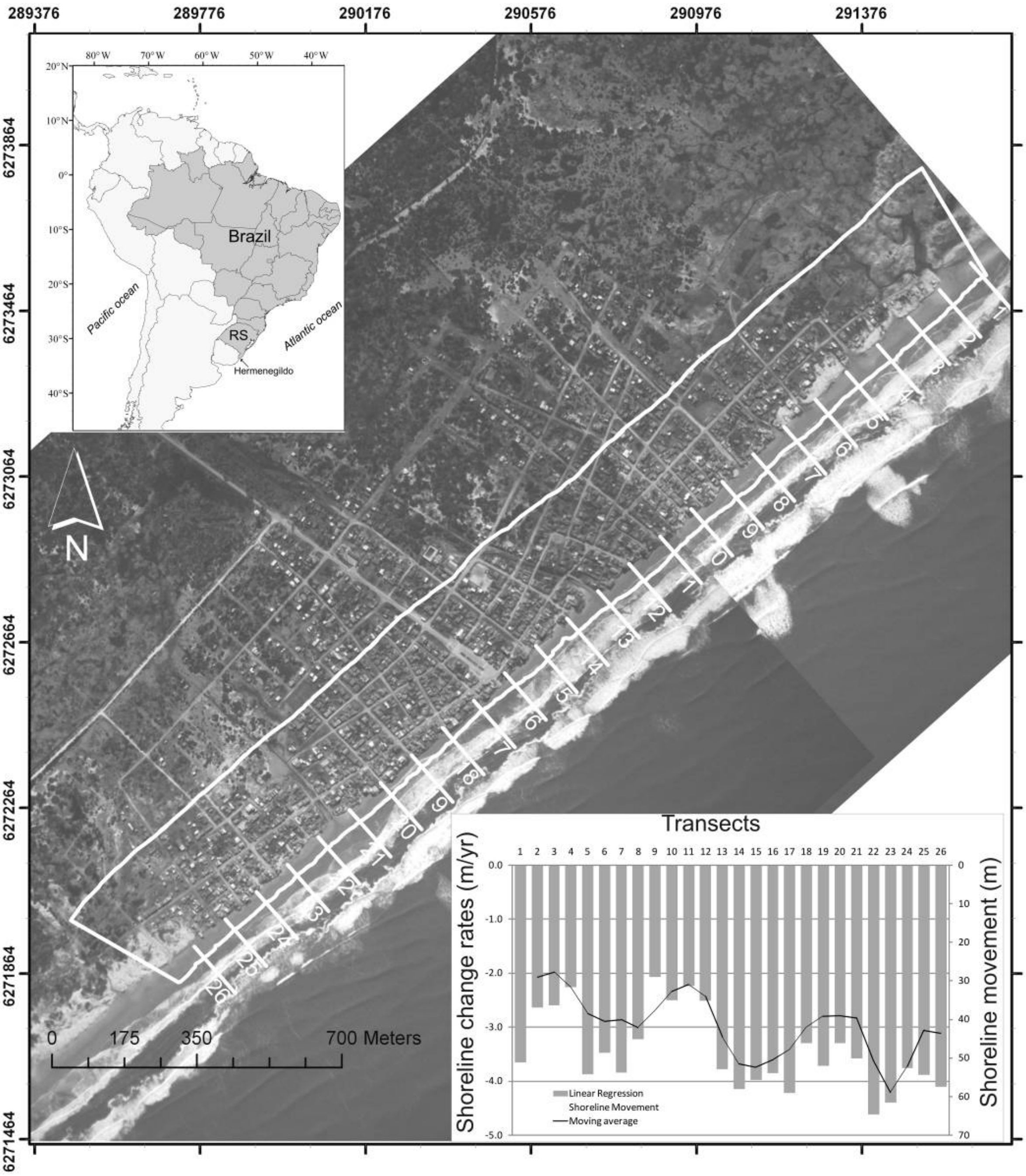


**Fig. 1** Aerial photograph of the study area showing the 26 cross-shore transects (numbered white lines) along which the shoreline change rates were estimated. The rectangular white outline marks the area within 300 m from the shoreline mapped in 2006 and shows the properties which are considered as irregular occupation by federal law. The column graph shows shoreline change rates and total shoreline movement observed for each transect.

shoreline. Local authorities have not been involved in coastal protection efforts, except occasionally with the provision of rocky blocks for repair of seawalls. The economic impacts of erosion include the loss of property and related local taxes, and a devaluation of beachfront properties by up to 80% compared with similar properties located farther from the beach.

DGPS mapping of shoreline positions were collected six times from 1997 to 2006 (Fig. 2) and were used to estimate beach erosion rates for the area of Hermenegildo (Fig. 1). Beachfront properties and existing coastal protection structures were mapped in 1999 (Esteves *et al*., 2000),

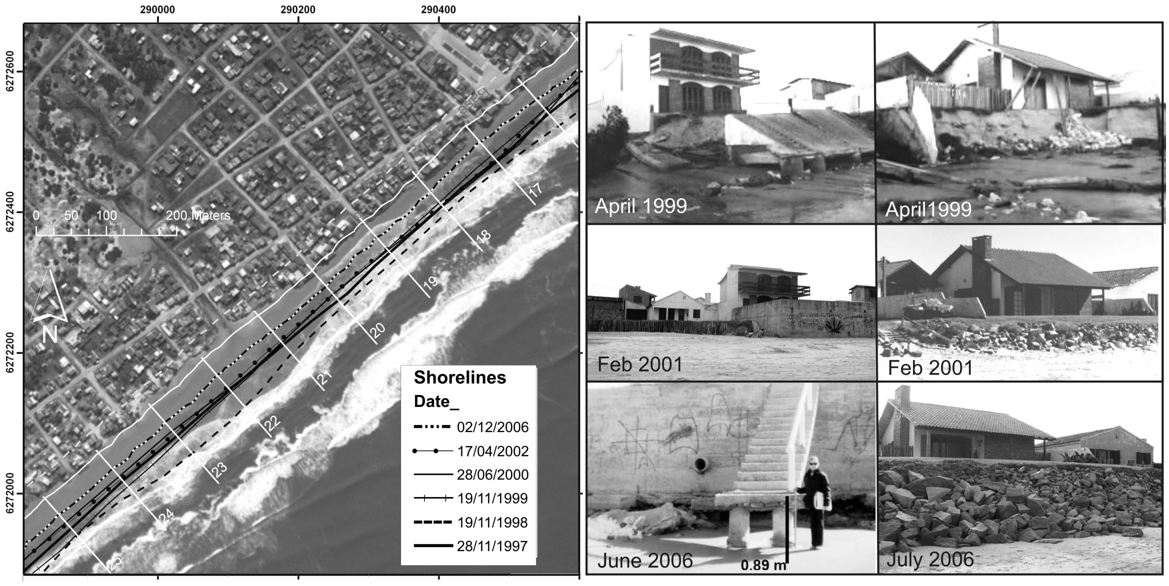


**Fig. 2** Mapped shoreline positions used to calculate shoreline change rates (black lines), cross-shore transects (numbered white lines) and the estimated shoreline positions in 2016 (white line) and 2026 (dashed grey line) are shown for a section of the study area in the left panel. In the right panel, sequences of photographs illustrate the conditions of coastal defences at different dates for two properties located at the northern section of the study area.

2001 (Esteves & Santos, 2001), 2003 and 2005, to assess the impact of storms and evaluate the response of property owners to beach erosion and flooding. Questionnaires were conducted in 2000 (Esteves *et al*., 2000) and 2005 to assess property owners' perceptions towards the effectiveness of existing coastal defences and to estimate their costs. Integrated coastal management principles (as discussed in Duxbury & Dickinson, 2007) are applied to suggest a viable alternative that could be adopted by small communities with limited resources. It is expected that the methods and results presented here can be applied at other locations worldwide facing similar problems.

## METHODS

This study uses long-term coastal evolution, beach erosion rates, evolution of beachfront coastal defences and socio-economic data to evaluate coastal management options that can be implemented to mitigate the impacts of erosion in the area of Hermenegildo, southern Brazil. Data from long-term coastal evolution were compiled from available sources (Tomazelli *et al.*, 1998; Dillenburg *et al.*, 2000, 2004; Esteves *et al.*, 2002). Beach erosion rates were estimated along transects located every 100 m along the 2.5 km urban shoreline of the study site (Fig. 1) using the Digital Shoreline Analysis System 3.2 (Thieler *et al.*, 2005). The erosion rates were calculated by the method of linear regression using shoreline positions mapped by kinematic GPS on 28/11/1997, 19/11/1998, 19/11/1999, 28/06/2000, 17/04/2002 (Esteves *et al*., 2006) and 02/12/2006. The high water line was used as the proxy for the shoreline positions, which were obtained in 2006 by a person carrying a GPS (Ashtech® ProMarc 2) antenna, collecting points every 5 s (post-processed accuracy of 0.5 cm). The other surveys were conducted with the GPS mounted in a vehicle as described in Esteves *et al.* (2006), which also provided estimates of errors due to tide level, wave run up and set up. The evolution of beachfront coastal defences was obtained by mapping the type and conditions of structures existing in each property in 1999 (Esteves *et al*., 2000), 2001 (Esteves & Santos, 2001), 2003 and 2005 (Table 1). Estimates of coastal protection costs were obtained through questionnaires given to beachfront property owners in 2001 (Esteves & Santos, 2001) and 2005. The economic impacts of beach erosion were assessed through interviews with real estate agencies and by analysis of data on tax revenue from the local government.

## RESULTS AND DISCUSSION

First, this section will present data characterising coastal changes in long and short time scales, including sea level fluctuations, geological settings and shoreline change rates. Second, the impact of beach erosion on the local economy will be discussed in terms of existing coastal defences, their estimated costs, depreciation of beachfront properties, and loss of property and related local taxes. Finally, alternative coastal management mechanisms are analysed based on the physical and socio-economic characteristics of the local area and the limitations of scientific knowledge, technical expertise and funding.

### Coastal changes in the long and short term

Hermenegildo is located at the ocean margin of a low-lying, flat coastal plain formed and shaped by sea level fluctuations during the Quaternary (Tomazelli *et al*., 1998). At the maximum of the last post-glacial transgression (around 5 ka), sea level was 2–4 m above the present level on the coast of Rio Grande do Sul, forming the most recent coastal barrier of this coastal plain (e.g. Dillenburg *et al*., 2004). Sea level curves established for the southern coast of Brazil indicate a sea level fall of 0.4–0.8 mm/year in the last 5 ka (Angulo *et al*., 1999, 2005). Modelling results obtained by Dillenburg *et al*. (2000) indicate that at that time the shape of the coastline was similar to the present, with two large-scale coastal projections and two embayments. As a result of an alongshore gradient of wave energy, dissipation of wave energy at the embayments promoted coastal progradation, while concentration of wave energy was causing retreat along the southern section of coastal projections (Dillenburg *et al*., 2000, 2004). Hermenegildo is located in the southern section of one of the large-scale coastal projections and has been subject to long-term erosion. Exhumation of peat and lagoonal muds at the base of the dunes and upper beach is evidence of this long-term retreat (Tomazelli *et al*., 1998; Dillenburg *et al*., 2004). These lagoonal muds have been $^{14}C$ dated as 4.33 ka (Tomazelli *et al*., 1998), indicating that, despite a slow sea-level fall in the last 5 ka, the Holocene barrier that provided the protected environment for the lagoonal muds to accumulate, has retreated to a position landward of its original inland margin. Dillenburg *et al*. (2004) examined the hypothesis that a rising sea level in the last 2 ka has caused the observed barrier retreat (see Tomazelli *et al*., 1998) and concluded that there is no evidence to support it. The authors suggest that a long-term sediment deficit exists as a result of: (a) the retention of inland sediment sources by the large Patos-Mirim lagoon system impeding new sediment supply reaching the coast in the last 5 ka; and (b) the concentration of wave energy along the southern section of the large coastal projections.

Studies focusing on shoreline changes at different time-scales and different processes have identified erosion in the area of Hermenegildo (e.g. Calliari *et al*., 1998a; Esteves *et al*., 2000, 2002; Dillenburg *et al*., 2004). Generally, the most intense erosive events are associated with the passage of extra-tropical cyclones, which have average wind velocities of about 75 km/h and generate storm surges reaching levels around 1 m above mean sea level. Recent records indicate that storms resulting in intense erosion and destruction of properties have impacted Hermenegildo once every two years, usually in April when the first storms of autumn strike the coast. Beach profile measurements in Hermenegildo showed that the storms on 14 July 1993 (Calliari *et al*., 1998b) and 16 April 1999 (Esteves *et al*., 2000) caused subaerial beach erosion of up to 60 $m^3$/m and 45 $m^3$/m, respectively. During storms the beach level is lowered, exposing foundations of houses and destroying weak coastal defences (Fig. 2). Existing beach profile surveys show that the beach level in front of the seawalls and revetments is generally 1 m lower and only half of the width of the beach in the northernmost section of Hermenegildo, where frontal dunes have not been removed. Average rates of shoreline change calculated for the period between 1997 and 2006 using the linear regression method show that Hermenegildo beach is eroding at 3.4 m/year. Shoreline change rates and the total shoreline movement were calculated for beach transects spaced at 100-m intervals alongshore (Fig. 1). The shoreline mobility was determined by the distance between the closest and farthest shoreline position mapped along each transect. Here the average shoreline mobility was 41 m, with minimum and maximum values of 26 m and 59 m, respectively. Areas showing higher erosion rates (above 3 m/year) are associated with greater shoreline mobility (correlation factor 0.83). This is an important factor as the shoreline mobility gives an idea of magnitudes of shoreline change in the shorter term, and helps identification of the properties most vulnerable to erosion and flooding during storms. It is also evident from Fig. 1 that shoreline mobility and erosion rates are lower in the northern half of the study area and increases in the southern half. The average values of erosion rate and shoreline mobility are 2.9 m/year and 35 m, respectively, for the northern area (transects 1 to 12) and 3.9 m/year and 47 m for the southern area (transects 13 to 26).

## Impacts of beach erosion on the local economy

Although the shoreline in Hermenegildo is dominated by a variety of armouring structures, these are built by individual property owners, without any project design or expert guidance (Esteves *et al.*, 2000). Filter layers and foundations are non-existent or inadequate, often resulting in the collapse of the structures when the beach level is lowered during storms (Fig. 2). Therefore, it is not surprising that the storms of April 1999 destroyed 20% of the beachfront houses and 65% of existing coastal protection structures (Esteves *et al.*, 2000). Table 1 presents the total number of beachfront properties with and without coastal defences, mapped at different times. The surveys in February and April 1999 reflect the impact of the storm of April 1999. Results from 81 interviews conducted in February 2001 with beachfront owners showed that the average spending per property with coastal armouring was US$2203 (Esteves & Santos, 2001), with some property owners spending more than US$25 000. Using the average value spent with shoreline armouring per property (average of 10-m width), the total cost to armour the 2.5 km shoreline at the present level would be over US$550 000. The same study identified that the cost of materials to build a rocky revetment varied from US$1500 to 4000 (depending on the rock size), a timber seawall varied from US$100 to 1000 (depending on the wood quality), and sand to restore the lost land varied from US$500 to 1250. After the damage caused by storms, property owners upgrade their coastal defences in type and size (Fig. 2), with seawalls becoming more popular than revetments after February 2001 (Table 1). The 2005 survey also showed that seven properties have adopted an "innovative idea" from one of the residents, who believes that a series of wooden poles in a zigzag arrangement would dissipate the wave energy and reduce erosion.

**Table 1** Number of protected and unprotected beachfront properties in Hermenegildo beach by type of coastal protection.

| Type of structure | Feb. 1999 | April 1999 | Feb. 2001 | Dec. 2003 | Dec. 2005 |
|---|---|---|---|---|---|
| None | 43 | 65 | 51 | 72 | 65 |
| Revetment | 33 | 16 | 27 | 20 | 19 |
| Seawall | 20 | 2 | 22 | 33 | 28 |
| Seawall and revetment | 14 | 5 | 23 | 14 | 20 |
| Wooden poles | 0 | 0 | 0 | 0 | 7 |
| Number of properties | 110 | 88 | 123 | 139 | 139 |

The frequent destruction of properties during storms has impacted the real estate market, increasing the number of properties for sale, reducing their market value and changing the profile of the beachfront property owners. Esteves & Santos (2001) explain that usually 20% of the beachfront properties are for sale at any time, they take more than one year to sell, and have a depreciation of 50 to 80% of their real value. While the old owners buy properties farther away from the beach or at a nearby beach village (Barra do Chuí), often the new owners come from Uruguay and are attracted by the low prices (perhaps not realising the high maintenance cost caused by the flooding and erosion). Based on the information provided by 44 of the 78 beachfront owners interviewed in December 2005, the average value of the beachfront properties is about US$15 350. Multiplying the average value by the number of existing beachfront properties in 2005 (139), it is estimated that the value of private properties at risk (not including house contents) is about US$2.13 million. Considering a storm impact similar to the experienced in April 1999, when 20% of the beachfront houses were destroyed, and only half of the revetments and 10% of the seawalls were not compromised, the estimated damage would be around US$414 450 in destruction of houses, US$36 000 in destruction of revetments, US$24 000 in destruction of seawalls and US$87 500 in loss of sand (if half of the properties restored the lost land area). The estimated total damage to private property is over US$560 000, similar to the estimated cost to armour the 2.5 km at the present level. However, protection at the present level is obviously inadequate and upgrading the coastal defences to withstand typical storm impacts would considerably increase the estimated cost. For example, using the costs and dimensions of the seawall shown in Fig. 2, it would cost over US$3.12 million to protect the 2.5-km shoreline, along which the beachfront properties have an estimated value of US$2.13 million.

The local government does not conduct surveys to update information on the area of land lots or modifications to the type and size of building. Therefore, when a house is destroyed or erosion reduces the size of the land lot, property owners have to inform the local authorities and request a re-evaluation of the local tax charges. Although construction permits must be obtained for new buildings, property owners often initiate their building works without requesting the permit. Property owners who do not inform local authorities about changes to their property are either liable to pay penalty charges (if they do not obtain permits to build or upgrade their properties) or a higher rate of local tax (if they do not request a re-evaluation of their property size or type). As a consequence, the local government does not have an updated record of the beachfront properties and there is a growing debt of local taxes, which was around US$64 500 for the registered properties in 2005. Although there are 139 beachfront properties on record, the local authorities have 111 as occupied properties, while this study identified 128 occupied properties. Due to the number of irregular properties built in protected areas (such as dunes), local authorities had to sign an agreement with the federal government in June 2005 committing themselves to: (a) resolve irregularities and impede or remove constructions in the area defined by a 300-m setback from the high spring tide line (area which is protected by the federal constitution); (b) to establish a land use and occupation plan for the area which has to be approved by the relevant environmental agency and has to include zones of specific use; and (c) to map and protect areas of environmental or ecological importance according to government regulations. The local government should have finished all the tasks listed in the agreement by the end of 2006. However, this still had not been achieved by April 2008, to the authors' knowledge. The restructuring and ecological-economic plan of the local government includes four themes with several related projects. For the area of Hermenegildo, four projects are listed that mainly consider the aesthetic improvement of public areas, including: (a) restoring and maintaining the natural drainage across the dunes into the sea, creating a "green pedestrian route" along the margins of three major creeks; (b) the creation of a green park; (c) the improvement of the main access road; and (d) the construction of an architectonic gate signalling the access to Hermenegildo. None of these proposed initiatives addresses the erosion problem or the irregular occupation in protected areas.

## Coastal management options

It is evident from the data presented here that no integrated coastal management of any form has been implemented or planned for Hermenegildo. Individual efforts of property owners are only postponing the inevitable loss of the threatened properties, which in the longer term will result in the piecemeal abandonment of properties. The present situation does not conform to Agenda 21 ideas and does not follow the principles for the sustainable management of the coastal zones, i.e. sustainability, adaptive management, participation and integration (Duxbury & Dickinson, 2007). Therefore there is no solution to Hermenegildo's erosion problem other than engaging the local government, residents and stakeholders in the design and implementation of an integrated management plan aiming to address the impacts of beach erosion and reduce the occupation of risk areas in the medium to long term. However, the narrow beach, the high erosion rates and the relatively low value of properties considerably limit the management options which could be technically and economically feasible for Hermenegildo.

Often, strong southerly winds push the shoreline to the base of the seawalls and revetments. If not properly built and maintained, such structures are not designed to withstand constant wave action and high water levels. Figure 2 shows a forecast for the position of the shoreline in 2016 and 2026, estimated using the position of the shoreline mapped in 2006 as a baseline and a constant average erosion rate of 3 m/year, which is close to the present average erosion rate in Hermenegildo (3.44 m/year). It is likely that in 2016, the shoreline position will be directly in front of the seawalls and revetments, leaving no adjacent dry beach if the present line of defences is maintained. In 2026, the shoreline would be landward of the beachfront properties along the entire beach, and behind the present location of the first block of houses in the central section (Fig. 2). Therefore, even if a seawall is built today along the entire shoreline of Hermenegildo, in less than one decade there will be no adjacent beach if erosion proceeds at the present rate. Having a second home in Hermenegildo will no longer be attractive and most owners will probably sell their property and spend summer somewhere else. This will increase the number of houses on the market, aggravating the existing depreciation of properties value and increasing the deficit in local tax revenue. Furthermore, the remaining residents will face spiralling costs just to maintain defences in front of a narrowing beach. Although desirable in some aspects, the building of a 2.5-km long seawall might not be economically feasible in Hermenegildo. As estimated in the previous section, the cost of such a construction is higher than the value of the assets at risk and is about four times higher than the cost of present armouring. Costs of other coastal defence options (such as beach nourishment, groynes, breakwaters, etc.) would also significantly exceed the values to be protected and would face constraints due to the lack of relevant data (wave climate, sediment transport rates, detailed bathymetry, etc.) and funding for project design, construction, monitoring and maintenance.

It is considered that the most sustainable option is a “planned retreat” policy supported by a series of regulations aiming to reduce the number of properties at risk. In essence, such a policy attends to the request from the federal government that local authorities deal with the irregular occupation in areas protected by the federal constitution. However, Fig. 1 shows that more than half of the urban area of Hermenegildo is within 300 m of the high spring tide level. Even considering the small size of the village, removing or relocating all those properties is not a viable management option. Nevertheless, in the new zoning plans, the local authorities should have included some restrictions on construction to reduce the number of properties at risk in the medium- to long-term. For example, reconstruction of beachfront properties destroyed by flooding or erosion should not be allowed, and removal of the remains of coastal defences and other constructions should be enforced. Strict control and regulation of the type and size of constructions should exist for areas at risk of erosion in the next 20 years (i.e. seaward of the shoreline position predicted for 2026, illustrated in Fig. 2). Other areas at risk of erosion in the longer term (e.g. 30 or 60 years time) should also be subject to coastal construction control lines, such as the ones established in Florida (Bush *et al*., 2004). Properties located in these areas could receive specific government grants or subsidies if relocated to “safe zones” before being damaged by erosion or flooding, or in imminent threat of collapse. A similar provision is given by the Upton-Jones Amendment in the USA (National Research Council, 1990). Safe zones could include new developments, promoted by the government or other funding sources, created in areas further inland (e.g. more than 500 m landward from the highest water level ever observed in the area), preferably at the northern section of Hermenegildo where slower erosion rates have been measured. In addition to the mechanisms suggested, a setback line should be established for the areas not yet occupied south and north of Hermenegildo, using either a conservative distance from the high water line (e.g. 500 m) or the position of the shoreline in 150 years (based on average erosion rates). These are examples of regulations and control mechanisms that could be adopted by local authorities to reduce the number of properties at risk.

A “planned retreat strategy” could be implemented as part of an integrated management plan, which would also have to include provisions for the continuous monitoring of the physical environment (shoreline change rates, beach profiles, etc.), the evaluation of socio-economic impacts of the policy, and establishing funding mechanisms to support policy actions. All the data presented in this article were obtained by undergraduate and postgraduate students under academic supervision without specific funding. Therefore, although the ideal situation is to have a permanent fund for monitoring studies (including the physical and socio-economic surveys), it is possible to obtain relevant data with certain regularity through partnerships with university departments. Costs to design and implement an integrated management plan could be shared by the local community and government agencies at local, state and federal levels. Results from questionnaires show that more than 60% of the beachfront owners are willing to pay an extra tax (up to 10% of their local tax) to support a management plan designed and implemented in partnership with the local government.

## CONCLUSIONS

Usually, lack of funding and limited technical expertise are major constraints for the implementation of integrated coastal management by local authorities in small communities. The case study presented here shows that beach erosion affects the local economy and isolated efforts from residents are not sufficient or adequate to mitigate its impacts. Partnerships between the local community, local government and universities can provide the mechanisms to support the design and implementation of management plans and overcome the constraints imposed by limited resources. The methods of, and results from this study can be applied to other small communities subjected to coastal erosion and restricted by the lack of funding, knowledge and technical expertise.

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