APPLICATION OF INDEXES FOR THE INTELLIGENT MANAGEMENT OF SEDIMENT ON BEACHES IN BARCELONA

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INTRODUCTION

Coastal erosion has intensified in recent decades due, among other factors, to increased human activities in coastal areas (eurosion.org). In urban areas, one of the most common techniques to protect coastal erosion is the construction of artificial beaches protected by ports and groins that minimize the effect of waves during storms, but limit the longitudinal transport of sediments by reducing their mobility (Ojeda et al., 2008). Therefore, it is necessary to have a broad knowledge of the dynamics and the balance profile of these beaches, through the development of indicators of the coastal state. These indices are determined in physical and environmental variables such as the width of the beach, the significant height of the waves or the slope of the beach (Serafum et al., 2019). Using these parameters, we can describe in a simple and quantitative way the evolutionary trends and the dynamic state of a coastal system, since they are still artificially necessary due to the lack of contributions of natural sediments (Davidson et al., 2007).

Digital technology has enabled continuous, higher frequency images of the shoreline to be obtained. The monitoring of the coast through the use of an video monitoring station is one of the tools used to quantify the evolution of a beach, since the nearshore is full of visible marks that can be captured by cameras (Holman et al., 2007). The coast is defined as the interface between water and land in a given period of time. In practice, this coastline varies constantly and is difficult to measure accurately (Bowman et al., 2009). Video monitoring systems allow a large volume of coastal data to be collected and studies to be conducted over short or long periods, allowing a broad understanding of coastal areas (Boak et al., 2005).

White (1974) defined vulnerability as the degree to which a system, subsystem, or system component is likely to be damaged by exposure to a hazard. This work gives a quick and low-cost approach to assessing the vulnerability of the La Barceloneta and Somorrostro beaches located at the Barcelona city, analyzing a large set of data on the positions of the shorelines automatically extracted from video images on these beaches. The final objective is to define indexes based on large volumes of data that allow the generation of simple parameters that inform about the current status, allow to determine the areas of greatest vulnerability on the beach, and enable to prioritize future management actions.

Study zone

The city of Barcelona is located in the NW of the Mediterranean Sea. It borders to the south with the Llobregat river and to the north with the Besós river (figure 1). The present

Barceloneta). The slope is approximately 0.09 and has an average orientation of 30º with respect to the north. The sediment has an average median diameter between 0.27 and 0.88 mm (Green Book Cataluña_Ficha Playa Barceloneta). Persistent erosion problems in the central area of the old beach caused the construction in 2006-2007 of a breakwater and an associated tombolo that divided the beach into two sections, Barceloneta to the north and Sant Sebastiá-Sant Miquel to the south. Subsequent studies showed that the new configuration of the beach did not totally solve the erosive problems of the beach (Sancho, 2013) (figure 2).

Somorrostro beach limits to the north with the Olympic Port and to the south with Barceloneta beach. It has an approximate length of 450 m and an average slope of 0.035. The average grain size d50 is 0.45 mm and its orientation is approximately 38º with respect to the north (Turki, 2012) (Figure 2).

Figure 2: Current situation of the beaches South of the city of Barcelona. Source: googleEarth

DATA AND METHODS

The coastal video monitoring system of the city of Barcelona is made up of 6 cameras (in this study we will only use camera 1 (C1)) located at the top of the Mapfre building, opposite the Olympic Port (Figure 3 a). This situation allows a panoramic view of the beaches of La Barceloneta, Somorrostro, Bogatell, Nova Icària and the Olympic Port (the beaches of Sant Sebastiá, Mar Bella and Nova Mar Bella have a lower resolution) (Figure 3 b) (https : //coo.icm.csic.es/es/service/video-monitorizaci%C3%B3n) (Figure 3 c). The system consists of 2 parts: the first part, called “Sirena Station”, is a software that processes digital images and obtains statistical data that it stores and sends in real time to a remote station via the Internet. The second part, called "Sirena Network Sistem" is a configuration of Barcelona's beaches are of anthropogenic origin and were created within the city's Renovation Plan for the 1992 Olympic Games. They are beaches with little longitudinal variability, with a narrow and steep beach front. They end up on a beach step. They are limited by breakwaters and dykes and have the typical shape of embayed beaches. They are a highly dynamic coastal system with a small tidal range (approximately 20 cm) and with a low energy wave regime subjected to a temperate climate most of the time (Guillén et al., 2009). The mean values of significant height (Hs) is around 0.7 m with maximum mean values of 4 m (Gómez et al., 2005). Storms are the main hydrodynamic factor of beach dynamics and, due to their orientation, the most important come from the East (Levante) during the period between October and April. They last approximately 1 to 2 days and are often associated with cyclonic activity in the Mediterranean (Ojeda et al., 2008). Due to the absence of contributions of natural sediments to the beaches of Barcelona, in 1992, 2002, 2006, 2009 and 2010, several beach nourishment works were carried out to try to solve the erosive processes that affect its coast (Mollier, 2017)

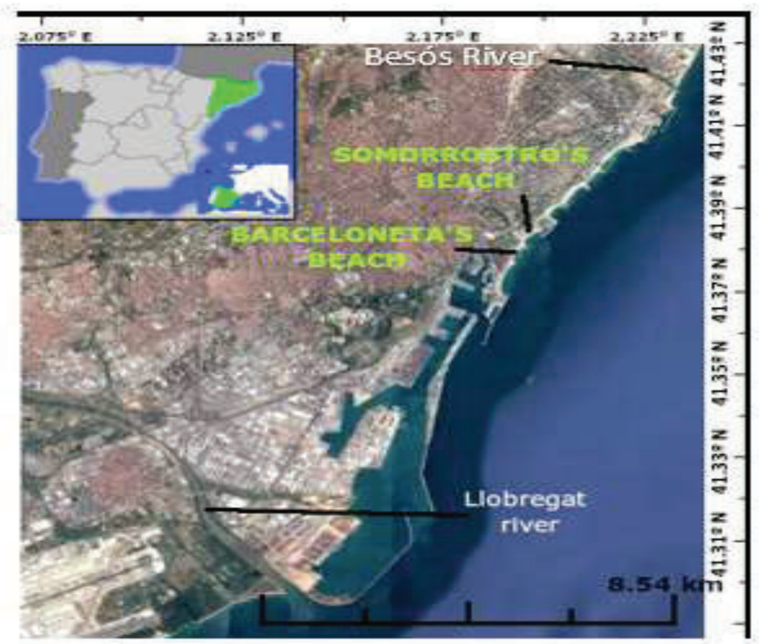

Figure 1. Top right, situation Spain in Europe. Red dot, situation Barcelona in Spain. Situation study area in Barcelona. Source. Google Earth

The Barceloneta beach is delimited by the south with the Sant Miquel beach and by the double Somorrostro dyke in the north. It has an approximate length of 440 m and an average width between 30 and 74 m (https://www.barcelona.cat/es/que-hacer-en-bcn/banos-y -playas / historia-de-las- beaches) (Green Book Cataluña_Ficha Playa software that is responsible for the post-processing of images. It is a free open source software, written in Java language and compatible with UNIX (Nieto et al., 2010)

Figure 3. a) Torre Mapfre situation, study area and profiles beaches (hemos calculado perfiles cada 0.5 m, pero por razones visuales, graficamos solo 8 perfiles por playa). b) Panoramic view. On the right, study area. c) One of the video monitoring cameras located in the Mapfre tower

Typically video monitoring stations are connected to a LINUX (UNIX) computer and collect three imaging products every hour. A product consists of a single snapshot at the beginning of each hour, to calibrate the camera and obtain useful data (Figure 4. a). The second product is time exposure images (timex), they are compilations per hour that represent the time average of the light intensities of the images of all the pixels collected during 10 minutes. This enables the area of the breakwater to be delineated and coastal lines, shoals, etc. to be detected. (figure 4.b). The product of the third image is the image of variance (var), where the standard deviation of the intensity of light in each pixel is calculated (figure 4.c) (Holman et al, 2007). Once the images are obtained, the open source software ULISES (complement to the SIRENA software) is used, which, as a novelty, uses the horizon line for the calibration process, avoiding that the user has to provide some initial guess (Simarro et al., 2017). Finally, an automatic extraction based on the variance images is applied, allowing the analysis of the entire field of vision (Simarro et al., 2015). To carry out this study, data was collected on the position of the coast of the beaches of La Barceloneta and Somorrostro during the period from December

1, 2016 to November 30, 2018. In this way, a database of 8568 and 8519 coastlines for La Barceloneta and Somorrostro respectively, was obtained.

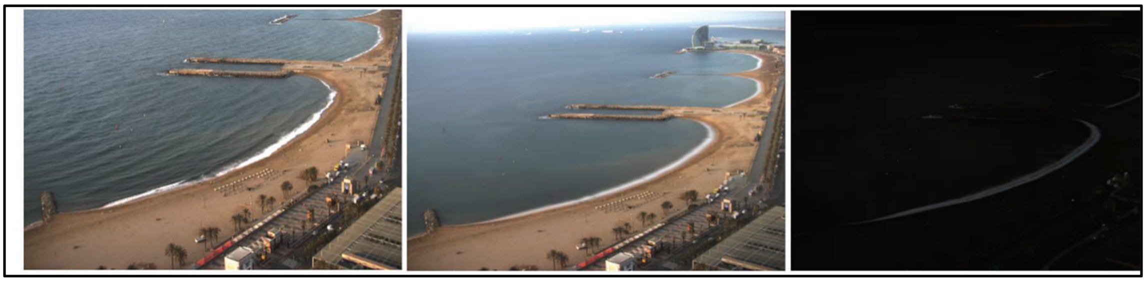

Figure 4. a. First image product (snap). b. Second image product (Timex). c. Third image product. Source http//coo.csic

Quality control and data processing

Automatic shoreline extraction should be processed to eliminate possible methodological errors during its collection, mainly related to image quality, georeferencing problems, weather conditions, etc. (figure 5). The MatLab language was used for this post-processing. Outliers were first identified in time and spatial series (isoutlier matlab) and replaced by linear interpolation of neighboring non-isolated values. Subsequently, part of the data is removed from both ends of the beach, as they generally have significant errors that are very difficult to correct. Later, each coastline is fit to a degree 5 polynomial curve, using the least squares method in the data corresponding to the "y" axis (polyfit matlab). Then, once the most significant erroneous data is removed, an interpolation is performed to fit each position of "y" to fixed positions (each meter) of "x" and, therefore, it is possible to evaluate the displacements of the line coastal in each profile along the entire beach (interp1 matlab).

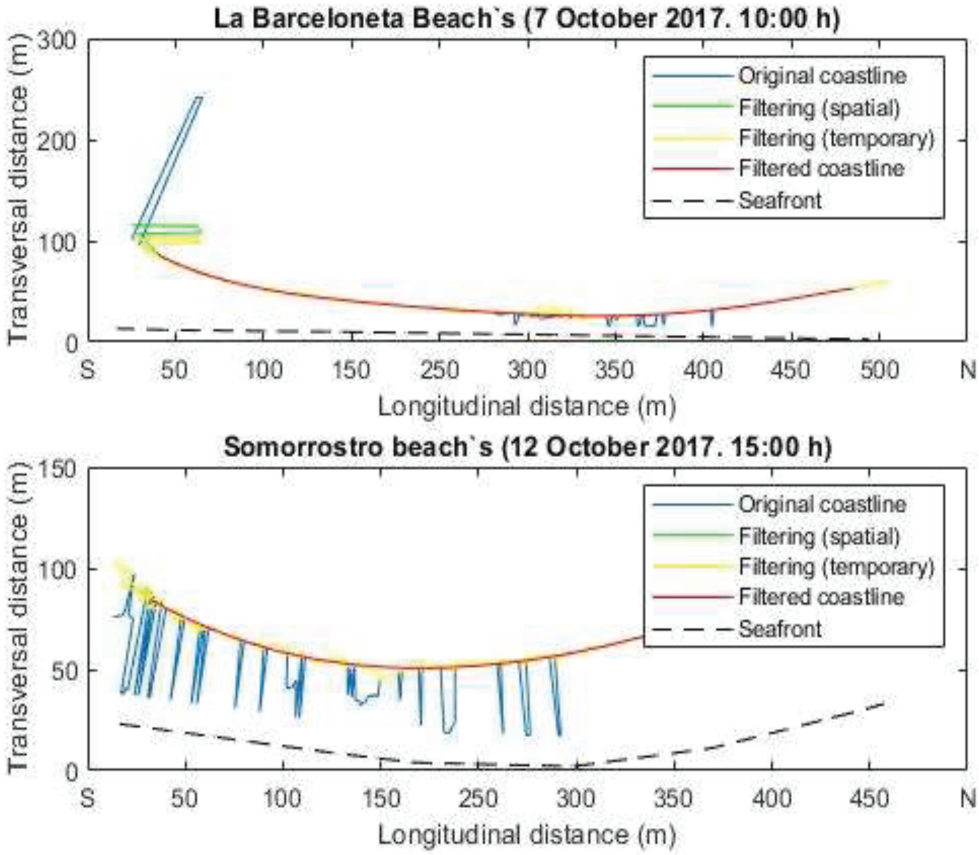

Figure 5. The results of the different filtrations applied to the original coastline are observed

A baseline shoreline was estimated as the mean of the shoreline position during the study period. A total of 752 (in the case of Barceloneta beach) and 630 (in the case of Somorrostro beach) profiles were defined every 0.5 m, perpendicular to the reference shoreline and cutting with the inner land limit (promenade) (figure 3a). The annual trend of each profile is calculated (erosion or accretion).

The emerged beach area is defined as the surface delimited by the shoreline and the hard structures at the back and side of the beaches (breakwater, promenade) using the polyarea function of matlab. To study the evolution of the area emerged from the beach during the study period, outliers (isoutlier matlab) were removed and a moving average filter (movemean) with a window of 9 was applied (because the coastline was obtained approximately 9 times per day). The width of the beach is related to the area emerged from the beach, and to measure it, the existing distance in each profile is calculated between the coastline and the internal limit of the beach (promenade) during a certain period of time (polyxpoly matlab). The minimum beach width index was calculated by measuring the amount of time (during the study period) as a percentage in which the width of the beach was minimum enough so that the daily activities of the area are not affected (less than 25 m in the case of La Barceloneta and 40 m in the Somorrostro beach).

The shoreline mobility index is defined as the standard deviation of the distance between the previously calculated mean shoreline and the boardwalk. The mobility of the beach indicates the sectors in which the position of the coast varies the most and, therefore, in which the width of the beach changes the most. Previous studies indicate that vulnerability is greater when beaches show a smaller beach width (Serafum et al., 2019).

Wave data

The wave data were obtained from the Barcelona II buoy (www.puertos.es/es-es/oceanografia/Paginas/portus.aspx) provided by Puertos del Estado, REDCOS coastal buoy network, BOYA 1731, until 05/31/2018, and it were directly collected from the website from that date until the end of the study. In the month of September there are no data from the Buoy II Barcelona, but analyzing the images and the monthly historical data of the point SIMAR712018020, it is observed that the average maximum height during the month of September 2018 is 2.33 m and an average direction of the swell of 77º. In the images provided by the cameras, a slightly significant storm event is observed as of 09/24/2018 (Event A. Table 1.)

The most relevant storms that affected the coast of Barcelona during the study period were subjectively defined by an Hs greater than or equal to 2 m during the peak of the storm, an Hs threshold of 1.5 m to estimate the duration, and a minimum duration of 12 h. The height of the waves can be below the threshold for less than 6 h during the same event. The wave directions that must be taken into account are those between approximately 65º and 130ºN, since they are the most influential due to the orientation of the coast (Table 1).

Event	Date	Hs average (m)	Hs max (m)	Direction	Duration (h)
1	16/12/16	2.27	3.7	92.9	150
2	16/01/17	2.7	3.6	91.1	139
3	11/02/17	2.1	3.43	107.4	87
4	04/03/17	1.7	2.6	189	13
5	24/03/17	1.2	2	154	45
6	19/04/17	1.5	2.4	78.3	30
7	02/12/17	1.6	2.3	82.7	25
8	10/12/17	1.8	2.8	181	45
9	28/02/18	2.6	3.9	96.7	29
10	24/03/18	1.7	2.8	103	29
11	07/04/18	1.8	2.6	169	110

A	24/09/18	-	2.33*	77*	**
12	30/10/18	1.9	3	186.5	46
13	30/10/18	1.9	3	186.5	47
14	18/11/18	1.6	2.5	129.2	70

Table 1. Storm events which took place in Barcelona during the study time and their magnitude * Data which corresponds to the average of the month of September 2018 ** Approximate duration (the data was obtained from the video surveillance images and the model SIMAR712018020)

RESULTS

Shoreline trends

During the study period, a general retreat of the coastline is observed at the two beaches. La Barceloneta beach showed an average decline trend of -1.06 m / year and Somorrostro beach of -0.66 m / year. However, different trends were observed along the two beaches during the study time: at La Barceloneta beach, the trend of the profiles located to the north (around profile 6) is -0.1 m / year, while that the profiles located to the south (around profile 3) show trend values of -2.3 m / year. On the Somorrostro beach, in the most northerly profiles (around profile 14) average trend values of -1.04 m / year are observed, while the profiles located south of the beach (between profiles 9-10) have an average trend of -0.33 m / year (Figure 7).

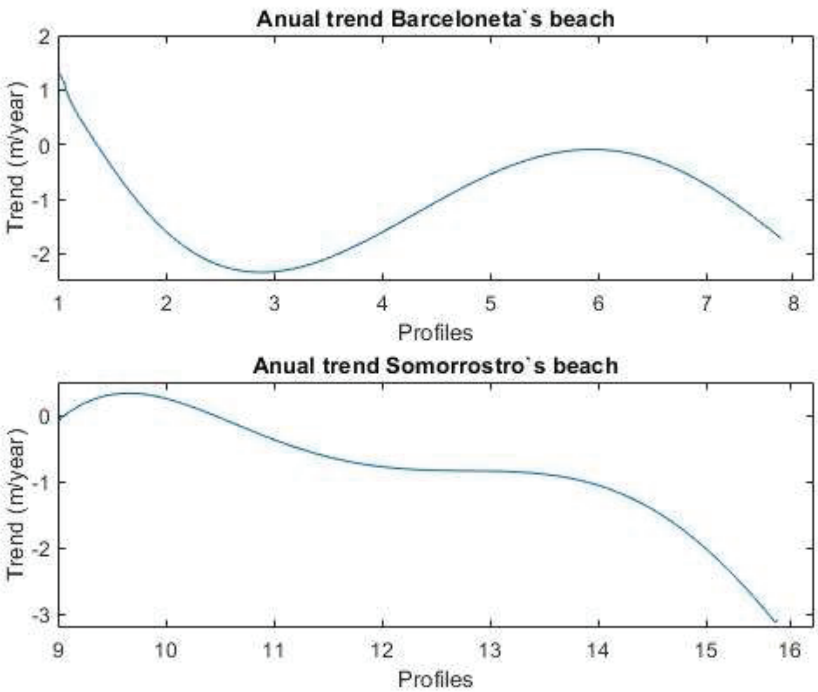

Figure 7. Annual trend of the coast along the beaches of La Barceloneta and Somorrostro

Emerged beach area

The emerged area of both beaches showed great variability, but even so, a seasonal pattern can be recognized (Figure 7). The beaches of La Barceloneta and Somorrostro showed an erosive trend throughout the study period of -359.75 m2 / year and -405.69 m2 / year respectively. Local minima occurred on both beaches in winter (January - March 2017, January - April 2018) and September 2018 until the end of the study period. Local maximums were also observed in the two beaches between April and August 2017 and May and July 2018. This seasonality is better observed in Somorrostro beach than in La Barceloneta beach (figure 8).

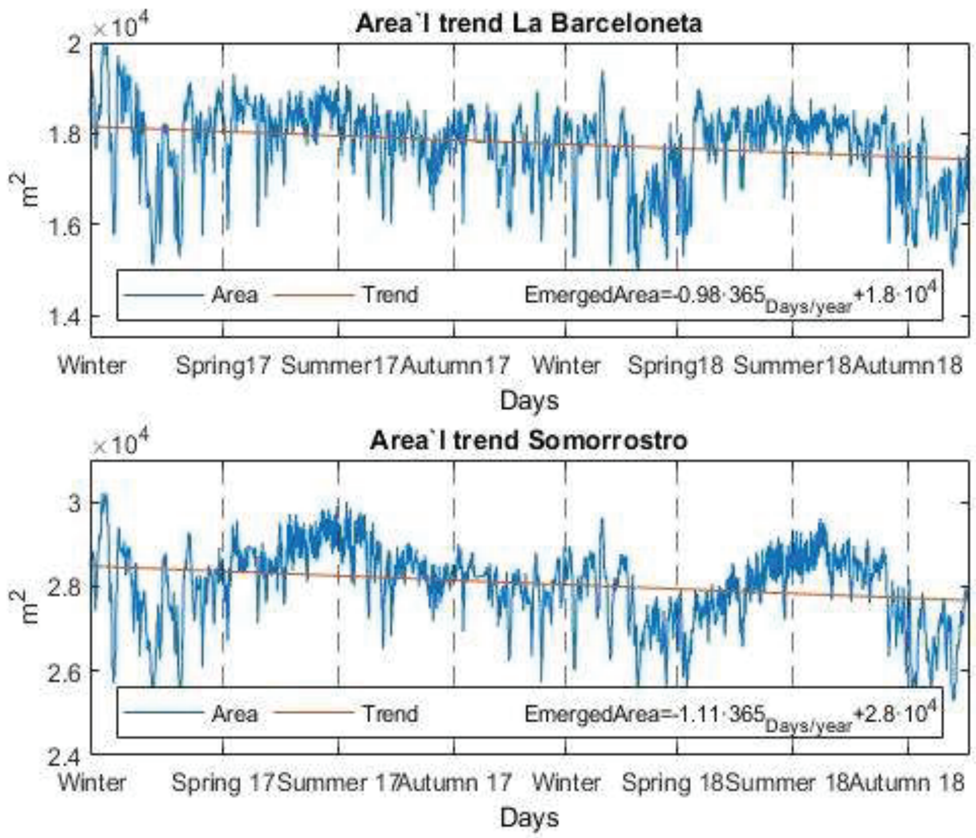

Figure 8. Surface of the emerged beach. Equation of the line

Variability of the shoreline

The average variations in the position of the coastline during the study period on the beaches of La Barceloneta and Somorrostro is ± 5 m on both. Seasonal erosive behavior is observed, dominated by storm events at the two beaches (being easier to observe at Somorrostro beach) during the autumn-winter months (Figure 9). In the spring-summer months, progress in the position of the coastline is observed progressively. In the case of La Barceloneta beach, in the spring-summer months of 2018, a beach rotation can be seen (Figure 9). The profiles located to the N of the beach (profiles 1-4) suffer a setback of the position of the coast line of similar magnitude to the advance of the position of the coast line that the profiles located to the south of the beach suffer (profiles 5-7). The maximum values of mobility of the coastline occurred at the ends of both beaches. In both, maximum values are observed in the profiles located to the south (variations between ± 10 m) (Figure 9)

Response of the shoreline to storm events

Throughout the study period, the city of Barcelona experienced 14 storm events. The beaches of La Barceloneta and Somorrostro responded similarly. The storm events that produced a greater retreat from the position of the coastline were those with mean directions of origin between 78.3º and 107.4º N (Table 1) (Figure 9). The first storm events (Event 1, 2 and 3), caused the retreat of the position of the coastline in general on the two beaches (retracements between 0 and -10 m), being slightly higher on the beach Somorrostro (Figure 9). Events 6 and 7 caused displacements less than -5 m on both beaches, while during events 9 and 10 displacements greater than -5 m are observed, especially in the profiles that are further south of the beaches (this situation best seen on Somorrostro beach) (Figure 9). During events 4, 5, 8, 11, 12, 13 and 14, the wind direction is between 129º and 187º N and no significant displacements of the coastline were observed. However, during event 11 (with a duration of 110 h) there is a reversal of the position of the coastline above -5 m. Finally, from event A, it is observed that after a period of calm, a retreat of the coastline occurs, which seems to be an inversion of the position of the coastline along the two beaches.

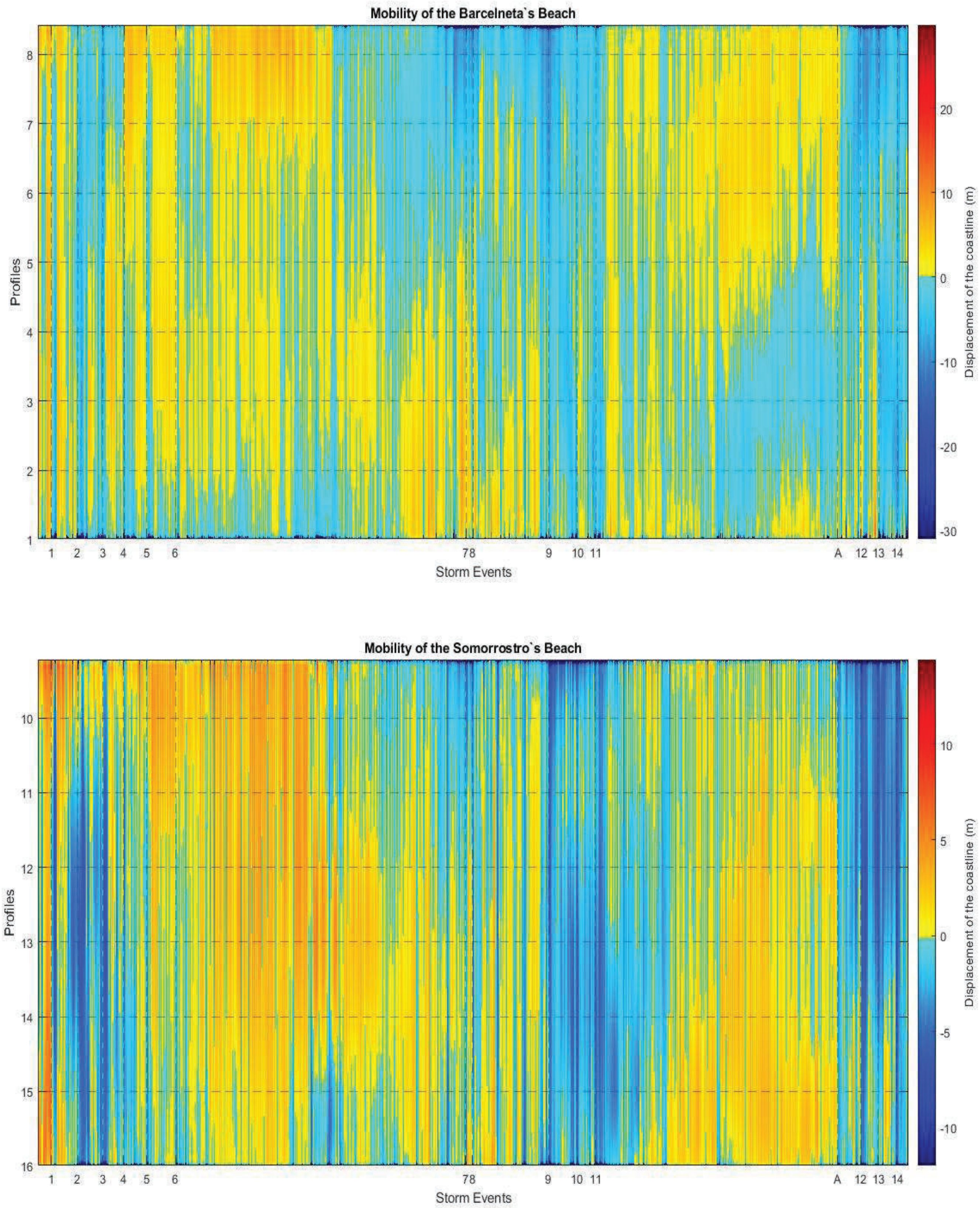

Figure 9. Displacement of the shoreline during the study period. The time axis (and storm events) are represented on the X axis and the beach profiles on the Y axis. The color scale indicates the displacements of the coastline during the study time

DISCUSSION

Previous studies have pointed out the importance of studying the dynamics of artificial embayed beaches and the development of simple indices based on physical parameters that inform about their current state. Video monitoring improves the identification of the sectors of the beaches that are most vulnerable to the action of waves and facilitates the development of coastal indexes that help carry out coastal management tasks (Davidson et al., 2007). The variation of the emerged area of the beach or the position of the coastline are simple characteristics based on physical parameters that indicate the balance of sediment on a beach and therefore the degree of vulnerability of each sector (Serafum et al., 2019). The embayed artificial beaches of Barcelona lack natural sedimentary supplies, so the general trend of the emerging area is negative (erosive). On the beaches of La Barceloneta and Somorrostro, the periods of greatest erosion occur during the season of storm events with wave directions perpendicular to the coast. Each beach has a different behavior during the same storm events since each one is an isolated sedimentary cell that is affected by specific wave conditions due to the different protection structures at each beach (Ojeda et al., 2008).

The minimum beach width index facilitates the observation of variations in beach width during a study period and gives information on the profiles that are most exposed to the action of the waves, giving an idea of the intensity of the erosive processes that take place in each beach profile during that time. In La Barceloneta beach, a smaller beach width is observed than in the case of Somorrostro beach, because the latter is more protected from the action of the waves due to the presence of the Olympic port (figure 10). At Barceloneta beach, during 45% of the study time, approximately at profile 5, the width is less than 25 m due to the incidence of waves during the study time at storm events. This situation prevents the normal use of beach facilities (figure 10). In the case of Somorrostro, during 50% of the time, between profiles 10 and 12, the width of the beach was less than 45 m (figure 10). The profiles in which the lowest mobility values have been observed are the narrowest profiles during the study time, since these areas have less displacement capacity and are therefore more vulnerable to wave action. Coastal mobility is calculated using the standard deviation of the position of the previously defined reference coastline

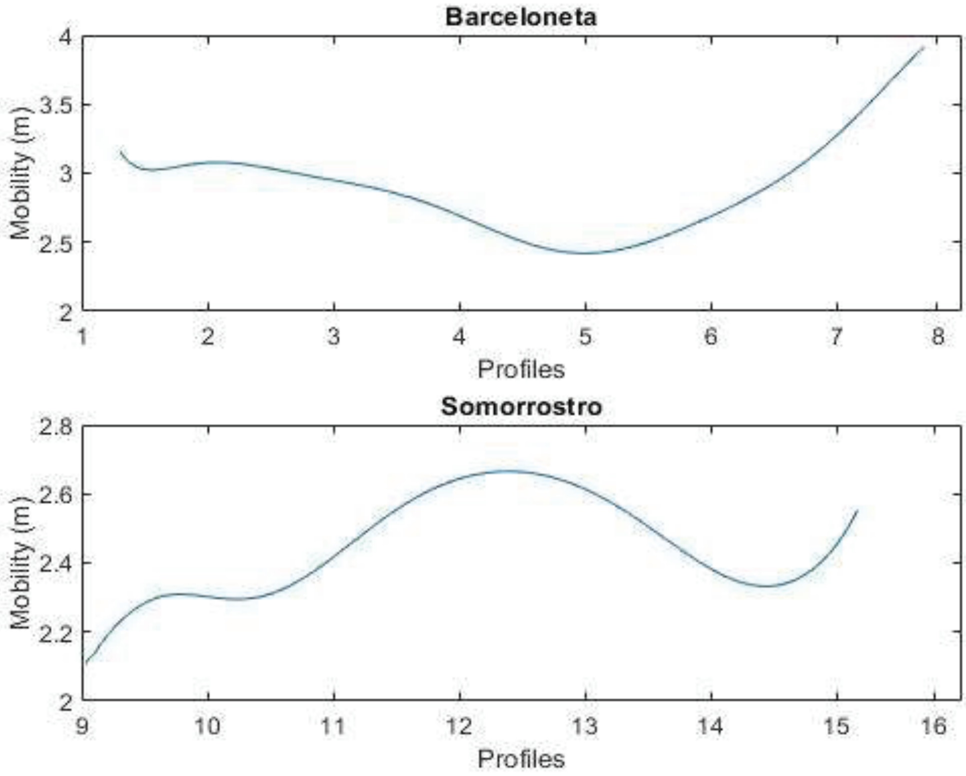

Figure 10. Shoreline mobility by profile during the study period

On artificial beaches such as Barcelona, the mobility of the coast depends on the anthropic actions that are carried out on each beach. When regeneration works are carried out, the mobility of the beach increases. Protective structures and rear boundaries (promenade) decrease mobility, because they limit the receding of the coast and the longitudinal transport of sediments along it. (Ojeda et al., 2008). During the study period, the mobility index showed the lowest values in the Somorrostro beach and not in Barceloneta, due, among other factors, to the protection from the action of the waves that the Olympic Port exerts on it (Figure 11) (Sancho et al 2013). In general, the highest mobility index values are found at the ends of the beaches and are generally related to events of beach rotation, sediment migration, or variation in the shape of the coast (Sancho et al 2013). In La Barceloneta beach, the maximum values of the mobility index are found at the ends of the beach and the minimum values in the central profiles (profiles 4-6) (Figure 11). In Somorrostro beach, the highest values of the mobility index are in the center of the beach since there were no significant beach rotation events and it is less exposed to the action of the waves (figure 11).

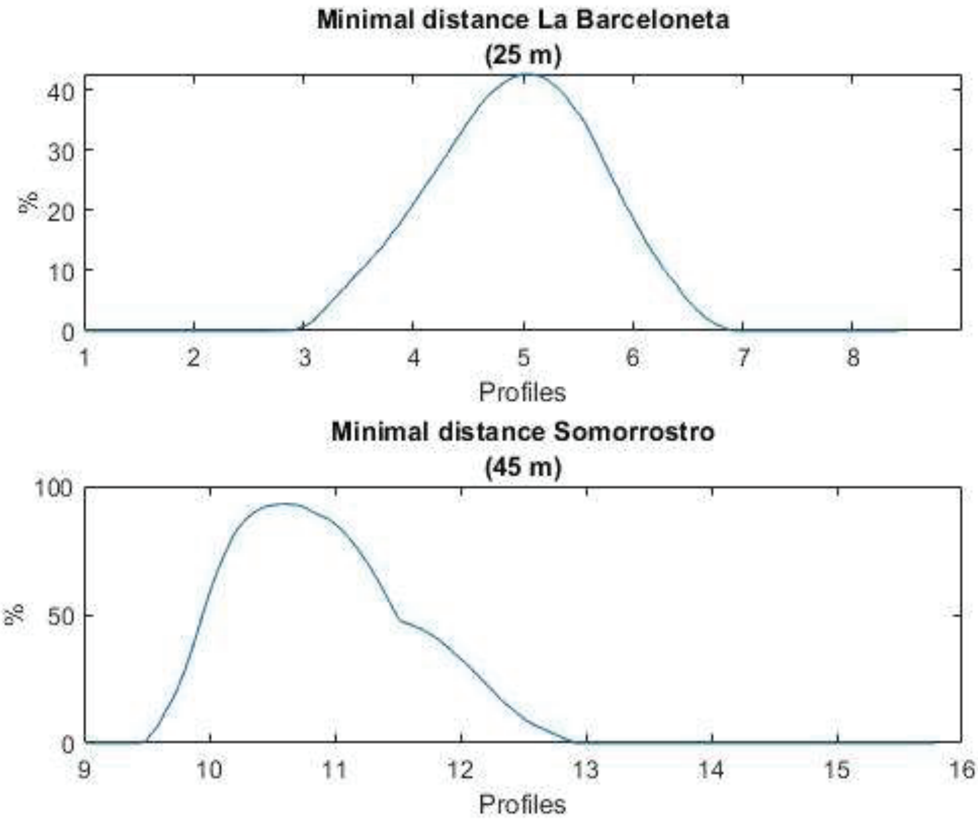

Figure 11. Minimum width

On La Barceloneta beach, the minimum beach width index of 25 m coincides with the lowest mobility index values because around profiles 4 - 5 (at the height of the terrace of the Xup! Xup! restaurant), a series of sandbags were placed as a wall that protects the normal operation of the restaurant from the retreat of the coastline (Figure 12). At Somorrostro beach, the minimum width index of 40 m also coincides with the minimum values of the mobility index.

Figure 12. Sandbags placed by the owner of the restaurant Xup! Xup! to protect the beach from the significant retreats of the shoreline

CONCLUSIONS

It has been observed that along the 2-years study period (December 2016 to November 2018) both beaches follow a long term erosive trend, which account for 360 and 405 m^2/year of beach area reduction at Barceloneta and Somorrostro beaches respectively. Superimposed to this trend, a seasonal pattern is also observed. This pattern consists on erosive periods during the autumn and winter months, followed by accretion during the spring - summer months. The response of the coast is different in each beach due to the protection structures that each one has, making them individual beaches with dynamics and independent processes. Somorrostro beach has a larger surface area (beach width) than Barceloneta beach because it is less exposed to the action of the waves, especially during storm events.

Analyzing each beach individually, it is observed that, on La Barceloneta beach, the areas that are most exposed to the action of the waves and, therefore, are most vulnerable during the study period, are those that are among the areas located in the center and north of the beach, since they show values of erosive tendency and minimal mobility. Furthermore, for more than 40% of the study time, the width of the beach was less than 25 m. It was also observed that at profile 4, a series of sand-filled bags are placed as a protective structure to prevent sediment losses in the area and that may affect the activities of a local restaurant. In the case of Somorrostro beach, the profiles that are most exposed to the action of the waves and therefore most vulnerable are those located in the area south of the beach, due to the dynamics of the area and the protection structures such as the Olympic Port. In these profiles, minimum values of trend and mobility are observed. As expected, the minimum width is in this area of the beach (less than 45 m for less than 50% of the study period). In both beaches, the minimum width index coincides with the lowest values of the mobility index, indicating the most vulnerable areas of La Barceloneta and Somorrostro beaches during the study period.

The use of massive data on the position of the coastline (the use of video monitoring system) allows the estimation of different parameters and indices that can provide a useful tool for beach management. In this work, the combination of the trends of the coast (including the surface area of the emerged beach), the minimum width index and the mobility index, are applied to recognize the most vulnerable areas and identify the places along the beach most likely to be affected by the action of the waves during storm events. It is proposed to complement the studies carried out by means of the video monitoring method of Barcelona's beaches and to expand the knowledge about them in order to carry out sustainable management tasks.

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