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# Application of Geomatic Techniques for the Assessment of Anthropogenic Changes in the Urban Beaches of "La Magdalena" (Santander, Spain)

**Germán Flor [1], Manuel Sánchez-Fernández [2], Germán Flor-Blanco [1,*] and José Juan de Sanjosé Blasco [2]**

1 Geocantabrica Fecyt Group, Department of Geology, University of Oviedo, Arias de Velasco, UNESCO IGCP 725 Forecasting Coastal Change, s/n, 33005 Oviedo, Spain
2 Department of Graphic Expression, INTERRA Research Institute for Sustainable Territorial Development, NEXUS Research Group Engineering, Territory and Heritage, University of Extremadura, Avenida de la Universidad, s/n, 10003 Cáceres, Spain
* Correspondence: florgerman@uniovi.es

**Abstract:** Since the 1970s, dredging sands have been poured onto the embayed beaches of La Magdalena in the western mouth of the estuarine Bay of Santander (N Spain) in order to increase beach width. Up until the year 2000, the sands were systematically fed by a trailing suction dredge, which was later replaced by truck sand transfers from the surplus sands of the western beach to the eastern ones and by mechanical redistribution to create artificial berms. A recent project aimed to solve sand losses after each storm by building two perpendicular breakwaters about 620 m apart. The eastern breakwater was built in the early summer of 2018, and wave storms in November 2018, February 2019, October 2020 and the last days of 2021 progressively dismantled the reconstructed upper beach areas and eroded other segments. The western breakwater, however, designed to retain the E–W sandy beach drift, was never built. Four photogrammetric restitutions from 2005, 2010, 2014 and 2017 and an aerial LiDAR in 2012 were obtained to better understand the previous topographic distribution of the back and foreshore. Numerous field observations were made, and six field surveys have been performed since 2018 using laser TLS and GNSS, which occurred in November 2018, March 2019, October 2019, March 2020, October 2020 and April 2021. The definitive results of the evolution of the sand loss are presented, a hypothesis is proposed to explain the dynamo-sedimentary trend, in which longitudinal transport dominates promoting the formation in the progress of a new sand beach, and some sustainable solutions are proposed. The results show that the constructive solution has failed to stabilize the beach and that the predictive models that justified it have not coincided with the real dynamic and sedimentary evolution.

**Keywords:** sandy beaches; breakwater; erosion; nourishment; aerial photogrammetry; TLS

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## 1. Introduction

Coastal landforms are created, reshaped, eliminated or customized to human requirements and needs [1]. In particular, beach environments comprise many varied and interacting human uses. The most common are the construction of shore protection structures and fishing harbors, the dredging of navigation channels and intensive sand extraction [2], which, in some cases, may affect adjacent systems through dynamic and sedimentary disturbances [3,4]. In this sense, commercial activities include sand mining, development for housing or infrastructure, waste dumping, tourism, surf carnivals and fishing. Recreational activities include sunbathing, sightseeing, angling, swimming, surfing and boating [5]. The preservation of a sufficiently large surface area for all kinds of leisure activities has created a series of needs in coastal towns that have led to the construction of fixed structures. For this reason, some selected shoreline stabilizations conducted to protect coastal cities have been studied [6] to learn of the local experiences of many types of shorelines, including sandy beaches.

In addition, many urban beaches need to maintain increased beach width for recreation and coastal safety in general by applying sand renourishment [7–9] after severe storm events [10], as well as by restoring the geometries of upper beaches, specifically the berm, in order to facilitate the recreational area in the summer. Nevertheless, differences between nourishment and the native material (size and composition) have an important influence on the dynamics of sediment stock [11]. Since 1999, the SAFE project, sponsored by the European Commission, has performed an inventory and has drawn up a comparison among the major countries involved, including many Spanish beaches [12,13], very common in the Mediterranean Sea (E Spain) and whose coastline has a significant sediment deficit [14].

Pioneering projects in the United States opted for the installation of rigid structures, such as breakwaters, seawalls, groynes, etc., to be replaced by sandy feeds or mixed solutions, such as beach nourishment accompanied by the construction of small jetties and revestments, but since the 1970s, most coastal protection measures consisted of beach nourishment [15]. These types of "soft" actions, so called because they do not introduce rigid elements on the beach, are often considered the most environment-friendly option [16,17]. On Spanish coasts alone, more than 600 projects were carried out between 1997 and 2002 [18], and until 2020, there were mainly conducted on the Mediterranean and SW Andalusian coasts [12,17,19–23]. In general, most activities are remedial nourishment measures conducted to restore "beach functionality", between 30–60 m of width [24].

Some noteworthy regenerated sand beaches are located along the Galicia and Cantabrian Sea [13], a coast on which much less frequent interventions have been applied compared with the rest of the Spanish coastline. This is the case of the sandy beaches of the city of Santander, with a particular and interesting problem on the sheltered beaches of La Magdalena (Figure 1), which are the object of this paper.

The importance of beach tourism has promoted intervention in the management of the coast, its leisure activities and its coastal inhabitants. To take in a greater number of tourists, avoiding erosion and creating new beaches or renewing narrow beaches have thus been justified as a social demand. The rationale for beach nourishment has been specified as follows: 1. combatting coastal erosion (chronic erosion), 2. preventing flooding (safety) and 3. maintaining wide recreational beaches [25].

It should be noted that the Spanish "economic miracle" during the 1960s and 1970s is considered the result of developmentalism in 1959–1976 [26], a historical period during which the bases of the Spanish economy were addressed, including the development of the sun-and-beach tourist industry and the intervention of numerous works on the coast. Spanish beaches are important economic resources, especially since the tourist boom of the late 1960s. The city of Santander, situated in N Spain (Figure 1), has been a tourist destination since the second half of the 19th century, when the bourgeois fashion of wave baths became established, even as a destination for the Spanish royal court in the early 20th century.

In the Cantabrian Sea, where wet weather makes the littoral attractive for only two or three months in the summer, the Spanish government implemented several beach plans. Some examples of embayed beaches in Asturias and Cantabria were described in [27], including two artificially created beaches and others which were nourished, specifically those of La Magdalena, made up of a set of four embayed beaches from W to E (La Fenómeno, Los Peligros, La Magdalena and Bikini), which are located in the city of Santander (Figure 1C).

The case studied is one of the urban beaches of Santander, the capital of Cantabria (N Spain), an example of mistaken Spanish policies of the 1970s (Figure 1A,B). The Port of Santander (Figure 1B) is a multipurpose natural port located in the southwestern tidal flats and marshes of the estuarine bay of the subsystem of Santander [28], the navigation channel of which requires periodic dredging in order to maintain a depth of 11 m [29]. For this reason, the subsystem of Santander underwent a reduction in the intertidal zone during the 20th century [30], with the period between 1970 and 1988 being the most significant, when the greatest denaturation took place, especially of the salt marshes, mainly for the construction of the port of Santander.

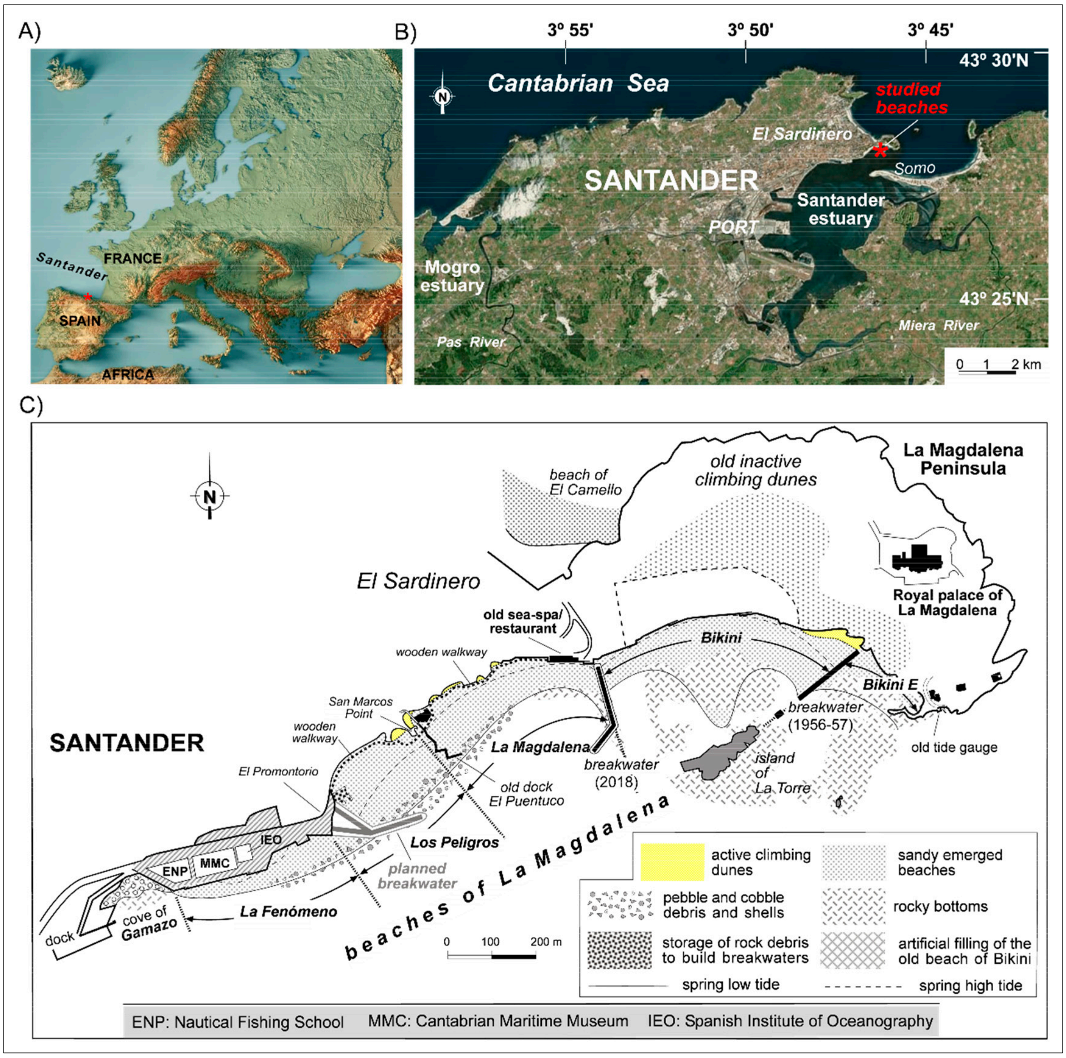


**Figure 1.** (**A**) Situation of the coast of Cantabria and city of Santander (Spain). (**B**) The area of study is situated in the outer western margin of the mouth of the Santander estuary. (**C**) Location of the beaches, the two breakwaters planned and other old civil structures and morphologies.

For this study, it was necessary to apply different surface and volume measurement techniques to obtain the most accurate results possible. Terrestrial Laser Scanning (TLS) techniques combined with the Global Navigation Satellite System (GNSS) facilitate accurate topographic and bathymetric maps, and from the acquired data, different products can be obtained, such as the determination of the coastline or the quantification of geomorphological changes to beaches [31–33]. Both traditional geomatics techniques (total station, GNSS and conventional photogrammetry) and new techniques aimed at obtaining large amounts of data, point clouds (terrestrial and aerial LiDAR (Light Detection and Ranging) and short-range terrestrial and aerial photogrammetry) have been used by different authors in studies on the evolution of sandy coasts [34] and long-term sandy beaches [35–37].

The aim of this work was to determine the transformations that took place from the end of the 20th century until 2021, and to analyze them in order to gain a necessary historical perspective. A further aim was to determine morpho-dynamic beach changes after changes in the management and construction of rigid structures, quantifying the volumes of deposited and eroded sediment over three consecutive years between 2018 and 2021, to predict the future evolution of these beaches. Using these measurements, environmental impacts on the system were established.

Additionally, some sustainable proposals have also been suggested for the best use of these beaches, both from the perspective of maintaining the morphology and sandy sediment, as well as from the perspective of environmental improvement.

## 2. Study Area

The rocky coast of Cantabria is long and straight (Figure 1A,B), with steep slopes running into the sea, mainly constituted by cliffs, among which sand beaches are intercalated, with less frequent pebble beaches, aeolian dune fields [38] and estuaries [39]. The coast of Cantabria, of which Santander is the capital city, has an oceanic climate following Köppen climate classification Cfb. It is temperate without a dry season and has a mild summer [40]. The annual thermal oscillation of average monthly temperatures reaches around 14.1 °C, the average yearly rainfall is 1097.3 mm, the minimum water temperature in February is 12.4 °C and the maximum in August is 21.7 °C [41].

This coastal sector occupies a shadow margin in the NE–SW direction, in which the reflective embayed beaches of La Magdalena (Figure 1B,C) develop in the highly urbanized rocky cliff edge of the western mouth of the estuarine bay of Santander [28]. The beaches run from E to W, with section lengths as follows: eastern Bikini, 170 m; main Bikini, 540 m; La Magdalena, 420 m; Los Peligros, 230 m; and La Fenómeno, 240 m, and a prograding lobe develops on the western dockside (Figure 1). In all of them, the backshore and foreshore are of variable widths, very short in the eastern area (35 m) and increasing in the W, reaching a maximum in Los Peligros at around 130 m, and decreasing in La Fenómeno to 35 m and to 15 m in the lobe. They share the same submerged sandy prism, which is almost non-existent at the latter-mentioned beach, where the intertidal and shallow bottoms comprise a rocky karst.

In the case of Bikini beach, the bottoms are mainly discontinuous karst. Behind it is the Magdalena Peninsula, where a dune field of climbing typology was developed (Figure 1C) before the 20th century [38], as well as some patches of aeolian dunes of the same typology as these beaches (Figure 1C). Almost all of the back beach of La Magdalena has developed dunes, and some of them are still inactive. The backshore of Los Peligros, with a maximum width of 100 m, is artificially maintained as a berm for recreational use in the summer.

In general, these mesotidal and wave-dominated beaches of La Magdalena (Figure 1B,C) are sheltered environments, protected by the Magdalena Peninsula (Figure 1B,C) from the waves of the open sea and occupy the western margin of the estuarine bay of Santander [28]. They were originally cut off at high tide as small embayed beaches, but as they shared the same subtidal area, they emerged in total continuity, particularly during spring low tides (Figure 1C). Under the original conditions, these beaches were dissipative and even developed a low-tide terrace in the summer, as was the case of La Magdalena in 1900 and with a much lower sedimentary volume.

With its NE–SW alignment (Figure 1B), the morphology of the bay of Santander indicates that the main wind directions are W and NW, as well as SW, NE and E (Figure 2A,B). The mean wind speed is about 2–3 m/s [42]. SW winds generate a Föhn effect to the north of the Cantabrian Range as an adiabatic heating and drying process and with strong winds along the coast. These southern winds are the most significant (Figure 2A,B) in the estuarine subsystem of Santander because they travel at about 7.75 km/h and generate an important fetch along the axis of the bay, with an average depth of about 6 m. Southerly winds are the strongest, and an average maximum speed of 90 km/h was recorded on 19 January 2013, with streaks recorded at the Parayas airport (Figure 1B) having exceeded 100 km/h in recent years [43]. In this sense, the record wind speed in Santander occurred on 12 December 1999 with a streak of 167 km/h, although the southern wind that caused the great fire in the city in 1941 may have exceeded 180 km/h [44]. Southern winds are relatively common at the beginning of spring and in autumn and may also occur during the winter, though they occur rarely in the summer [45].

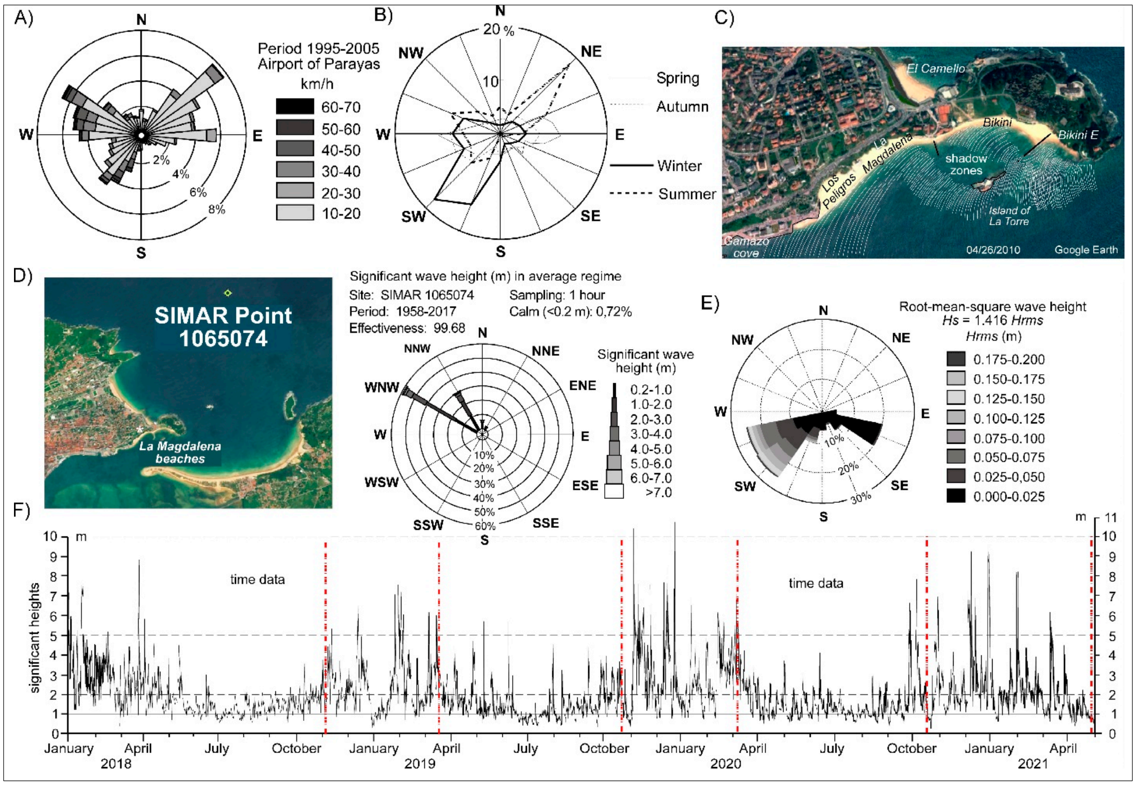

**Figure 2.** (**A**,**B**) Average directions and velocities (m/s) of winds at Santander Airport [28]. (**C**) More frequent wave refraction (lines represent swell wave crests) along the beaches. (**D**) Situation of SIMAR Point: 1065074 used in calculations [46]. (**E**) The wave rose was calculated at the end of the spit of Somo [47]. (**F**) Time series of mean significant wave heights (Hs) recorded from January 2018 to May 2021 (Puertos del Estado, Spain; https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx (accessed on 20 October 2022). The vertical lines in red correspond with measurement surveys.

In addition, they are responsible for the formation of small climbing coastal dunes along the beaches of Los Peligros of La Magdalena, and for the most extensive dunes on the eastern back beach of Bikini, occupying about 6500 $m^2$ (Figure 1C). This last beach was the source of the sand for the formation of the old field of climbing dunes (Figure 1C) on the La Magdalena Peninsula [38,48], but there are older sand dunes beneath the active ones.

The Cantabrian coast is an open cliff coastline exposed to a large fetch whose swell comes mainly from the WNW and NW, and the NE is less important, often under anticyclone weather conditions. The predominant wave direction is NW (37%), followed by WNW (29%) and to a lesser extent, NNW (16%), with significant wave heights of less than 2.0 m and periods between 8 and 12 s [49]. Moreover, typical winter storms have approximately 4 m in significant wave height, and major wave periods range from 8 to 12 s [50], recorded in the open sea. These waves from the third quadrant enter the bay of Santander, refracting and deriving in a highly mitigated swell with an oblique direction (NE–SW) to the beaches of La Magdalena (Figure 2C). Consequently, it is an energetic shadow environment, as the waves generated along the estuarine axis by winds from the SW are important and have a fetch about 7 km, affecting the beaches of La Magdalena Figure 2E).

Calms (wave height <0.25 m) are of less than 0.5%. In winter, the average parameters are 2 m and 7 s, although waves of more than 9 m and 16 s have been measured. In summer, the significant wave height varies between 0.5 and 1.0 m, and the period is 4–6 s. Very strong waves usually occur in the winter, with heights of over 6–7 m and long periods of more than 8 s [52]. Major episodes were considered between 1996 and 2016 when wave height were >6.5 m and with peak wave periods and durations and maximum Storm Power Index values [52,53].

Partially based on these authors, significant wave heights greater than 6 m, peak wave periods and durations, and SPI values of main storms events for the study period were calculated (Table 1). November and December are typical months in which major storm surges are concentrated, with higher Hs and longer durations with higher SPIs, increasing towards December 2020 (Table 1). Nevertheless, the following waves of more than 12 m have been recorded: 15.22 m, 19.77 m and 26.13 in 2007, 2008 and 2009, measured by the Augusto González Linares' weather buoy (43°54′14.4″N; 4°00′39.6″W) in Santander [54]. However, along the shoreline, the maximum height is usually in the range between 1.5 and 1.9 times the significant wave height.

**Table 1.** Data of wave storms between November 2018 and March 2021: Hs (significant wave height in meters) up 6 m, and Tp (peak wave period in seconds), duration of the maximum event (hours) and the Storm Power Index [51], obtained from SIMAR Point 1065074 (https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx (accessed on 20 October 2022)). The days of field surveys are included in bold letters as a reference to storm events between surveys.

| Maximum Storm Date | Significant Wave Heights (Hs, m) | Peak Wave Periods (Ts, s) | Duration (Hours) | Storm Power Index ($m^2$ h) |
|---|---|---|---|---|
| **6 November 2018** | **3.79** | **11.01** | – | – |
| 9 December 2018 | 6.47 | 17.32 | 23 | 962.80 |
| 23 January 2019 | 6.57 | 16.12 | 28 | 1208.62 |
| 27 January 2019 | 7.15 | 11.01 | 68 | 3476.33 |
| 4 March 2019 | 6.13 | 14.66 | 21 | 789.11 |
| **12 March 2019** | **3.63** | **9.10** | – | – |
| **26 October 2019** | **1.05** | **12.01** | – | – |
| 3 November 2019 | 10.38 | 12.03 | 79 | 8511.81 |
| 8 November 2019 | 7.57 | 13.32 | 25 | 1432.62 |
| 23 November 2019 | 7.52 | 10.85 | 18 | 1017.91 |
| 9 December 2019 | 7.62 | 10.01 | 7 | 406.45 |
| 13 December 2019 | 8.50 | 13.32 | 76 | 5491.00 |
| 22 December 2019 | 10.69 | 11.01 | 32 | 3656.84 |
| 10 January 2020 | 6.81 | 13.32 | 18 | 834.77 |
| 10 February 2020 | 6.09 | 14.66 | 63 | 2336.55 |
| 3 March 2020 | 7.03 | 11.01 | 24 | 1186.10 |
| 6 March 2020 | 6.29 | 10.01 | 31 | 1226.49 |
| **9 March 2020** | **3.58** | **11.11** | – | – |
| 25 September 2020 | 6.29 | 13.32 | 46 | 1819.95 |
| 3 October 2020 | 7.73 | 13.32 | 68 | 4063.20 |
| **18 October 2020** | **0.93** | **10.01** | – | – |
| 29 October 2020 | 6.84 | 12.11 | 40 | 1871.42 |
| 4 December 2020 | 7.16 | 13.32 | 65 | 3332.26 |
| 7 December 2020 | 9.26 | 10.01 | 45 | 3858.64 |
| 12 December 2020 | 6.67 | 12.11 | 29 | 1290.18 |
| 28 December 2020 | 8.99 | 11.01 | 93 | 7516.27 |
| 30 January 2021 | 8.32 | 12.11 | 33 | 2284.34 |
| 11 March 2021 | 6.23 | 17.74 | 11 | 426.94 |
| **29 March 2021** | **1.03** | **12.11** | – | – |

The annual average significant wave height in the average regime for oceanic waves is about 2.50 m, and the average period is 5 s. The significant storm wave height in the scalar regime for a confidence of 90% is approximately 18 m, and the peak period is 17 s [55]. The NW and SW wave storms almost always produce an increase in tide height of 0.3 to 0.5 m [45], which is very common on the beaches of La Magdalena that produce an over-elevation, with greater erosive power being more intense when it coincides with high tides in the spring.

Waves enter the La Magdalena beach segment (along 165 m) in an SW–NE direction (Figure 2D), in both calm and stormy conditions [56], breaking at an angle of 63° (θ) where the old sea-spa/restaurant is located. Velocities vary from 15 to 18 knots [49].

Regarding the tides, they are semidiurnal and mesotidal for 68.52% of the year, with a typical spring–neap cycle. The mean range is 2.85 m, and spring tides have a maximum of 5.464 m and a minimum of 0.033 m [45]. Flood tide currents penetrate through the main channel along the western side, sweeping the beaches of La Magdalena, and the ebb tide drains through the eastern side, with speeds in the range of 0.5 m/s and with a maximum speed at both tidal times of 1 m/s at the mouth, both in and out. The ebb currents are more intense, reaching up to 1.54 m/s in spring tides, which increases further during episodes of rain due to discharges from the Miera River (Figure 1B) in the estuarine subsystem of Cubas [28], in the sphere of influence of which it can reach speeds of up to 2.60 m/s [57].

## 3. Methodology

Successive ups and downs observed on the beaches of La Magdalena have led us to investigate the behavior of these beaches through topographic monitoring, mainly since the construction of the breakwater in the summer of 2018, and its application to future evolution. Laser techniques were adopted both for greater fieldwork speed and for the precision and resolution of the data obtained, from which it was possible to reconstruct cross-sectional profiles, surfaces indicative of erosion, sedimentation or equilibrium processes. The geomatics methods of aerial photogrammetry, LiDAR (Light Detection and Ranging) and TLS (Terrestrial Laser Scanning) were used to evaluate the coastal dynamics of La Magdalena beach. The Digital Elevation Models obtained using these techniques (Aerial photogrammetry: 2005, 2010, 2014 and 2017; LiDAR: 2012; TLS: from 2018 to 2021) were used to compare volumes and cross sections (9 profiles perpendicular to the coast).

The work was followed up in 6 field surveys over four consecutive years. The first record, using TLS on 6 November 2018, was incomplete, as the lower tide belt failed to reach the zero sea level of the port. Nevertheless, the state of the beach in terms of its length was checked by means of transverse representative profiles. The five subsequent records were all completed during spring tides (maximum level of 0.60 cm) on 12 March 2019; 26 October 2019; 9 March 2020; 18 October 2020; and 19 April 2021.

### *3.1. Aerial Photogrammetry (2005–2017)*

A review of historical vertical flights was consulted on scales of 1:44,000 from 1945; 1:33,000 from 1956 (US Army Map Services); 1:18,000 from 1953 (Aerotécnica-Diputación de Santander), 1970 (Compañía Española de Trabajos Fotogramétricos Aéreos-CETFA), 1974 (Aeropost-Jefatura de Costas) and 1973 (Instituto Geográfico Nacional-IGN); 1:30,000 (IGN) from 1985; 1:15,000 from a framing review of 1988; and different scales for photogrammetric flights from 2001 to the present (IGN). Oblique and satellite photographs were also collated, whose origins were the Google Earth and Bing Maps web platforms, as well as the latest detailed topographic maps (1/5000) from the Cartographic Service of the Government of Cantabria [58] and IGN [59]. Many interesting aerial photographs can be obtained from the digital photo library [60].

As indicated above, photogrammetric flights have been conducted over the city of Santander since 1946, but flights prior to 2005 could not be taken into consideration for this research due to their low quality. Camera calibration certificates are only available for the 2005, 2010, 2014 and 2017 photogrammetric flights provided by the National Geographic Institute (IGN). The support points for photogrammetric orientation were provided by GNSS, a fact which provides a suitable guarantee of quality to be able to carry out the cartography of these years on a scale of 1:1000, in which the maximum error in the restitution of flights must not be greater than 0.2 m.

The cartography was carried out in the official Spanish coordinate system (ETRS 89), in which the altimetry refers to the Mean Sea Level in Alicante (origin altitude in Spain). The cartography obtained has contour lines of 1 m, the lowest altitude being that of level 0, since, below this level, the beach appears submerged in most flights. Moreover, the LiDAR flight from IGN dating from the summer of 2012 was used.

### *3.2. Terrestrial Laser Scanner (2018–2021)*

The application of Terrestrial Laser Scanning (TLS) for the monitoring and analysis of geomorphological dynamics on sandy coasts with millimetric precision is relatively recent and highly efficient at detecting even annual changes [61], and it complements traditional analytical methods. The scanner measures the 3D position of data points in the survey area, the x, y and z coordinates, and also collects the reflection intensity of each point [62]. The spatial position accuracy of the points measured with the Faro Focus X-330 is given as ±6 mm at a distance of 100 m. This uncertainty, added to the positioning error of the targets which are determined by GNSS in RTK mode (±20 mm), yields an estimated position uncertainty of ≤3 cm. The spatial point information of the resulting point cloud can then be used to derive accurate Digital Elevation Models (DEMs) [63,64].

The total number of points measured by TLS with the configuration used was approximately 700 million points. In total, in each survey, an average of 17 scenes were obtained. The individual shot accuracy was <1 cm, and the survey joint accuracy at relative coordinates was <2 cm. Finally, the accuracy of the georeferenced point cloud was <3 cm, including the GNSS error. Two measurements were made per year to evaluate the evolution of the beaches during the winter (October–March) and the summer (April–September). Six measurements were made using TLS since October 2018. The areas that were submerged during the measurement time with TLS were observed with GNSS in RTK mode. The digital terrain models were interpolated using the Triangular Irregular Network (TIN) algorithm from the filtered and sampled terrain point clouds with a mesh density of 0.20 × 0.20 m. The processes of filtering, sampling and obtaining the DTM were carried out in Trimble RealWorks® software version 10.4. The filtering of the point clouds was performed in two steps: first, from an automatic process in the software, and second, manually. The filtering allowed for the removal of existing vegetation, noise produced by moving elements and noise produced by the scanner reading in areas where water deposits were present. Information on submerged areas was included in the TLS DEMs from the DEMs obtained by the combination of TLS and GNSS. The beach dynamics were studied from nine critical sections of the study area in the period covered by the work (Figure 3) and on an overall level from comparisons among the obtained DEMs.

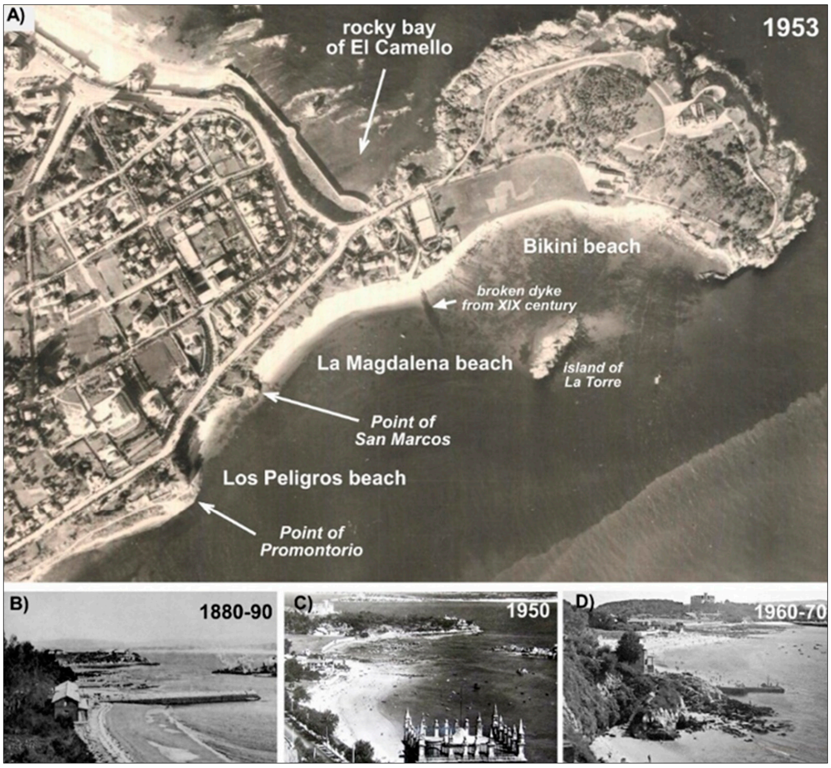


**Figure 3.** (**A**) Beach area of La Magdalena. Vertical photograph from 1953 (Diputación de Santander). (**B**) Eastern area of La Magdalena with the old sea-spa building and the breakwater (XIX century, now disappeared). (**C**) La Magdalena beach and, in the background, the Bikini beach, with its rocky outcrop at low tide (1950). (**D**) Eastern area of Los Peligros beach in the foreground and the point of San Marcos and the elongated dyke named El Puentuco (old dock), where the eastern side of La Magdalena beach begins (1960–1970).

## 4. Results

### 4.1. Background

Between 1870 and 1960, 13.85 × $10^6$ $m^3$ was dredged from the Bay of Santander as a whole [65], but in the last ten years, around 100,000 $m^3$/yr of sand was dumped on the continental shelf northeast of the bay, with less sand in the study area [66]. Contaminated sands were disposed of 9 miles offshore [28] and with smaller volumes on the studied beaches [66].

The beaches of La Magdalena, which are managed by the city council with the permission of Coast Demarcation (Ministry of Environment), began to lose sand in an obvious way from 1969 and even more so since 2001 due to remodeling of the access to La Magdalena beach [67], with escarps of over 1 m generated in the upper foreshore after each wave storm.

These beaches had a different distribution with less sedimentary volume than that at present, with variable widths of 15 m in the central part and 27 m to the W (attached to the recently constructed seawall), and on the beach of La Magdalena, widths varied between 19 m to the west and 39 m to the east. In addition, the beach of Los Peligros had a maximum width of 30 m and was disconnected from those described above, and the beach of La Fenómeno did not exist (Figure 3A).

With the aim of increasing the area of use, authorities decided to feed them once more in 1970 by dredging the Santander Bay navigation channel located oppositely. A large volume of sand was replaced on La Magdalena [67], and sand was dumped on the beaches of El Sardinero (Primera and Segunda). For this purpose, more than 10 million cubic meters was dredged along the navigation channel of the bay during the development of the new port of Raos in Santander (Figure 1B), volumes which were not exceeded in the following decades [66]. In this estuarine subsystem of Santander, from the original surface of 43,345,000 $m^2$, the intertidal area occupied 34,765,000 $m^2$, and, by the end of the 1970s, this was reduced to 14,872,000 $m^2$ [30].

This sediment was used to discharge surplus sand on the beaches of El Sardinero (Figure 1B,C) and La Magdalena (Figure 1B,C) and created the new beach of El Camello on a rocky bay (Figure 1B,C and Figure 3A). Subsequently, in 1973, sand dumping from the Somo spit (Figure 1B) began with the aim of consolidating the beaches of La Magdalena, which continued two years later with the dumping of a total of 80,000 $m^3$, a practice that continued until 2018, simply through sand transfers.

Some sporadic rather than periodic sand nourishments were carried out until the end of the 1980s and in the late 1990s. Dredging with suction ships was systematized, generally in the autumn off the submerged beach and with discharging on the emerged beaches. Occasionally, such as in the autumn of 2000, there were important sand invasions by the wind on the Bikini back beach, and the sand covered the southern access road to the Palace of La Magdalena and nearby slopes and forming climbing dunes. The high cost of the dredging technique led to its replacement in 2001, when sand began to be transferred via truck from the La Fenómeno beach to the eastern beaches, with volumes commonly between 25,000 and 30,000 $m^3$ per year, though these rose to 43,000 $m^3$ in 2013. The sands were used to build a berm in the upper areas of Los Peligros, La Magdalena and Bikini beaches to protect the wooden walkway and to create more recreational areas for sunbathers. This group of beaches contains a much larger volume of sand than it did originally, especially that of Los Peligros.

With the sand fillings, dissipative beaches with low tide terraces (Figure 3B–D) were reflective, narrower and steeper. Sand depletion due to the repeated erosion of these beaches, including urban furniture and the cost of restoration operations, triggered the implementation of a project of stabilization, which was supposedly definitive and has turned out to be highly controversial.

### 4.2. The Breakwaters Project

The morpho-sedimentary and dynamic functioning of the beach established under the conditions prior to the intervention by the construction of the first dyke clearly reveals the transfers of sand from the Magdalena beach to the beaches of Los Peligros and La Fenómeno (Figure 4).

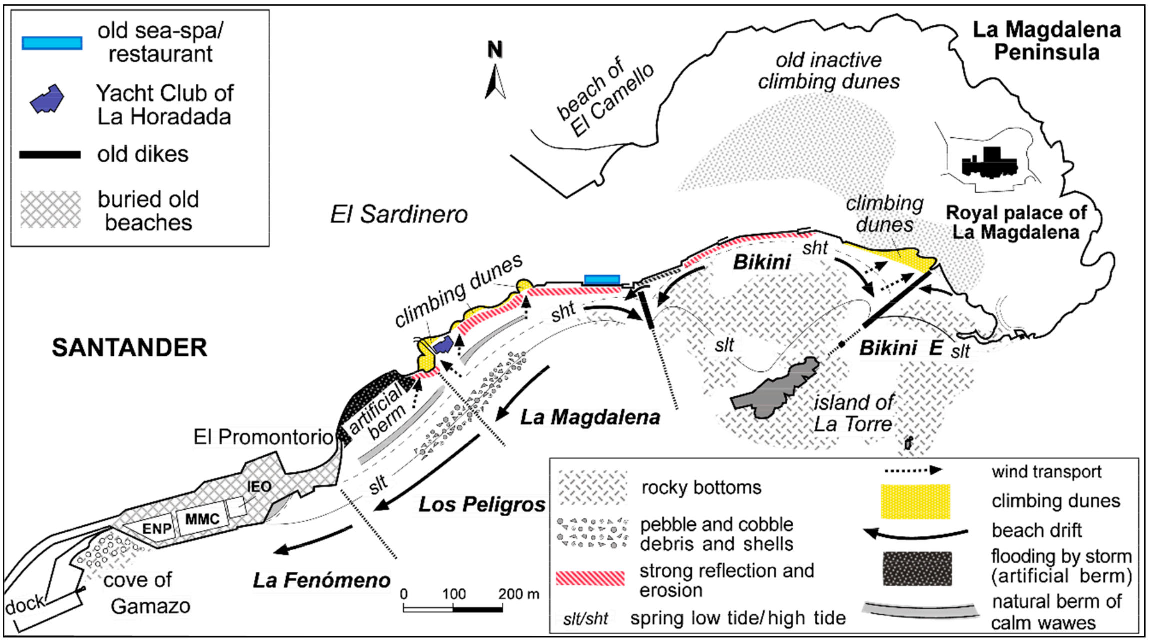


**Figure 4.** Dynamic-sedimentary processes pre-2018, representing a period of artificial sedimentary transfers between the eastern beaches to La Fenómeno, and from their foreshores to the climbing dunes.

According to the official order of Environmental Impact Assessment (BOE number 13, 15 January 2001), since the early years of the 21st century, the possibility of building two perpendicular breakwaters has been contemplated in what was considered to be the definitive solution to the stabilization of the sand, with one on the west side in order to prevent sand from escaping into the esplanade of San Martín (Figure 1C) and another close to the pier in front of the old sea-spa/restaurant in order to avoid the action of the waves that trigger erosion. In this case, however, it was decided to extract approximately 85,000 m$^3$ of sand from La Fenómeno (SW), although this is known not to be a definitive solution, as the beach was not in equilibrium. The project stipulated 28,000 m$^3$ to nourish the beaches of Los Peligros and La Magdalena and 25,449 m$^3$ for Bikini, which was also obtained from the beach of La Fenómeno. The remaining 27,061 m$^3$ was to come from the dredging of submerged bottoms (BOE number 46, 23 February 2016). The nourishment modality applied to these beaches is what [68] calls type B: Nourishment of Visible Beach. The sand is mainly placed to build a wider and higher berm above the upper foreshore. The project only acted on the beaches of La Magdalena and Los Peligros, with a built breakwater having been located in the extreme NE and another discarded breakwater in the SW (Figure 1C). Construction of the eastern breakwater began in January 2018 and was completed in May 2018 (Figure 1C). It was from this moment that the system configuration began to change, so we decided to study the changes.

The actions for the protection of the coast throughout the provinces of Spain, managed by the Ministry for the Ecological Transition and the Demographic Challenge, can be consulted at https://www.miteco.gob.es/es/costas/temas/proteccion-costa/actuaciones-proteccion-costa/default.aspx, and specifically, the "Project of Stabilization of the Magdalena-Peligros" can be found at https://www.miteco.gob.es/es/costas/temas/proteccion-costa/actuaciones-proteccion-costa/cantabria/39PM2017-Magdalena-Peligros.aspx.

In summary, the project was budgeted at 2,293,000 euros with more than 43,000 additional euros for the repairs of a part of the rear slope following storms in 2021. Although the project did not include dumping the sediment from dredging, this work will encounter further costs, as sand will have to be replaced from time to time, even more so following storms. Neither the continuous movement of sediment by machinery nor the reconstruction of the accesses destroyed by the storm "Gloria" of January 2020 were contemplated. To all this must be added previous sediment, environmental characterization studies and other additional costs that beach regeneration works invariably incur.

### *4.3. Measurements and Volume Controls*

#### 4.3.1. Previous Records (2005–2017)

Prior to breakwater construction, large flat surfaces were built as berms in the sunbathing area (backshore zone) by the addition of sand extracted from La Fenómeno beach (SW) to regenerate the berms of Los Peligros, La Magdalena and Bikini beaches. The maximum width of Los Peligros is 65 m in its central area, La Magdalena has a regular 60 m width and Bikini is about 30 m wide. Former embayed beaches did have such narrow surfaces. The beach of Los Peligros was isolated at high tide (Figure 4). Between the beaches of La Magdalena and Bikini, a small sand spit or salient grew to a length of 50 m (Figure 3) due to the construction of a breakwater in the 19th century (Figure 3A).

The noticeably increasing widths led to the connection of the upper beach of Los Peligros with La Magdalena in total continuity. The beaches of La Magdalena and Bikini always had a small connection in the upper foreshore. Moreover, back and foreshore widths were greatest in Los Peligros beach (110 m), decreasing in a concave arc to the east of Bikini beach (50 m).

Based on SIMAR Point 1065074 (Figure 2D,F), in the XXI century, a historical wave storm was in 2009 (Hs = 13.57 m). Subsequent storms with Hs > 10 m, such as those of 2014 (11.03 m) and 2020 (10.38 and 10.69 m in November and December, respectively) and slightly lower heights in 2021 (8.32 m in January) (Table 1), caused damage and strong erosion on different beaches. In this sense, the general morphodynamic behavior of the study area during these storms indicated erosion on the large upper foreshore, sometimes forming escarpments of 1 m, promoting accretion on the front of the climbing dunes and flooding on the artificial berm in Los Peligros beach. During calm periods, narrow berms in the upper foreshore and a belt of angular pebbles and cobbles formed on the lower foreshore, and sedimentary transport towards La Fenómeno was already taking place (Figure 4). Sedimentary accumulation in the backshore by mechanical means was also frequent.

The western area of La Magdalena beach underwent changes, with notable losses in 2018, and the rest of this beach was subject to losses until the breakwater was implanted in 2018, after which accretion took place at the eastern end. Practically the whole of Los Peligros beach remains with bypassing sands, and La Fenómeno receives most of its eroded sand from the aforementioned beaches.

These beaches behaved reflectively, being highly degraded by the dumping of large volumes of artificial gravels from various civil works since the late XIX century. This was manifested by a steeper lower foreshore (0–5 m) that showed homogeneity with few transversal changes during the sedimentation and erosion cycles (calm and storm conditions, respectively). Further changes can be deduced in the backshore both due to wind sedimentation with strong SW winds promoting aeolian sandy transport to the inner berm of eastern area of Los Peligros and to some active climbing dunes, which reached heights of 10 m in 2012, and due to the artificial reconstruction of the berm of La Magdalena as a recreational area in 2017 (Figure 5). We considered dividing the study area into the following zones:

**Zone 1**. In the western part of the Bikini beach from 2005 to 2017, there was a considerable increase in sand of around 2 m depth (profile 1, Figure 5). Since 2012 (black line), it is noteworthy that this area began to accrete, a process that became more evident in 2018 (Figure 5A).

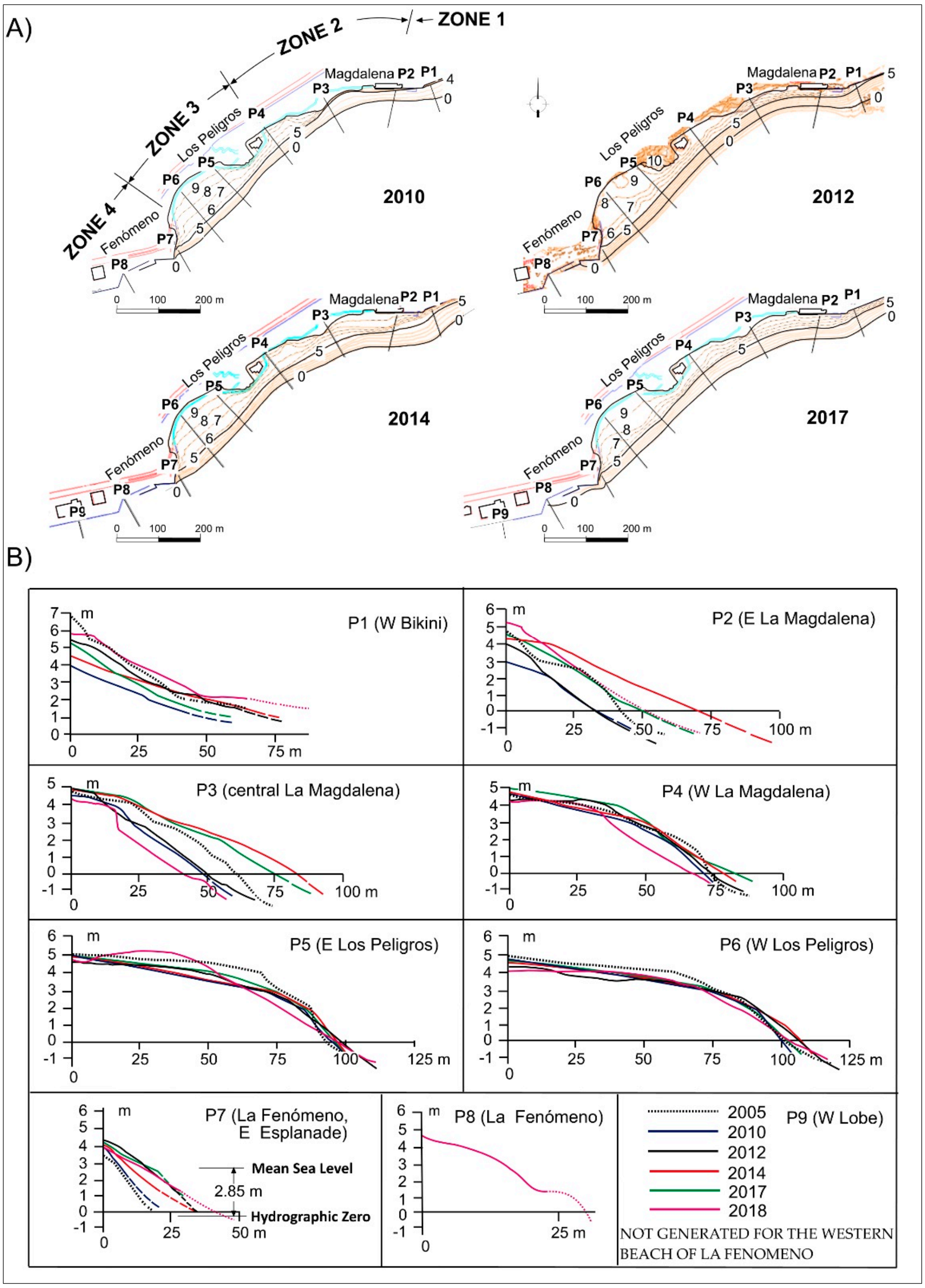


**Figure 5.** (**A**) Los Peligros and La Magdalena in 2005 (only the transverse profiles), 2010, 2012 (LiDAR), 2014 and 2017 from aerial photographs. The highest contour lines of +5 m are highlighted. (**B**) Nine overlapping longitudinal profiles (P1-P9) representative of the years 2005, 2010, 2012 (LiDAR), 2014, 2017 (some of which have been prolonged at its lower end) and 2018 (TLS), which aid in understanding the evolution of the emerged beaches.

**Zone 2**. In the eastern area of la Magdalena, profile 2 was hardly eroded between 2005 to 2012. During 2009 and 2010, this beach (Figure 5A) was a faithful reflection of intense erosions appearing in the eastern half (blue line in Figure 5B), which threatened the stability of the restaurant/old sea-spa building (profile 2). Nevertheless, the most significant loss in volume was suffered during the historic storms of the winter of 2013/14, which narrowed the beach with sharp slopes. Although these storms in February and March 2014 caused significant destruction along the entire coastline, the orthophotograph from the same year shows significant recovery in P2 due to artificial nourishment, mainly from La Fenómeno, which was also conducted in 2017 (green line). Similar accretion occurred in P3, whose minor variations occurred where the berm was located until 2018 (pink line), which was when the greatest losses were incurred in the intertidal belt, and the upper beach took on a bulging appearance (Figure 5B) with vertical variations of up to 3 m. Profile 4 represents a very different state, acquiring a generalized convex shape with very little change, with vertical losses of 1.0 to 1.5 m and with a marked retreat in 2018. Throughout this interval, the dock of El Puentuco (between P4 and P5) had not yet been outcropped.

**Zone 3**. In Los Peligros beach, transverse profiles are smooth, but the foreshore is more reflective without significant variations up to the backshore, mainly due to mechanical sediment distribution, which created a permanent artificial berm (P5 and P6 in Figure 5B). Vertical differences are somewhat greater in profile 5.

**Zone 4**. The first evidence of this beach was from the beginning of this century. Its geometry was similar up until 2012 and was subsequently altered by sand extractions to replenish the beaches of Los Peligros, La Magdalena and Bikini. Its dimensions were significantly reduced by the extractions of 2014, with about 21,000 $m^3$ of sand from La Fenómeno. The growth of this new beach has been evident since 2010, as corroborated in profile 7, in which the slopes are steeper (maximum of 30°) and the progradation is seaward (Figure 5B). Lobe formation to the west had already increased before 2018 (P8).

The records between 2010 and 2018 (Table 2), prior to breakwater construction, represent a loss of 3094.7 $m^3$. The comparison reveals that the maximum erosions occurred on the beaches of Los Peligros and La Magdalena [56], which reached a loss of 22,729 $m^3$ (Table 2). These data, among other considerations, were decisive in proposing the project. During this interval, there were numerous artificial sand transfers from the eastern part of La Fenómeno (P7 and 8) to other western beaches, interventions which were not counted, and the final balance of La Fenómeno was a gain greater than 3242.8 $m^3$. In terms of annual rates, the broad period from November 2010 to November 2018 [56] reached losses of 386.84 $m^3$/yr in this sector.

**Table 2.** Sedimentary balance ($m^3$) between 2010 and 2018, both in November, which indicate that there was a general loss of sand on these beaches [56].

| Beach | La Fenómeno | Los Peligros and La Magdalena | Breakwater of La Magdalena-Bikini | Bikini | Total |
|---|---|---|---|---|---|
| **Gain ($m^3$)** | 3242.8 | 3097.5 | 11,452.7 | 8039.5 | 25,805.5 |
| **Loss ($m^3$)** | −688.1 | −22,729.0 | −215.2 | −5267.9 | −28,900.2 |
| **Balance ($m^3$)** | 2554.7 | −19,631.5 | 11,210.5 | 2771.6 | −3094.7 |

#### 4.3.2. Evolution Following Breakwater Construction (2018–2021)

To better understand variations in the beach during this period, the same nine most representative cross-shore profiles were obtained (Figure 6). Detailed observation of the profiles revealed the characteristics of their shapes. They were perpendicular to the beach line and related to seasonal changes, and the evolution of changes in the longitudinal direction will serve to complement the knowledge of the volumes obtained between two consecutive records and of the total, which will mark the trends of gains and losses of sediment.

After the construction of the breakwater of La Magdalena (summer 2018), TLS monitoring was first carried out in the autumn of 2018 to record the initial state of the beaches. The position of the tide prevented access to the lower foreshore belt, which is why the data were extrapolated to zero.

Consecutive records were quantitatively calculated in November 2018, March 2019, October 2019, March 2020, October 2020 and April 2021. The last one was made in April 2021, as well as the total from the first to the last (Table 3, Figure 6). Figure 6 was drawn up in a simplified format to facilitate a clear comparison.

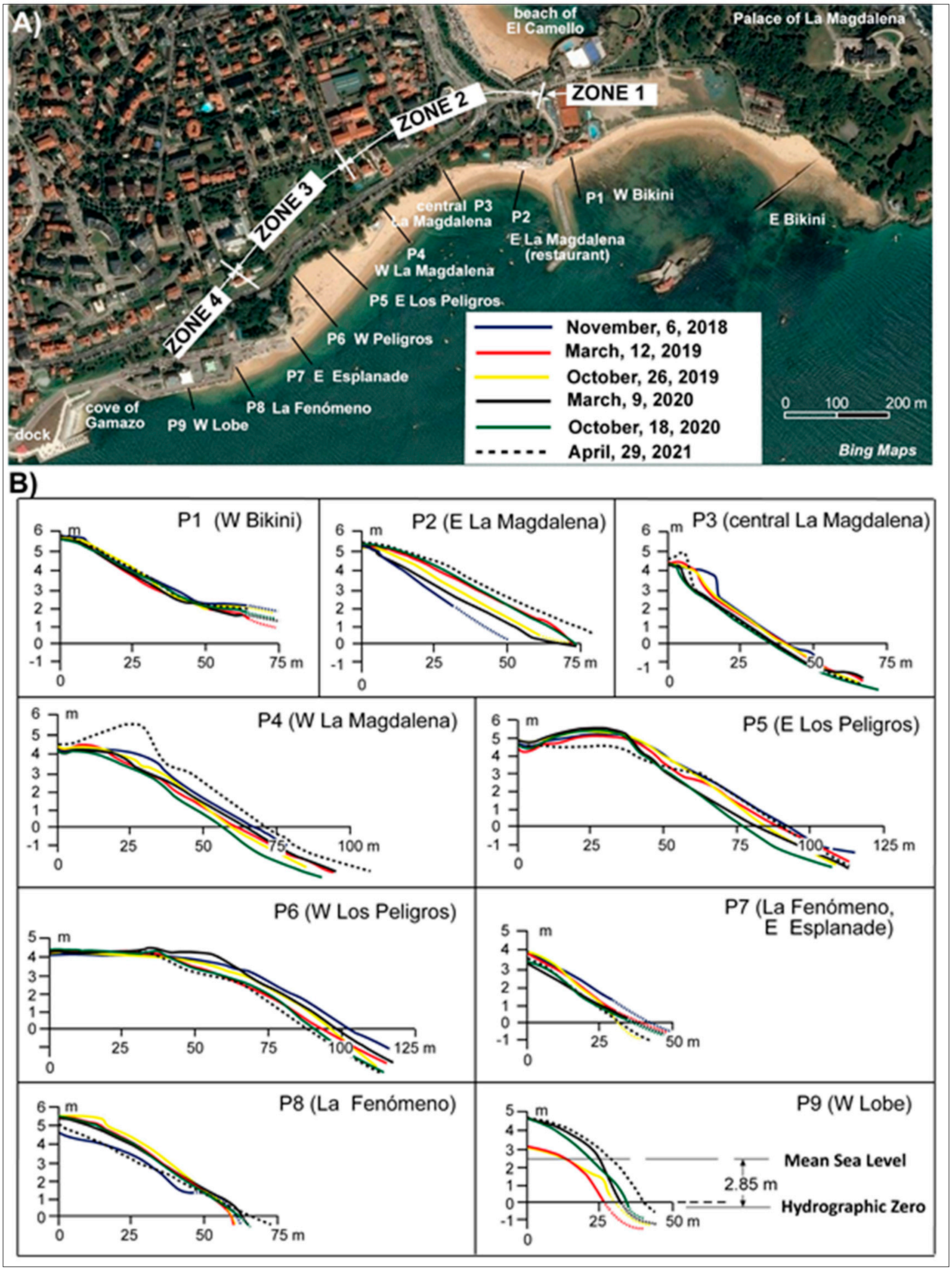


**Figure 6.** (**A**) Situation of the nine transverse beach profiles (P1-P9) from 2018 to 2021. (**B**) Overlapping profiles from western Bikini (P1) to the lobe (P9) of La Fenómeno to obtain the first picture of the temporal evolution.

**Table 3.** Sedimentary balances ($m^3$) between two consecutive records and the total balance from November 6/2018 to April 19/2021, showing the general gains and losses of sand after the construction of the breakwater in summer 2018.

| Zone | Since | To | *Erosion* ($m^3$) | *Sedimentation* ($m^3$) | Balance ($m^3$) |
|---|---|---|---|---|---|
| Zone 01 Bikini | 2018/11 | 2019/03 | 21.96 | 2318.97 | 2297.01 |
| | 2019/03 | 2019/10 | 84.44 | 2744.51 | 2660.07 |
| | 2019/10 | 2020/03 | 2103.31 | 1971.48 | −131.83 |
| | 2020/03 | 2020/10 | 665.38 | 1714.38 | 1049.00 |
| | 2020/10 | 2021/04 | 3476.05 | 740.67 | −2735.38 |
| ***beginning to end*** | ***2018/11*** | ***2021/04*** | ***424.03*** | ***908.31*** | ***484.28*** |
| Zone 02 Breakwater of La Magdalena-Bikini | 2018/11 | 2019/03 | 4619.00 | 343.20 | −4275.80 |
| | 2019/03 | 2019/10 | 3284.59 | 12,23.53 | −2061.06 |
| | 2019/10 | 2020/03 | 5056.26 | 708.01 | −4348.25 |
| | 2020/03 | 2020/10 | 4840.48 | 269.03 | −4571.45 |
| | 2020/10 | 2021/04 | 4378.72 | 492.48 | −3886.24 |
| ***beginning to end*** | ***2018/11*** | ***2021/04*** | ***19,604.86*** | ***554.09*** | ***−19,050.77*** |
| Zone 3 Los Peligros and La Magdalena | 2018/11 | 2019/03 | 3369.90 | 1758.92 | −1610.98 |
| | 2019/03 | 2019/10 | 2224.06 | 2643.95 | 419.89 |
| | 2019/10 | 2020/03 | 4147.84 | 4300.60 | 152.76 |
| | 2020/03 | 2020/10 | 2913.37 | 1101.08 | −1812.29 |
| | 2020/10 | 2021/04 | 1957.30 | 3803.78 | 1846.48 |
| ***beginning to end*** | ***2018/11*** | ***2021/04*** | ***10,152.03*** | ***5393.87*** | ***−4758.16*** |
| Zone 4 La Fenómeno | 2018/11 | 2019/03 | 493.90 | 7.05 | −486.85 |
| | 2019/03 | 2019/10 | 71.99 | 485.11 | 413.12 |
| | 2019/10 | 2020/03 | 557.97 | 33.73 | −524.24 |
| | 2020/03 | 2020/10 | 35.39 | 417.92 | 382.53 |
| | 2020/10 | 2021/04 | 50.83 | 177.80 | 126.97 |
| ***beginning to end*** | ***2018/11*** | ***2021/04*** | ***250.83*** | ***141.36*** | ***−109.47*** |

**Zone 1**, represented by Bikini beach, is one of the areas with the least variation during the measurement period (109.47 $m^3$), with alternating periods of gains and losses, though they were not significant. Since November 2018, profile 1 has decreased slightly, and the greatest variations were caused by the construction of a low tide bar (Figure 6B). As a whole, it acquired a distribution typical of a perched beach.

In **Zone 2**, due to the construction of the breakwater, maximum sedimentation takes place in the sheltered area (east of La Magdalena). The topmost area of the beach preserved the same height, and the foreshore prograded seaward during the studied interval (profile 2, Figure 6B), with gradual widening. The upper profile of the beach was more convex than that of the present day and has become narrower (Figure 6A). This change in the width of the profile is fundamental to the impact of storms in terms of the damage they cause.

The volume of sand decreased, and the beach narrowed considerably in central Zone 2 (profile 3, Figure 6B), but vertical variations barely exceeded one meter. The upper beach in the profile of April 2021 (black dashed line) represents artificial stacking after a wave storm in January, which was recorded in profile 4 (Figure 6B), where more sand was accumulated.

In the western part of La Magdalena (**Zone 2**), the beach widened, even to the west (profile 4, Figure 6B). Its vertical variations are more important than those in profile 2 previously. The stockpiles made during 2021 are evidenced by a very pronounced berm on the backshore and by gains of almost 2 m (black dotted line).

In **Zone 3**, until October 2020, the overlapping profiles (P5) revealed a retreat of the beach (Table 2), but before April 2021, it recovered, except for the upper beach, which was intensely eroded (profile 5, Figure 6B). The western beach of Los Peligros retained the almost-unaltered artificial berm (upper beach), but the foreshore was heavily eroded more than 1.5 m vertically (profile 6, Figure 6B).

**Zone 4** is a complex sector due to the arrival of sediment from the previous zones and is dredged from time to time to return the sediment. The eastern zone can be considered a bypassing corridor, narrower 15 m, which gradually widened slightly until 2021 and whose foreshore varied by about 0.5 m vertically, with very constant slopes (profile 7, Figure 6B). The most representative profile of La Fenómeno beach (P8) shows the increasing convexity of 60 to 70 m wide. In this area, the transverse records of November 2018 and April 2021 are very similar, but they regularize the profile with a straight slope.

Finally, lobe deposits on the western beach of La Fenómeno (profile 9, Figure 6B) since March 2019 are represented as about 25 m width, gradually increasing, even in 2021 (40 m). The profiles show a considerable increase in the vertical of the emerged beach, with about 2 m of sand gain between the red profile (March 2019) and the last record (April 2021), which is related to sedimentation progressing westwards.

4.3.3. Quantitative Gains and Losses

During this monitored period, a total loss of sandy volume occurred in the emerged beaches of western La Magdalena and eastern Los Peligros, including the destruction of small berms and eroding the fronts of climbing dunes due to the occurrence of strong wave storms, much more so in the winter or early spring (Table 3 and Figure 7).

The first one shows the effects of washing and transporting material to the southwestern areas (profiles 3 and 4), which continue on the beaches of Los Peligros (profiles 5 and 6) and La Fenómeno (profiles 7, 8 and 9).

Once the breakwater was built, gains in sand were produced in the backshore of western Bikini (Zone 1), but an overall volumetric loss of only 109.47 $m^3$ was certified (Table 3, Figures 6 and 8), thus making it become even more independent from the rest of the beaches. Prior to 2018, this environment registered vertical variations of up to 2 m (profile 1, Figure 5B), indicative of an active dynamic in the construction of the back beach. It is one of the areas with the least variation during the measurement period, with alternating periods of gains and losses, but they were not significant.

On the beach of La Magdalena (**Zone 1**), the maximum sedimentation (>1.0 m) occurred in the eastern upper foreshore and backshore (Figure 8, blue surfaces) due to the shadow effect produced by the breakwater. Despite the sediment distribution carried out by the local council's machines, vertical sediment losses of up to 1 m in Zones 2 and 3 (Figure 7) began to appear, to the extent of the western limit of **Zones 2 and 3** in 2019. The El Puentuco breakwater, with an orientation perpendicular to the shoreline, began to outcrop and emerged in its entirety from the first months of 2020, retaining part of the sand drift in the eastern side (west of the Figure 9), and on the downstream side (Los Peligros beach) it showed erosion with a sand deficit (east of the Figure 9). This structure had not surfaced for decades except in exceptional storms, but it has now become just another element on the beach.

When volumes between the first (2018) and the last measurements (2021) were compared, two defined erosion belts were observed in the western zone (red surfaces: <1.0 $m^3$). In **Zone 2**, there was a significant sedimentary loss, with up to 4758.15 $m^3$ of displaced sedimentary volume (Table 3, Figures 7 and 8).

**Zone 3** of Los Peligros underwent double erosion by storms on the upper beach (short times) and by beach drift (broader area) in the lower foreshore, which occurred over longer periods, both separated by a dashed white line (Figure 8). The maximum sand loss took place in Los Peligros, where the backshore was artificially maintained (profiles 5 and 6) by stockpiling and machinery movements; however, even in 2021, there was erosion of more than 1.0 m of vertical loss. There was widespread loss in the foreshore, which has occurred gradually since 2018 and became more pronounced in 2021. The loss rates are very marked, reaching −19,050.77 $m^3$ (Table 3, Figures 7 and 8).

Much of this sediment has ended up settling in the submerged zone and has increased the surface of La Fenómeno (**Zone 4**) to form a lobe (Figures 7 and 8) which, during spring low tides can be seen further south where the rocky cove of Gamazo has been covered (Figures 1C and 4) since summer of 2021. No nourishment was carried out between November 2018 and April 2021 except for a calculated sand volume involving a total gain of 484.28 $m^3$ (Table 3, Figures 7 and 8). This sediment must be considered, as this sand volume will never return to the beach system. For almost two and a half years of this work, from November 2018 to April 2021, it resulted in gains of 200.12 $m^3$/yr.

There was sediment coarsening in lower intertidal bottoms and shallow submerged beaches due to the beach drift, which transported the sandy fractions predominantly and was the only fraction in the lobe of western La Fenómeno. Moreover, angular gravels and shells gradually outcropped to form a concentrated deposit along the western half of La Magdalena, all the beaches of Los Peligros and the eastern area of La Fenómeno, increasing from 2018 to 2021.

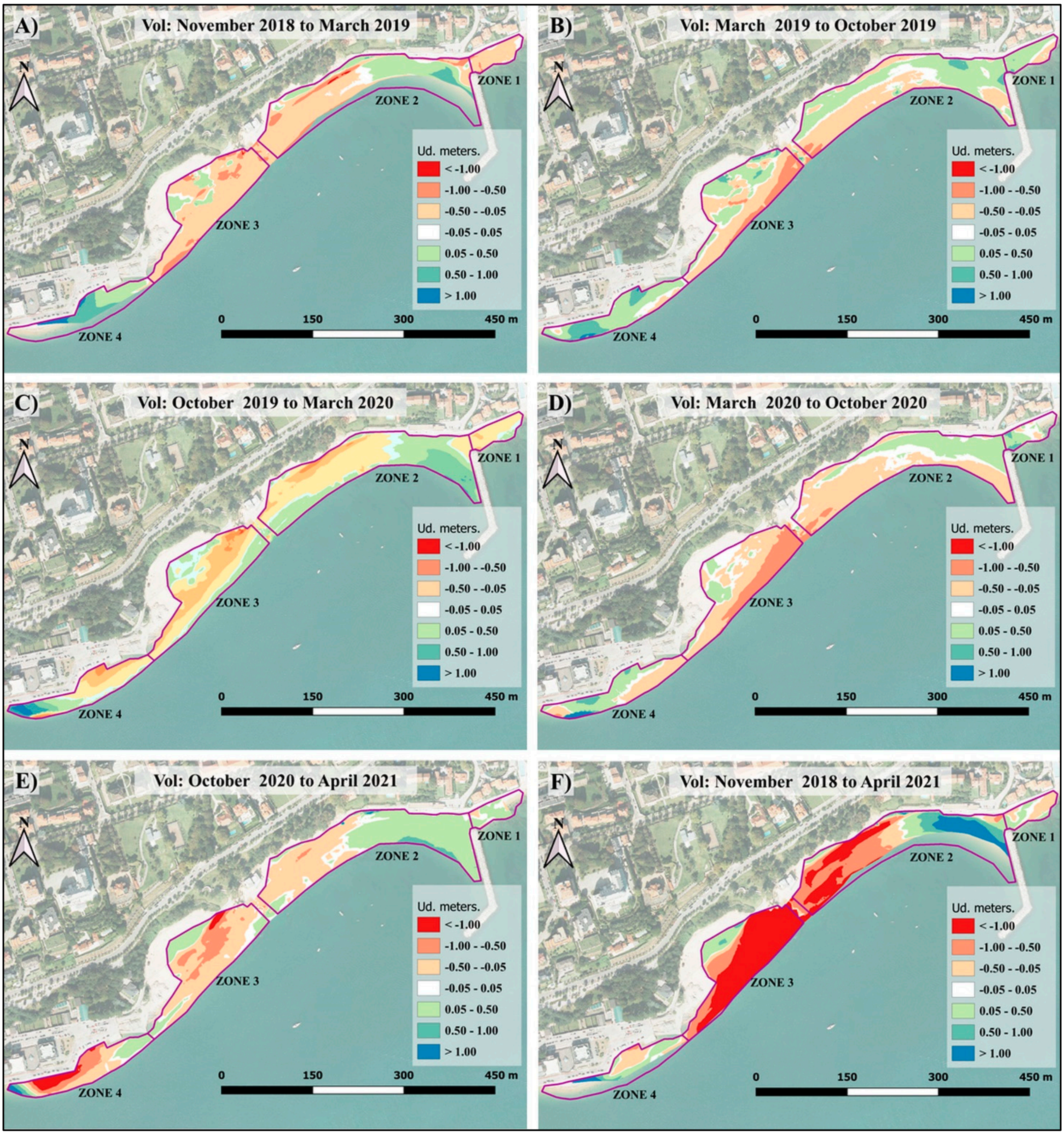


**Figure 7.** Comparison of beach sand surplus and deficit surfaces: (**A**) November 2018–March 2019. (**B**) March 2019–October 2019. (**C**) October 2019–March 2020. (**D**) March 2020–October 2020. (**E**) October 2020–April 2021. (**F**) Final summary: November 2018–April 2021.

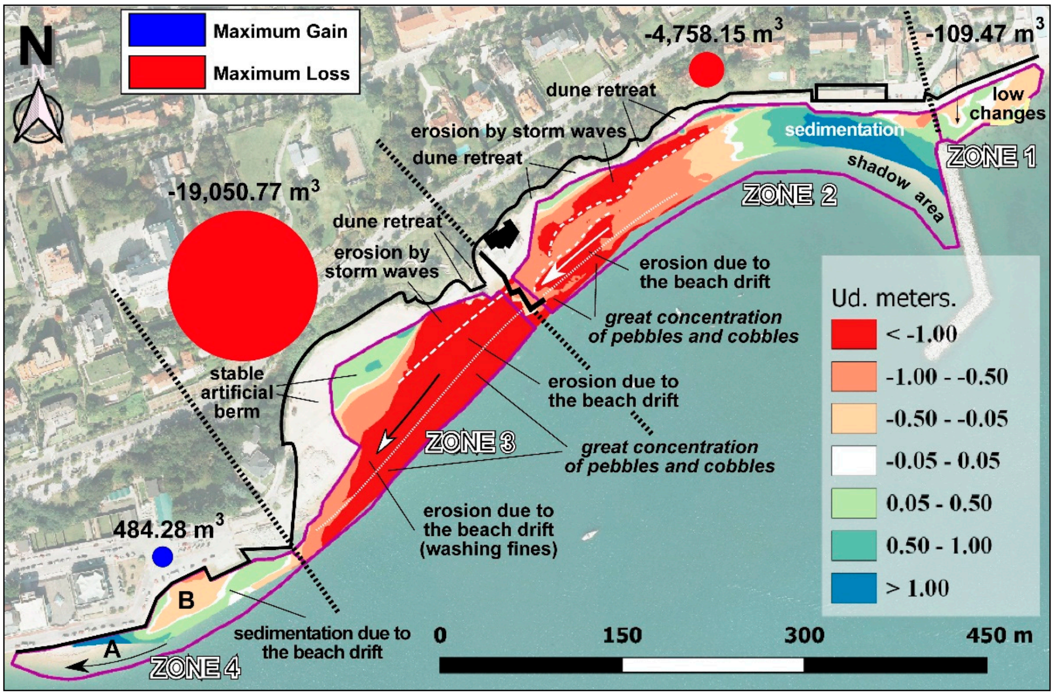


**Figure 8.** Synthesis of sedimentary balances between November 2018 and April 2021, and morphosedimentary dynamic trends; erosion occurred in the foreshore, backshore and dune fronts of Los Peligros and eastern La Magdalena, with main sedimentation in the sheltered area of the breakwater and the lobe of La Fenómeno. Persistent beach drift occurred southwestward.

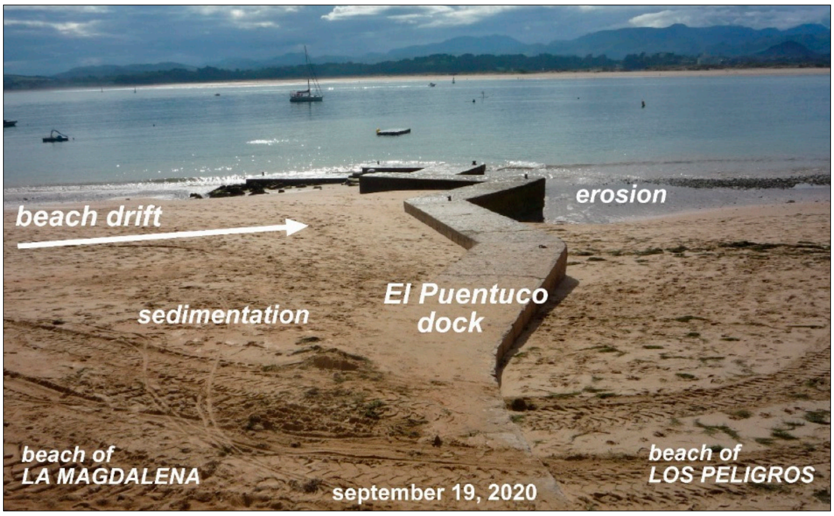


**Figure 9.** El Puentuco dock is situated at the dividing point between Zone 2 (La Magdalena) and 3 (Los Peligros). It has been covered by sand in the last decades and became visible in 2020 after the construction of the breakwater. Now, it retains part of the sand drift from La Magdalena.

## 5. Discussion

### *5.1. General Features*

The submitted work is yet another example of how a project conducted to build rigid structures on an urban beach can have detrimental effects on the dynamics and sedimentation of the system. For this research, theoretical modelling was put aside, and a laborious campaign of in situ mapping and topographic measurements using GNSS and TLS was carried out over a period of more than 3 years. TLS techniques combined with GNSS and photogrammetry were applied and gave satisfactory results on the coast of Cantabria by de Sanjosé et al. 2018 [69]. Consequently, they were applied to these beaches in order to maximize accuracy for calculating sand volumes for more than 3 years. Quantitative data are thus available that allow for decisions to be made in the management of these beaches.

In order to understand the problems that have arisen and attempts to conserve sediment on urban beaches, it is necessary to take into account the extreme storm events that continually shake the Atlantic coastline and the Cantabrian coast in particular. Despite the fact that many wave storms have been recorded in the last 70 years, it is during the 21st century that an increase in the recurrence of strong storms was detected in the Cantabrian Sea and Atlantic [70], affecting beaches, coastal dunes and infrastructure, such as in Somo, the sand-spit mouth of Santander estuary [69] across the bay from our study area. For example, in the Peñas buoy in Asturias, previous winter storms registered 12.18 m in December of 2007, which represented the beginning of the dune recession on the Cantabrian coast. Moreover, a surge storm called "Klaus", measuring 10.10 m (maximum Hs) in January of 2009, showed similar results in France, in which the maximum significant wave was 12.3 m with a period of 11.13 s [71]. The storm "Becky" in November 2010 [72] affected the Bay of Santander, bringing wave heights of around 8 m and a storm surge of 0.6 m [73], causing serious damage. Sea level rise, storm surges and erosion will affect the size of the beaches in Santander [74], and the municipality of Santander estimates the costs of damages and the subsequent clean-up to exceed €400,000 alone for this sole event [72].

Nevertheless, as a result of the historically destructive storms of February and March 2014 [39,69,75–77], a turning point appears to have been reached, and through their actions, authorities are beginning to consider proposals to mitigate future damages. During these and previous storms, these beaches suffered strong erosion and damage to public facilities, so these events justify this proposal. Areal erosion processes occurred cyclically, with wave heights greater than 6 m (Table 1), which was the strongest event in November (10.38 m) and December (10.69 m) 2019, and with dilated rugged waves from October 2020 to March 2021.

These storms were very pronounced in the eastern sector of La Magdalena (150 m), including the building of the old sea-spa/restaurant, the attached ramp and another 65 m of the upper beach, gradually dissipating towards the W. In the beach of Bikini, waves are reflected against the wall, preventing the formation of the berm. Subsequently, authorities built artificial sandy prisms, extending the upper beach as a recreational area for users (Figures 10 and 11A).

Knowing the previous dynamic model and the dynamo sedimentary behavior in the monitored years, the current dynamic model can be inferred (Figure 10). A portion of the sediment is carried along the shoreline and is redeposited westward of La Fenómeno (Figure 11B), where the lobe migrates in that direction (Figure 11C).

In the coastal zone, storm waves cause sediments to move foreshore and shallow offshore in the short-term, forming a sandy prism that lowers the foreshore slope and buries the angular gravels (Figure 11D), and fair-weather waves and swell return the sediments shoreward [78]. Wave storms mainly erode the backshore, and the foreshore and seasonal berms are eliminated. The front of the climbing dunes is eroded, including, preferably, those on both sides of the San Marcos point (Zone 3). The greatest effects are concentrated from the east of Los Peligros to the La Magdalena beach in its entirety, both before (Figure 11F) and after the breakwater was built (Figures 4 and 10). A portion of the sediment is carried along the shoreline and is redeposited west of the La Fenómeno (Figure 11B), where the lobe migrates in that direction (Figure 11C). Broken waves can sweep the artificial berm of Los Peligros much more strongly during high tides in the spring and can cause flood damage to urban furniture. It is concentrated with greater virulence, which affects the containment walls of the restaurant (Figure 11G) and the upper beach at the western end. They also dismantle the wooden walkway (Figure 11H) in some areas along the way (Figure 11E–G,I–L).

Once the weather calms the constructive equilibrium profile of the beaches [79] in a long-term building trend (accreting conditions), the sand drift slowly moves great sand volumes longitudinally along the beach. This is the most important sedimentary dynamic that requires sustainable management and which the construction of the breakwater has been unable to slow down. This highlights the creation of an energy shadow zone to the W of the breakwater, the continued activity of beach drift and the progressive appearance of angular gravels in the lower foreshore and shallow subtidal (Figure 11E).

The process is completed by the continued loss of sand and the rocky cove of Gamazo (Figure 11N) becoming filled, thus turning it into a new sandy beach (SW) resting on a concrete ramp. Contrasting the previously described beaches (Figure 12A) and following this construction, a longitudinal elongation of the set of emerging beaches (Figure 12B,C) is observed, growing uninterruptedly in the western area (La Fenómeno). Throughout this year of 2022, the sandy flow has increased with the filling of Gamazo beach (Figure 12D), which will continue in the future. Basically, the same dynamic and sedimentary trends remain.

In summary, with the construction of the breakwater, Bikini beach is almost totally isolated from the dynamics of the remaining beaches, with episodic small exchanges in its upper part and the adjacent beach of La Magdalena. Most of the year, under calm conditions, waves enter with heights of less than 0.5 m, and the upper foreshore remains unchanged. Nevertheless, between La Magdalena and La Fenómeno, a narrow berm (5–6 m wide) is built, best developed in Los Peligros (Figures 8 and 10), and a steeply sloping foreshore seaward gradually decreases the slope on the submerged beach (Figure 8).

Clearly, the plan shape of La Magdalena beach has changed, becoming more concave seaward in the sheltered area of the breakwater (Figure 12B–D) compared with the previous morphology (Figure 12A). The effects of storms are more destructive, generating erosive steps above 2 m in height (Figure 11H–K), backshore narrowing and the disappearance of the sandy prism in front of the restaurant, as occurring in 2018 (Figure 11G) as well as on walkways and promenades (Figure 11H–K).

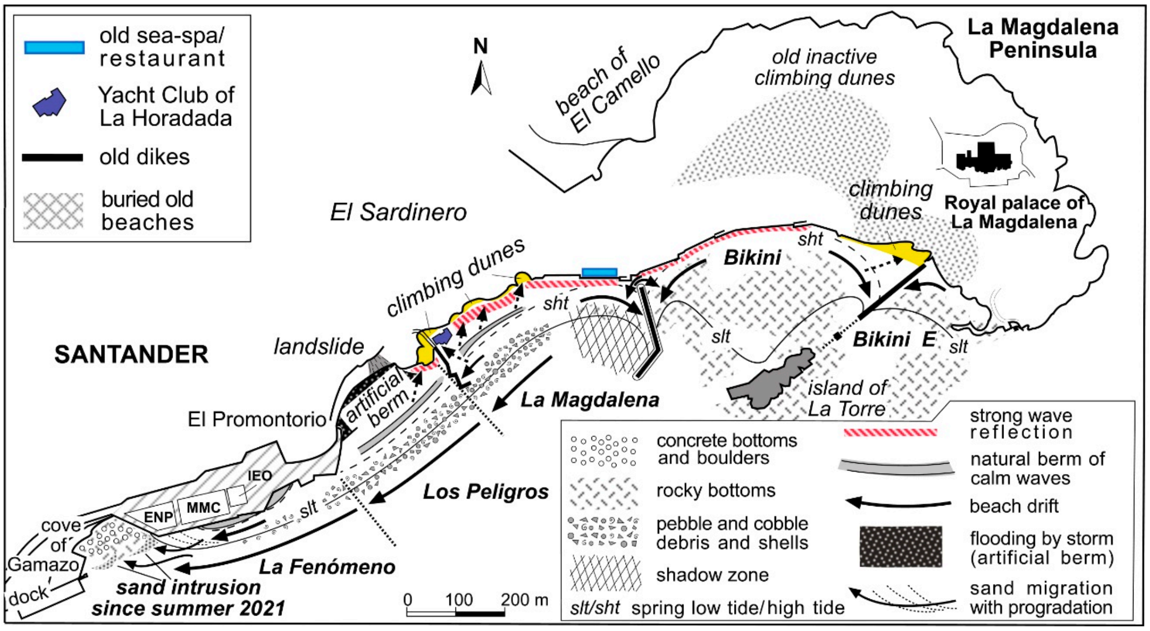


**Figure 10.** Morphodynamic conceptual model after the construction of the breakwater (2018), highlighting the following main processes: reflection in the upper beach during storm, which has only been artificially recovered; westward beach drift; and aeolian transport to the small outcrops of climbing dunes mainly of Los Peligros and La Magdalena. The former cove of Gamazo, with calcareous and concrete bottoms and boulders, is turning into a sandy beach.

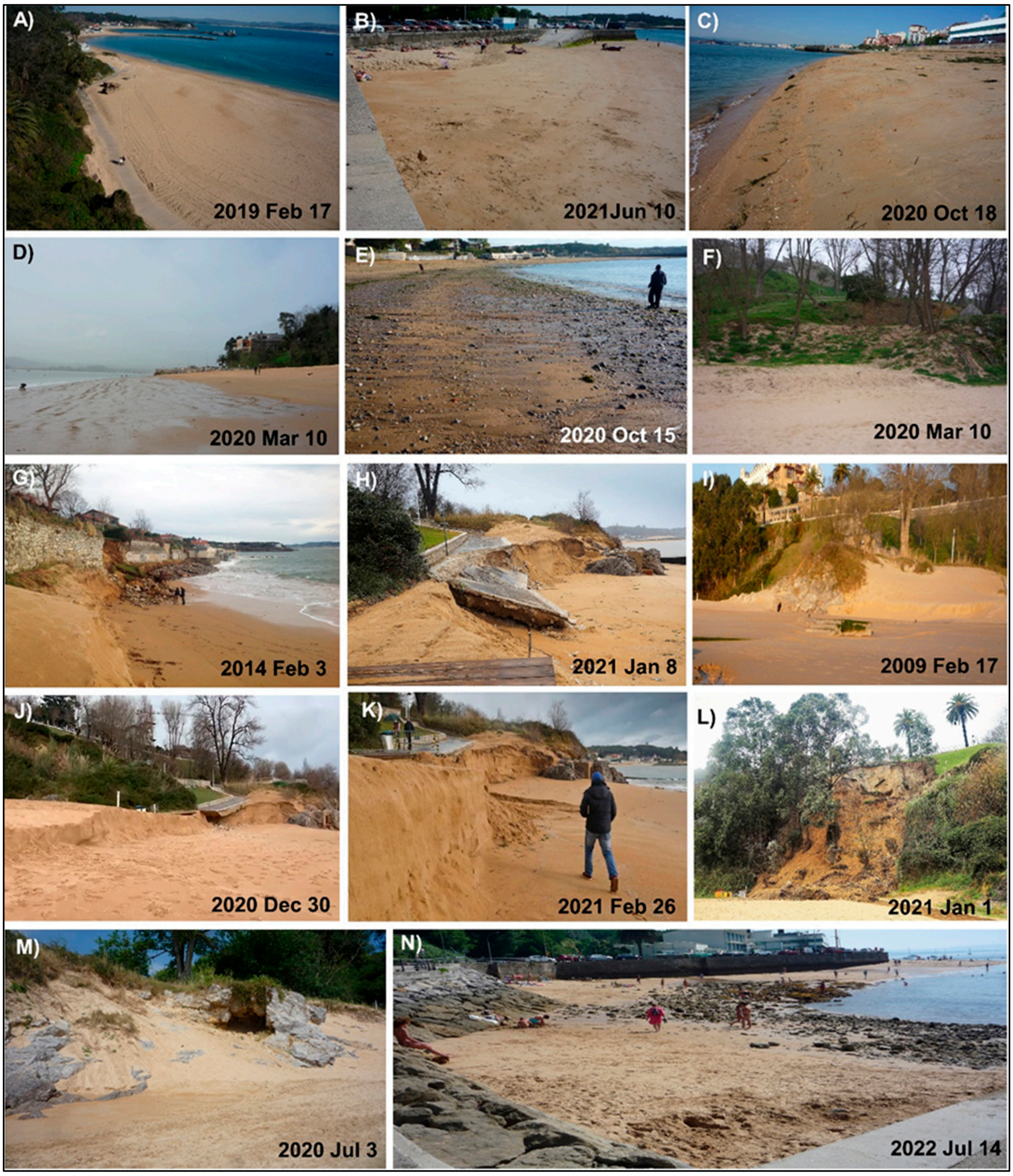


**Figure 11.** (**A**) The broad artificial berm at Los Peligros beach, affected by storm floods. In the background is the breakwater built in 2018. (**B**) Small upper beach of La Fenómeno after a storm. (**C**) Sand lobe migrating westward (background). (**D**) Sand prism built in the foreshore (wet belt) after a wave storm. (**E**) Lower intertidal beach (western half of La Magdalena). The angular gravels have concentrated due to strong washing by beach drift. (**F**) Partially vegetated climbing dunes (W La Magdalena). (**G**) Destructive effects in La Magdalena beach in 2014. (**H**) Accesses destroyed during the storm in January 2021 in Los Peligros. (**I**) Active climbing dunes on both sides of San Marcos Point (grey limestones), with an erosion scarp. (**J**) Erosive scarps in the upper foreshore of Los Peligros and strong erosion on the climbing dune. (**K**) Detail of the escarpment up to 2 m, after two months with respect to the previous H. (**L**) Landslide developed at the cliff of Los Peligros (storm of 31 December 2021). (**M**) Intense erosion on the climbing dunes (W of La Magdalena). (**N**) New beach of Gamazo. Rocky cove has begun to be filled with migrating sands, since summer 2021, from La Fenómeno (view from the west side).


**Figure 12.** Google Earth satellite images: (**A**) Changes in the beach plan shape of La Magdalena beaches before the construction of the breakwater in 2014. (**B**,**C**) Afterwards in 2020. (**D**) In 2022, with the profile modified by the redistribution of sediment with machinery. The western Bikini beach grew towards the breakwater, as well as the foreshore of La Magdalena, and the eastern half of La Magdalena widened.

Another relevant fact is the evolution of the shoreface of all beaches of La Magdalena, which reflects a loss of sand, since the surface of the beaches increased through the artificial addition of sand, after which it was decided to not add more sand. The latest storms have not been as intense as those of 2007, 2009 and 2014; of January and February 2016; of February and March 2017; of December 2017; and of January 2018, with the exception of those of November 3 (10.38 m) and December 22 (10.69 m) 2019. However, the change in the profiles of the beaches was very marked, so, in December 2020 (several events) and January 2021, storms occurred with wave heights greater than 9 m and durations of 93 h and 33 h, respectively (Figure 2F, Table 1). Access to Los Peligros beach was destroyed (Figure 11J,K), and rain and the impact of the waves caused the back slope of this same beach to fall (Figures 8 and 11L), which had never happened before the change in the concavity of the profile of this beach.

### 5.2. Sustainable Solutions

In recent decades, on La Magdalena beaches, sand nourishment has been widely applied, and there is still debate as to whether this is the best solution to the problem of beach erosion [15,80]. The most important advantages of sand nourishment are that they (1) are flexible and allow the cost to be spread; (2) do not necessarily disturb recreational beaches; (3) are less expensive than breakwaters; and (4) match the natural character of the coast [81]. This solution is used to maintain recreational beaches, and in recent years, sediment has been obtainable from a submerged sand deposit whose characteristics must be compatible [82], mainly in terms of grain sizes and quartz/carbonate bioclasts, with those of the beach. Otherwise, at least, a solution approximate to this can be used. It is also essential to estimate the amount of sand needed for beach nourishment [83].

Beach nourishment can also involve beach bulldozing or scraping, dune creation, restoration and reshaping. Beach maintenance is often carried out by scraping [84], which consists of redistributing sand on the beach from the intertidal or submerged zone to the upper beach by mechanical means (bulldozing).

The ideal scenario is to carry out beach nourishment to at least maintain what has been performed throughout the 21st century, which is to supply enough sand to achieve the natural stability of the beach [85]. For this reason, the simplest and cheapest way to regenerate it is to take sand from the beach itself in areas of excess; other possibilities focus on the continental platform, the submerged beach front, rivers or some sandbox of the Quaternary or older formations, etc. [86].

According to the placement of the sand fill, nourishment includes [87] coastal dunes, the subaerial beach (berm), profile nourishment (subaerial and submerged) and bar or shore face nourishment (submerged fill). It takes into account the beneficial action of management through the discharge of sandy sediment as the cheapest and most sustainable practice, eliminating any future project of implementation of rigid structures.

A conceptual change has been sought in the management of these beaches based on the results offered by morpho-dynamic and sedimentary variations, thus favoring better management [24]. Faced with this reality, the balance of beach systems requires intervention to reproduce the most important morphologies, such as berms during the summer, which are the places that are in the highest demand for sunbathing.

The current practice of shore nourishment has been described in Germany, Denmark, the Netherlands, Belgium, Spain, the UK, the USA and Australia [24], and since 1993, the Spanish Environmental Ministry has been conducting an integrated program to restore existing beaches and build new ones [88].

Few articles have reported the experiences made in Spain about beach management despite the fact that many beaches have been intervened with greater assiduity in the Mediterranean [12] with the so-called process of "mediterraneanisation", supporting the 'sun and beach' tourist industry since the developmentalism of the 1960s [89]. Some of these studies are related to theoretical analyses [13,88,90].

Some studies in Andalusia (S. Spain) focused on the most common practice of beach regeneration, for example, on the beach of El Portil (W. Huelva). The work consisted of two phases: sand is applied in the spring, and another greater supply is applied for the summer season [20]. Moreover, in the province of Alicante [91], six beaches were analyzed from aerial images over a period between 1956 and 2017, during which the filling material was lost, returning the beaches to their initial state and even causing environmental damage to the nearby *Posidonia oceanica* meadows.

On the other hand, in the north of the Iberian Peninsula, some nourishment projects of beaches have been carried out but with coarse sediments. The best-known beaches are worth mentioning, such as those of Riazor and Orzán (Galicia); Salinas; El Gayo and Arbeyal in Asturias; the new gravelly calcareous beach of Ostende in Cantabria [27]; and Bakio, Laida, Ondarreta and La Zurriola [92] in the Basque Country. In our case, what is clear is that this rigid construction has triggered a change in morphodynamics, which has made the system more fragile in the face of storms, which are not always extraordinary. In previous reports to the administration, some of the authors of this study have proposed that, for nourished beaches in semi-natural environments, such as La Magdalena (i.e., San Lorenzo beach-Gijón, Asturias), the original grain size of the beach, similar biogenic carbonate content and, if possible, a similar sediment color should prevail. Nourishment with sand with a different color potentially induces controversy among stakeholders, such as that which occurred in some parts of Italia, where the preference of beach users included a prevalence of light-colored sand (Pranzini et al., 2010). These studies should be performed by instrumental analysis within certified and perceptually uniform color spaces, as have been applied in different coasts of Europe [93,94].

The idea of completing the project to build the SW breakwater does not imply an improvement in the dynamic behavior of the system, as the transverse profile of the resulting beaches would continue to be concave, and the sediment would continue to be lost.

As far as the current short-term scenario is concerned, intense erosion caused by wave storms requires urgent repositioning. However, due the loss of sand over the lobe (A), there have been important changes, such as the long-term need for nourishment, preferably from the environment (B) of the beach of La Fenómeno (Figure 8). The same mineralogical composition is an added positive factor when deciding on the transfer of sand.

### 5.3. Suplementary Performances

There is a need, preferably through nearby dredging, to obtain a volume of sand of around 48,000 $m^3$ for the final balance configuration and to distribute it among the most used beaches, such as Los Peligros and particularly La Magdalena to preserve the most suitable recreational areas.

Some sustainable solutions have been suggested for the best use of these beaches, of which the most important is the prompt replenishment of sandy volumes lost following intense erosion by severe wave storms. It is advisable to replace the most sensitive morphologies, particularly in front of sites where the largest retreats have occurred (old sea-spa/restaurant). Another necessary intervention is the elimination of angular debris (Figure 11H), which has been artificially introduced over the last 50 years, because it obstructs walking and bathing activities on the beach, the replacement of wooden walkways, etc.

If suitable action is not taken within a few years, the sands will invade the rocky cove of Gamazo, creating a new sandy beach, a very fast process, as evidenced after the last record in April 2021 and recently (Figure 12D). The surface of the cove of Gamazo, about 2580.4 $m^3$, is being filled relatively quickly with sand from the lobe (Figure 11N). A recalculation of the volume of introduced sand was carried out due to the high speed of the change. Assuming an average sandy thickness of 0.65 m, the volume was calculated to reach 1677.26 $m^3$ by the autumn of 2022, which is about 3.5 times the volume of losses from 2018 to 2021 (484.28 $m^3$). It may also be the case that the authorities know this dynamic and prefer to wait for a new beach space.

The existing wooden walkway should be replaced in order to minimize damage usually caused by storms. There are printed concrete slabs in imitation wood that are very resistant, which is a solution applied to many beaches. Suggested measurements for rectangular slabs are $0.8 \times 2.0$ m with a thickness of 0.15 m, which should be enough for this case. Prior to the summer of 2022, the municipal authority decided to eliminate this infrastructure.

Extreme wave and storm events are occurring more and more frequently, and as the volume of sand decreases, the width of these beaches is also quickly decreasing. Consequently, damage is increasingly common, and maintenance is more expensive. Moreover, it should not be forgotten that the role of sea level rise is difficult to evaluate and that it has the potential for a greater retreat in the long term.

Finally, the extraction of sand must be carried out on the foreshore for its discharge in the upper foreshore and backshore. The existence of the port of Santander, whose navigation channel needs to be dredged regularly, has the advantage that these sandy bottoms can be used for this purpose, since their mineralogy and average grain sizes are compatible. However, the needs of the beaches of Somo and Loredo cannot be neglected, as they are clearly in a process of regression. The discharge of 27,061 $m^3$ by dredging the submerged bottoms at the mouth of the Bay of Santander, as contemplated in the project, should not be ruled out.

## 6. Conclusions

Techniques of photogrammetry were applied for the topographic reconstruction of emerged beaches (2.5 m below topographic zero, lower foreshore) up to the breakwater construction, where the erosion–sedimentation processes of the beaches and the consequent sandy drifts mainly occur.

During the research period with remote sensing (TLS and GNSS), from November 2018 to April 2021, after the construction of the breakwater of La Magdalena, the energy levels of incident waves have increased, which, together with the suspension of the sediment redistribution work and the construction of artificial berms, has contributed to the maintenance of the E–W sandy drift from the beach of La Magdalena to Los Peligros and La Fenómeno.

The cross-sectional profiles carried out between 2018 and 2021 in the four areas revealed the gradual loss of sand in the distal area of the beaches (westward), which means that the constructed breakwater has not stopped or slowed down the drift process, consequently demonstrating its inefficiency.

Wave storms have caused erosion processes and similar damage levels, which have been concentrated in the same back areas of the spa and both sides of the Point of San Marcos, and flooding has occurred in the upper part of Los Peligros, as they had before the construction. This has only served to increase sedimentation in the shaded area, shaping a typical parabolic plant but without the construction of the calm berm. Moreover, it has been verified that the operation of new breakwater erosion processes have intensified, with strong retreats of dune fronts as well as increased outcropping of angular gravels. Consequently, they revealed the uselessness of its construction.

Throughout the study period from 2018 to 2021, without any transfer, meaning that the drift was free of any intervention, the calculated sandy volume of 484.28 $m^3$ (200.12 $m^3$/yr) was a gain from the beach of La Fenómeno. Conversely, it represents the loss of sediment from the northeastern beaches. From the dynamo-sedimentary point of view, part of this volume, affected by intense coastal drift and exceeding the largest portion of the beach of west La Fenómeno (A), has started to fill the rocky Gamazo cove in the last year (2021), which represents the construction of a new sandy beach and will likely continue in the medium term in the future.

It is difficult to compare both balances, before and after the construction of the breakwater, since, in the period of 2010–2018, the rate was 386.84 $m^3$/yr, including sand transfers from La Fenómeno, and in the recorded period of 2018–2021, without any transfer, it has been reduced to 200.12 $m^3$/yr. It must be taken into account that the wave climate of 2010–2018 and 2018–2021 were not exactly the same, and it is likely necessary in the future to extend monitoring to a few more years.

The relatively low gain in La Fenómeno was due to sandy retention in the eastern half of La Magdalena, brought about by the shading effect of the breakwater, until the new parabolic profile was configured in a plan. This new plan is narrower, between profiles 2 and 3, which allows us to concentrate on this segment and the restaurant/old sea-spa. The greatest damage was caused by storms, increasing the destructive power.

Our approach to the negativity in the construction of this rigid structure was validated by the ministry's decision to remove it. Future sustainable solutions consisting of the transfer of sand from La Fenómeno beach (B) must be taken into account, compensating the E–W sand drift for its redistribution and the creation of berm surfaces in La Magdalena and the western area of Bikini. Other minor interventions, which are nevertheless of great importance for the recreational use of the beach and for guaranteeing safety and the enjoyment of citizens, consist of the elimination of angular gravels, preventing enclosures at the fronts of the climbing dunes, which can be preserved, and the replacement of the pedestrian and cyclist promenade with more consistent elements, such as freeway concrete walkways.

Finally, the unbuilt western breakwater would barely hold back the flow of sand because the main body would be raised by only 1 m from port "0", i.e., it would be promptly saturated within a few weeks or a few months. In addition to the elimination of the breakwater, it would be acceptable if dredging of about 27,000 $m^3$ was taken into account in the project.

In summary, with storms of lower wave height than those of 2014, damage has been very substantial. This shows that changes in the profile of the beach have been transcendental and that work has not had the expected result.

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