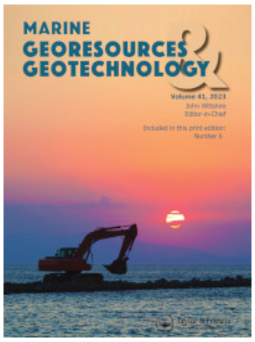

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ABSTRACT

Coastal erosion is a natural phenomenon that is becoming a growing problem along coastlines around the world. In this research, the evolution of two beaches located in Benidorm (Spain) has been studied: Poniente Beach and Levante Beach. Both have similar characteristics, but present a different morphological behaviour. An analysis of shoreline evolution has been carried out using aerial images. Then, waves and incident storms were studied and, finally, a sedimentological analysis was performed. From the results obtained, the eastern zone of Poniente Beach presents higher rates of erosion than the western zone. This erosion trend disappeared in the last analysed period due to a change in the incoming wave regime. A decrease in the frequency of waves coming from the east caused the erosion and tilting suffered by this beach. In Levante Beach, the intensity of the waves was reduced, making erosion rates lower. Furthermore, important differences were found from the sedimentological study, such as the lack of homogeneity in sediment grain sizes and a worse wear behaviour on Poniente Beach compared to Levante Beach, which means that these two beaches behave differently facing erosion. This accurate knowledge of the factors mentioned will provide adequate tools for its future management.

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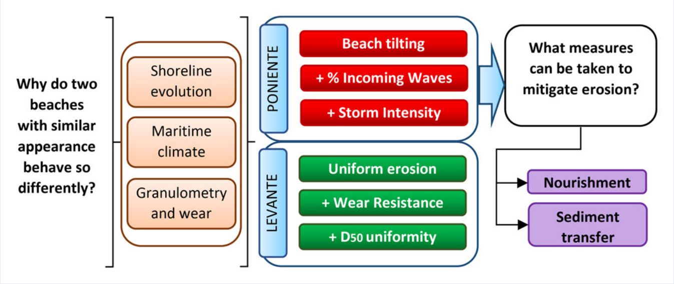
KEYWORDS
Shoreline evolution; beach erosion; beach morphology; storms; beach nourishment

GRAPHICAL ABSTRACT



1. Introduction

Throughout the world, coastal areas are constantly threatened by erosion. This problem is the result of multiple factors, which can be included in two large groups: (i) The factors generated by the anthropogenic action that exists in the area, (Pagán et al. 2016; Ratnayake et al. 2018; Mishra et al. 2019), and (ii) those related to the morphology, the maritime climate of the area and the quality of the sediment that makes up the beach (M. López et al. 2016; Zuo et al. 2017; Boretto et al. 2018).

Anthropogenic pressures have been extensively reviewed in the literature (Baby, Nathawat, and Al-Sarawi 2014; Giardino, Santinelli, and Vuik 2014; Danladi, Kore, and Gül 2017). We find actions such as the construction of dams on adjacent rivers (Aragonés et al. 2016), massive tourist developments in many coastal areas (Pagán et al. 2016) or the construction of dikes and breakwaters to protect the coast from storms (Martin et al. 2021). All this has modified coastal natural dynamics as a result of sediment retention or the lack of erosion of the hydrographic basins, which has generated retreats of the coastline throughout the world (Anthony, Marriner, and Morhange 2014; De Leo et al. 2017; Warrick et al. 2019). Another example of these anthropogenic actions is the nourishment of the beaches. Any discharge of material will presumably have consequences for the environment, since it will cause changes in water currents (De Zeeuw et al. 2012), turbidity (Chiva et al. 2018) and even the destruction of natural habitats, such as *Posidonia Oceanica* meadows. A discharge that invades the meadow can cause its death and transform its profile to a more vertical one, causing a retreat of the shoreline (Aragonés et al. 2015). In any case, it is necessary, before any

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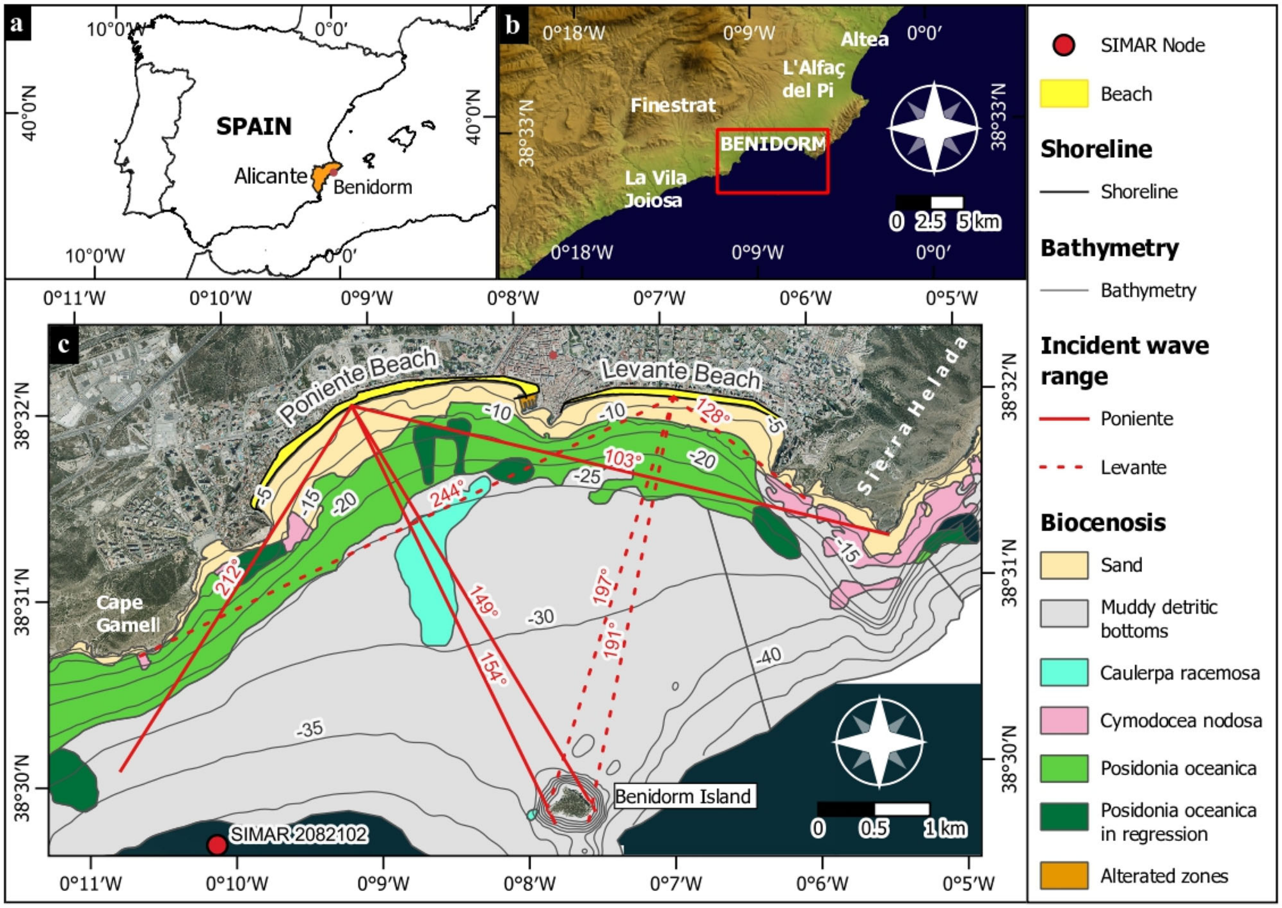

Figure 1. (a) Location of the study area in SE Spain. (b) Location of the study areas. (c) Location of the SIMAR node, incident wave ranges and biocenosis in the study area.

nourishment, to assess the environmental impact of each of these factors to determine the viability of the action carried out.

The magnitude and speed of the shoreline change for a given wave energy will depend on the size of the material in which it occurs (Pardo-Pascual and Sanjaume Saumell 2001; Gunasinghe et al. 2021). For this reason, the average size of the D_{50} sediment has been one of the most used factors in coastal nourishment (Sanchez et al. 2019; Santos-Vendoiro et al. 2021), since its position in the beach profile depends on its size (Yoshii, Tanaka, and Matsuyama 2018; Vu and Lee 2021). Therefore, further research is necessary in studies that take into account material characteristics used in feeding the beaches (I. López et al. 2016) and the position of the sediment in the beach profile (Aragonés et al. 2018; Valiente, Masselink, et al. 2019; Valiente, McCarroll, et al. 2019). Storms, as the main generator of waves, are causing changes in the direction of the waves, as well as in their intensity and frequency, are another aspect that influences the evolution of the coastline (Tsimplis et al. 2005). The World Meteorological Organization (Isa 2005) defines storm as the wind whose speed is between 44 and 50 knots, and usually corresponds to a rough sea state, with wave heights higher than 2.5 m. Therefore, it is essential for the coastal engineer to have adequate knowledge of the factors aforementioned, as it will provide him with the right tools for proper future management of the coast.

Consequently, the objectives of this research are to understand how the morphology and morphodynamics affect the sandy beaches of Benidorm (reference in international tourism), to identify the key research needs and the management implications of this complex and little studied coastal system and be distributed globally. To do this, within the geomorphological context of the study beaches and the anthropic interventions executed, a study of the historical evolution of the shoreline will be carried out in which: (i) the granulometry will be analysed, (ii) wave energy will be evaluated, and finally, (iii) the role of *P. Oceanica* in the stability of the beach profile will be analysed. This study aims to show the ease of applying the methodology and exporting the solutions to other beaches with similar problems.

2. Study area

The study area includes the two main beaches of Benidorm (Spain): Poniente Beach and Levante Beach. Both beaches are located on the eastern coast of the Iberian Peninsula (Figure 1a), and represent a fundamental tourist destination for both the Valencian Community and the rest of Spain (Femenia-Serra and Ivars-Baidal 2021). Part of the success of these beaches is due to the fine sediment size that form them and the morphology that characterizes them (length and width). Poniente Beach is 3 km long, while Levante Beach is 2.3 km long.

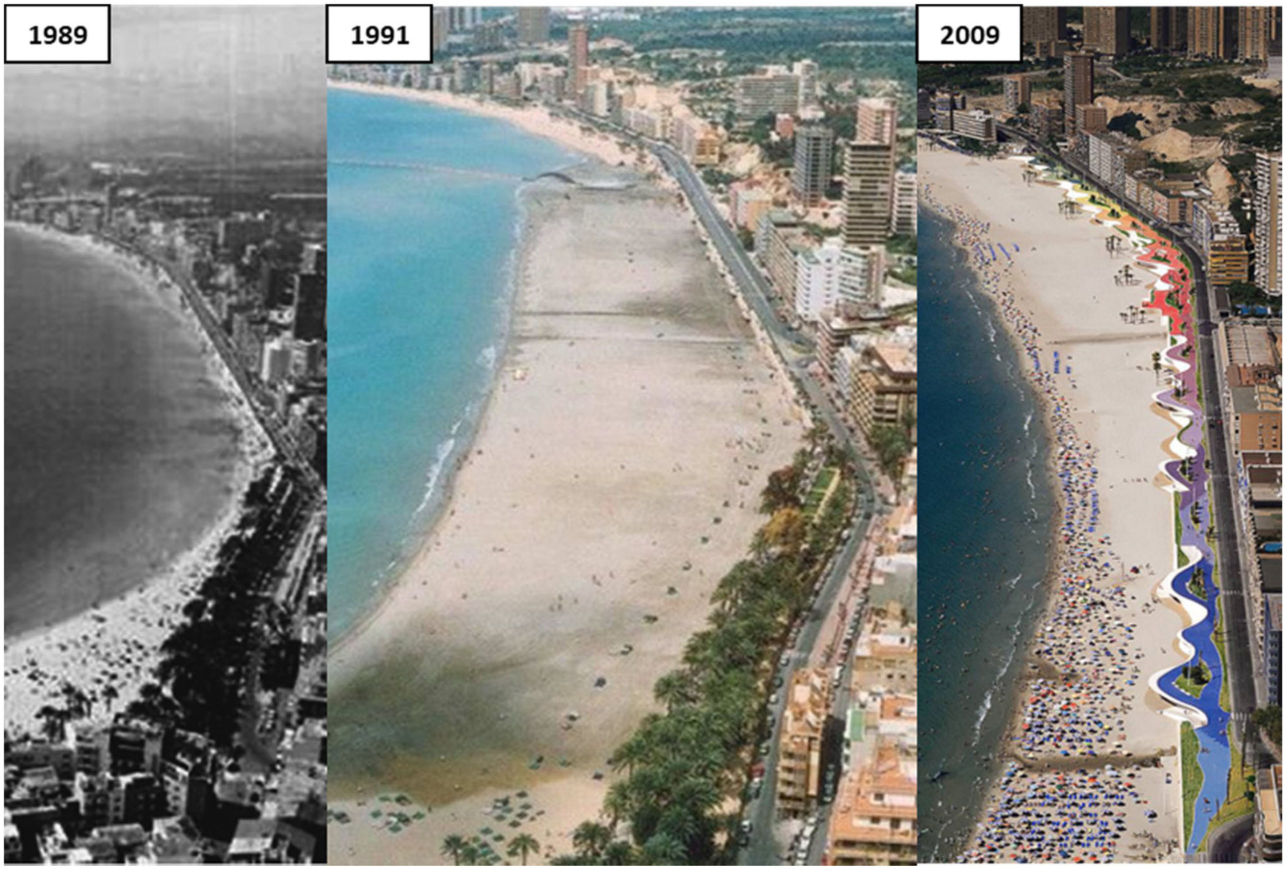

Figure 2. Aerial image of Poniente Beach location before nourishment (left), during nourishment (center), and 18 years after nourishment. Source: MOPT, OAB.

Both beaches are included in a closed littoral system (Figure 1c), forming a headland embayment. These ones are facing south and Sierra Helada massif provides protection against waves coming from the east (the most frequent direction in this area). That means the impact of storms is lower than in other parts of eastern Spain (Amores et al. 2020). The waves in the area are conditioned by Sierra Helada to the east and Cape Gamell to the west, as well as by Benidorm Island (Figure 1c).

The continuous coastal erosion suffered in the study area meant that in 1991 an intervention was carried out on the east side of Poniente beach, which included a breakwater and an artificial supply of 710,847 m^3 of sand from dredging (Figure 2). This meant an increase of 70 m in beach width (MOPT 1991).

In addition, the nourishment carried out had a fundamental influence on the location of *P. Oceanica* within the cross-shore profile of the beach, making it recede more than 100 m offshore and descending between 3 m and 5 m with respect to the depth prior to nourishment. This event occurred because an excessive discharge of sand buried part of the *P. Oceanica* meadow causing its death. As a consequence, the beach profile became less steep and backshore surface was lost (Aragonés et al. 2015).

The study area is located in a microtidal zone, where oscillations due to atmospheric pressure are more important than the tides themselves. Astronomical tides reach a maximum value of 0.3 m, while meteorological tides can reach values of up to 0.45 m (Ecolevante 2006).

3. Methodology

3.1. Historical evolution of the shoreline

The study of the evolution of the shoreline was carried out by vectorizing the shoreline from aerial images since 1956 (Table 1). Satellite images have not been used given the low resolution compared to the orthophotos used for this work. Since not all the images used to study evolution of the shoreline were georeferenced, the first step was the photogrammetric restitution of all those non-georeferenced images (Pagán et al. 2016).

Once the mosaics with the orthophotos of each year were loaded in the GIS (Geographical Information System) environment, the next step was the vectorization of the shoreline. The methodology consists in the visual identification of the last wet mark of the tide on the beach profile, namely the wet-dry boundary in the intertidal zone (Ojeda Zújar et al. 2010). On Mediterranean coasts this criterion is appropriate due to the low variation in tides. This feature eliminates possible variations due to sea state at the moment of capturing the aerial image. Since all the aerial images were collected in summer and the sea state was relatively calm, the shorelines obtained are suitable for comparative study. The

Table 1. Summary of available aerial images.

Date	Source	Image	Format	Resolution	Spatial reference
04/07/1956	American Fly	Orthophoto	ECW	50 cm	UTM ETRS89 H30N
02/1977, 03/1989	Cartoteca, IGN	Aerial	ECW	1 m/pixel	None
07/1981, 07/1986 07/1990, 07/1992 07/1994, 07/1996 22/08/1998	DGC – SPC Alicante	Aerial	ECW	1 m/pixel	None
08/2000, 29/09/2005, 27/08/2007, 18/08/2009, 24/06/2012, 28/06/2014	PNOA	Orthophoto	ECW	25 cm/pixel–50 cm/pixel	UTM ETRS89 H30N
22/08/2017, 15/06/2018, 17/06/2019, 21/05/2020, 26/06/2021	IDEV	Orthophoto	ECW	25 cm/pixel	UTM ETRS89 H30N

5.3 km of shoreline were vectorized for each of the 21 available years (Table 1). A series of transects perpendicular to the coast, spatially separated every 100 m, were created. The origin of these transects is located at the baseline, drawn following the promenade. From its intersection with the previously vectorized shoreline, it was possible to obtain the width of the beach in each transect for each period studied, and thus its evolution over time. Subsequently, beach surface was obtained and the areas of each period were compared to analyse the evolution of the beach (accretion or regression of the coastline).

Four periods were chosen to study the evolution of the shoreline. The first period was from 1956 to 1990, from the first aerial image available to the last one before Poniente Beach regeneration in 1991. The second period was 1990–1992 and includes that feeding. The next period studied was 1992–2007 and allows analysis of the evolution in both beaches, especially after the feeding of the Poniente beach. The last period analysed was 2007–2021, latest orthophotos available.

3.2. Maritime climate

Wave data (significant wave height, period, and direction) were provided by Puertos del Estado, based on the SIMAR series (simulated data from numerical modelling), this being one of the most complete databases in the Mediterranean (Infantes et al. 2009). This is hourly data collected over 63 years, during the period 1958–2021.

For this work, the database of SIMAR Node 2082102 (0.167° W, 38.500° N), located about 5 km east of the study area, was used (Figure 1c). The data from this location were processed by the CAROL v1.0 software (developed by the IH-Cantabria), obtaining for each of the study periods the wave height $H_{s,12}$ (wave height with a 0.137% probability of not being exceeded), and their corresponding periods, directions and probabilities of occurrence. Wave diffraction was not considered given the proximity of Benidorm Island to the study beaches (Figure 1c).

In addition, average wave flow was calculated for the three sectors into which each beach has been divided (west, centre, and east) and for each period of analysis. The average wave flow will give clues as to whether there is a longshore transport of sediments on the study beaches. This average flow was calculated at a depth of 5 m, since it is considered a reasonable value for the maximum limit of cross-shore sediment transport on the beaches in this area.

Finally, a key point was the analysis of storms. An analysis of the storms that occurred since there are records in the SIMAR Node was carried out. There is no universally accepted climatic definition for the term "storm." In our study, it was considered storm when a significant wave height of the 95th percentile is exceeded for a minimum period of six consecutive hours and with a delimitation of at least 24 h without exceeding that threshold (Morales-Márquez et al. 2018; Wiggins et al. 2019). The end of the storm occurs when at least one full day elapses without exceeding that wave height at any time of the day. This study focused on the duration of the storms, the predominant direction and their intensity (m^2h). The last one was defined as a product of the maximum H_s (m), squared, multiplied by the average storm duration (in hours), thus, obtaining an approximation of its total energy (Senechal et al. 2015).

3.3. Sedimentology

Another variable studied was the sedimentology of the Poniente and Levante beaches. 12 sand samples were taken on each beach, which were distributed in (i) four locations across the beach (breaker zone, 3 m from this zone, centre, and backshore) and in (ii) three sectors parallel to the beach (west, centre, and east). Sediment collection was carried out outside the drainage areas to the beach. The samples were taken by the University of Alicante in October and November 2021.

These samples were dried after their extraction for 24 h in an oven to subsequently proceed to their granulometric test. These tests were carried out following the UNE-EN ISO 17892-4 standard, and in a complementary way the UNE 7050-2 and the UNE 103 100. Obtaining, the size of the particles (mm) at the beginning of each cycle, their average size D_{50} calculated in two different ways: (i) with the entire sample and ii) eliminating the part of fines from it (sizes < 0.063 mm), reduction of D_{50} (%), after each cycle, specific surface, at the beginning of each cycle and without counting the fine particles (pass through a 0.063 mm sieve), mass loss in g and in % after each cycle: material whose diameter has been reduced to a size of less than 0.063 mm. The mesh size of the sieves used for the analysis were the following: Ø 2 (mm), Ø 1.6 (mm), Ø 1.25 (mm), Ø 1 (mm), Ø 0.8 (mm), Ø 0.63 (mm), Ø 0.5 (mm), Ø 0.4 (mm), Ø 0.32 (mm), Ø 0.25 (mm), Ø 0.20 (mm). Ø 0.16 (mm), Ø 0.125 (mm), Ø 0.100 (mm), Ø 0.080 (mm), Ø 0.063 (mm), Ø 0.050 (mm). The following parameters were obtained from these tests: Quantile Ø50, mean (Folk and Ward 1957), Sorting (So), Skewness (Sk), and Kurtosis (K). However, among all of them, the value of the second quartile -equivalent to parameter D_{50}- and the skewness (Sk) were the variables chosen to carry out the sedimentological comparison between both beaches.

To simulate the erosion suffered by sand particles due to waves on the beach (particle collision, carbonate dissolution, and particle separation as the causes of the decrease in sample size), the accelerated particle wear (APW) test was used (I. López et al. 2016). The test allows analysing the decrease in the D_{50} of the sample, due in part to the dissolution of carbonates contained in the particles that form the beach. In this test, 75 g of beach sand sample and 500 mL of seawater from the studied beach were poured into a magnetic stirrer at 1600 rpm in 24-h cycles. The number of cycles applied to each sediment sample to reduce the particle size below 0.063 mm was the reference for the wear resistance analysis. The granulometry of the sand sample was carried out according to UNE-EN ISO 17892-4 after each cycle. In addition, after each cycle, the $CaCO_3$ content in the water was measured using the Bernard's calcimeter method according to UNE 103200-93.

Finally, a brief multivariate statistical analysis has been carried out with the SPSS software to justify the results obtained. First, a normality test was performed, specifically the Kolmogorov–Smirnov (K–S) test, whose null hypothesis is that the distribution of the selected variable comes from a normal distribution. If Sig. (p-value) $>$ .05 we accept the hypothesis, while if Sig. (p-value) $<$ .05 we reject it. Secondly, a bivariate correlation analysis has been carried out to measure the degree of relationship between the different variables two by two. The strength of the correlation will be the following: $r = 1–0.8$ very strong; $r = 0.8–0.6$ Strong; $r = 0.6–0.4$ Moderate; $r = 0.4–0.2$ Weak; $r = 0.2–0$ Very weak (Wuensch and Evans 1996). Finally, three multiple linear regression studies were carried out including different variables as a dependent variable: (i) beach width; (ii) width gained or lost; and (iii) rate of accretion or erosion.

4. Results

4.1. Historical evolution of the shoreline

The eastern zone of Poniente Beach is more unstable than the central zone and the western zone, which present a global stability (Figure 3). The period prior to the nourishment carried out in the eastern part of said beach (1956–1990) highlighted, where in transect P5 16 m of beach width were lost, setting a minimum of only 5 m in 1989 (Figure 4). Following beach feeding between 1990 and 1992 where more than 70 m of beach width were gained, a great retreat occurred in the eastern half. An average of 30 m of beach width was lost in the eastern half of the beach, highlighting 52 m in P7 during the period 1992–2007. However, during the same time interval in the central zone and the western zone, the beach remains stable or even accretions of up to 20 m are detected (Figure 3h). For the last period analysed, the erosion rates were gentler, since in no transect of Poniente Beach were more than 10 m of beach width lost (Figure 4e). In Levante Beach, changes suffered are much slighter, especially in the sections located in the centre and east of the beach (L8–L18), where only 4 m of beach width were lost throughout the period studied (1956–2021). A minimum beach width of 50 m is maintained for all the years analysed. Erosion rates were also observed in the last two periods, highlighting 12 m of width lost in L3 in the west of that beach in 1992–2007 period (Figure 4g).

The loss of beach width means a significant loss of beach area. Thus, from 1956 to 2021 more than 10,000 m^2 of coastal area were lost in Levante Beach due to erosion (Table 2). In case of Poniente Beach, the global calculation was an accretion of 52,000 m^2, due to the contribution of material during the nourishment carried out in 1991. The continuous loss of surface area in the period 1956–1990 (more than 40,000 m^2, −27.2%) was the reason why this anthropic action was carried out. After that, the regressive trend continued in Poniente Beach, losing more than 25,500 m^2 (−11.1%) in the following 15 years. However, this erosive trend stopped in 2007, where since then a surface gain of almost 3000 m^2 (1.47%) was observed up to the present. The regressive trend also stopped in 2007 in Levante Beach, where until then 5472 m^2 (−4.52%) and 8067 m^2 (−6.77%) had been lost in the periods 1956–1990 and 1992–2007, respectively. As of 2007, a relative stability might be seen, losing only 397 m^2 (−0.36%) in the following 14 years.

Sectorizing Poniente Beach, the different behaviour of the areas in which the beach was divided was more evident (Table 3). The eastern zone showed more negative erosion rates than the western zone in all the periods studied, except in the period of beach nourishment in 1991. In this last zone, erosion rates are observed 3 times higher in the period after regeneration (−2.09 mL/year), than in the period prior to this (−0.60 mL/year). This rate was reduced to −0.11 mL/year in the last period. As for western zone, only a negative rate appeared in the first period. After feeding, accretion rates were detected, being higher in the third period (1992–2007), than in the last one (2007–2021).

4.2. Maritime climate

Both in Poniente and Levante beaches, a great increase in wave height exceeding 12 h per year ($H_{s,12}$) was detected in the period 2007–2021 for almost all incoming directions (Figure 5). Remarkable were the cases of waves coming from the west (SSW, SW, WSW). The SSW swell at Poniente Beach doubled its wave height in the last period compared to the previous one (1.44 m vs. 2.86 m), while at Levante Beach the wave height for SSW, SW and WSW directions increased by 69%, 66%, and 39%, respectively. The waves coming from the west also increased with respect to the incident waves for the period 2007–2021 compared to the period 1992–2007. At Poniente Beach, the frequency of SSW wave entry doubled, while the frequency of the ESE and S was reduced. Similarly, an increase of 12% might be seen for Levante Beach and 4% for the SSW and SW directions, respectively, while losing 15% in the S direction.

The direction of the average wave flow of the waves and the orientation of the beaches are ostensibly different for both beaches (Table 4). Poniente Beach has an orientation of 153° at its midpoint and an average wave flow of 166°

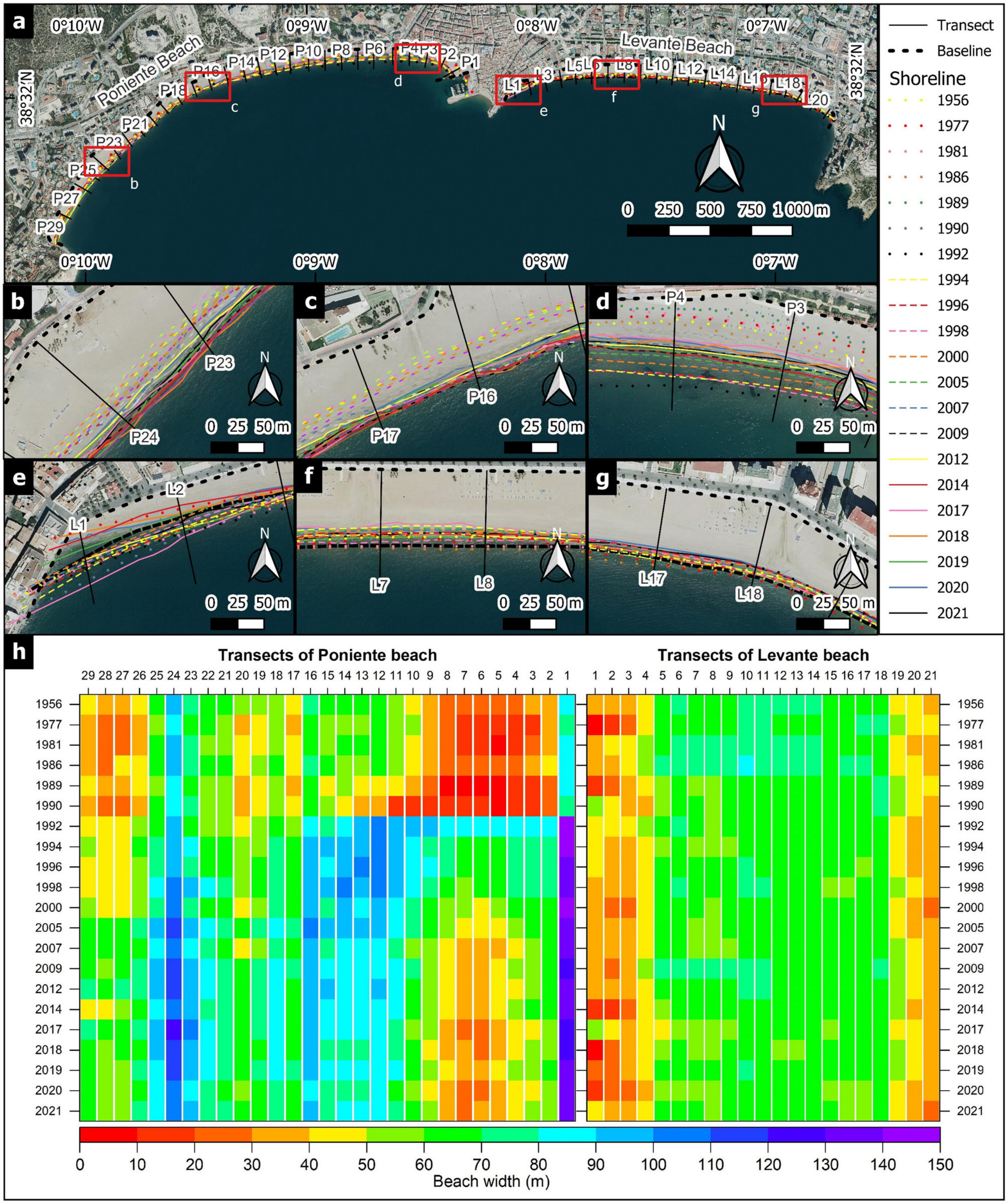

Figure 3. Shoreline evolution. (a) Location of the beach sectors. (b) Western area of Poniente Beach. (c) Central area of Poniente Beach. (d) Eastern area of Poniente Beach. (e) Western area of Levante Beach. (f) Central area of Levante Beach. (g) Eastern area of Levante Beach. (h) Beach width for each transect and for each period.

for the period 2007–2021. As for Levante Beach, it has an orientation of 186° at its midpoint and an average wave flow of 177°. The orientations of the beaches are perpendicular to the average wave flow, except in their central zone. Also, the average flow remains relatively stable during the periods analysed, except for the last two. In the period 1992–2007 there is a 6° clockwise rotation in the central section of Poniente Beach and a 5° rotation in the east of Levante Beach. With respect to the last period, in the western sector of Levante the turn was 5° clockwise, while for the eastern and western sectors of Poniente it was 3° clockwise.

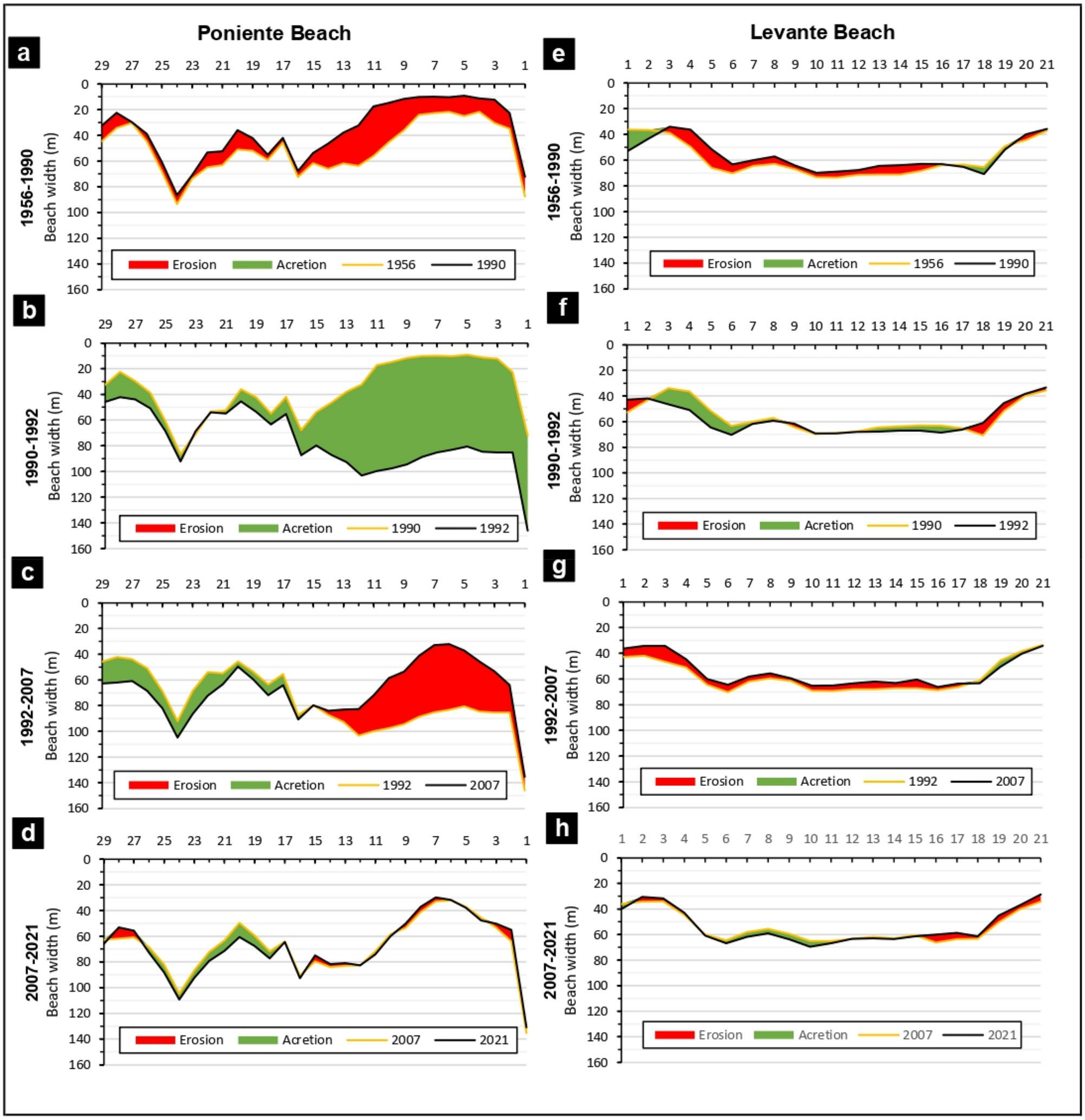

Figure 4. Evolution of the shoreline and beach surface of the study areas. (a) Poniente 1956–1990. (b) Poniente 1990–1992. (c) Poniente 1992–2007. (d) Poniente 2007–2021. (e) Levante 1956–1990. (f) Levante 1990–1992. (g) Levante 1992–2007. (h) Levante 2007–2021.

Poniente Beach receives a greater number of waves than Levante Beach regarding the total, both if the influence that the island gives is considered and if not (Table 5). Poniente shows very similar incoming wave percentages in both cases: 63.16% vs. 62.05% in the 1958–1990 period, 61.89% vs. 60.79% in the 1992–2007 period, and 56.34% vs. 55.22% in the 2007–2021 period. Striking is the case of the latter where it fell by more than 5% compared to the previous period. In case of Levante, these percentages present a greater difference. In the first period the frequency increases from 32.52% to 36.12%, in the third it goes from 32.73% to 36.21% and in the last, from 32.19% to 37.55%. It is also detected that the absence of the island would increase the entry of waves by more than 1% in the period 2007–2021.

Lastly, incoming storms were analysed on the Poniente and Levante beaches since 1958. The threshold wave height was 1.15 m for Poniente and 1.05 m for Levante (Figure 5). Poniente Beach presented a longer duration and greater intensity in storms, compared to Levante Beach. In the first of them, storms exceed 240 h per year on average for all the periods analysed, except in the 2007–2021 period, where 200 h were not reached (Figure 6a). That represented a reduction of 19.7% in the duration of storms compared to the period 1992–2007. The year with the longest storm duration was 1989 with 530 h. This fact caused a significant erosion on the beach, which led to its subsequent nourishment in 1991. However, the decrease seen in the duration by periods was not reflected in the same way in the Storm Power

Table 2. Area balance in m^2 for each period.

	Poniente Beach			Levante Beach		
	Accretion	Erosion	Total	Accretion	Erosion	Total
1956–1977	895	−19,208	−18,312	4659	−7271	−2611
1977–1981	8177	−4877	3300	11,961	−4952	7009
1981–1986	16,923	−706	16,217	4691	−1181	3511
1986–1989	2457	−33,052	−30,594	2583	−17,749	−15,166
1989–1990	4479	−15,617	−11,138	6643	−4858	1785
1990–1992	115,523	−207	115,316	6819	−3156	3662
1992–1994	13,925	−13,041	884	1000	−7952	−6952
1994–1996	3502	−5162	−1660	5598	−3497	2101
1996–1998	9950	−3898	6052	4149	−2569	1580
1998–2000	3085	−23,822	−20,737	1751	−7307	−5556
2000–2005	21,666	−5493	16,173	5008	−1904	3104
2005–2007	77	−26,329	−26,252	1236	−3578	−2343
2007–2009	20,835	−997	19,837	11,750	−1380	10,371
2009–2012	6492	−4130	2362	3012	−5237	−2225
2012–2014	2126	−16,101	−13,975	71	−11,229	−11,158
2014–2017	12,190	−9349	2840	8864	−4238	4627
2017–2018	2928	−11,254	−8326	3302	−8645	−5343
2018–2019	16,179	−761	15,417	7254	−79	7175
2019–2020	114	−27,168	−27,053	17	−10,220	−10,203
2020–2021	12,399	−595	11,804	7454	−1093	6360
1956–1990	2	−40,530	−40,528	3086	−8558	−5472
1990–1992	115,523	−207	115,316	6819	−3156	3662
1992–2007	18,312	−43,852	−25,541	814	−8881	−8067
2007–2021	7201	−4294	2907	2561	−2958	−397
1956–2021	**52,155**	**0**	**52,155**	**266**	**−10,540**	**−10,273**

Index, where there was a clear stability in the last two periods studied (Figure 6b). At Levante Beach, both the number of hours of storm and the Storm Power Index indicated a maximum in the 2007–2021 period. The duration increased by 34.5% with respect to the 1992–2007 period, while the intensity of the storms rose by 84%, which reflected an increase in wave height. The clockwise rotation of the order of 70° at Poniente Beach between the 1992–2007 and 2007–2021 periods was remarkable (Figure 6c). The most powerful storms come mainly from the SSW, relegating the ESE direction to the background. As for Levante Beach, this change in the direction of the storms was not so important. Between the last two periods analysed, the highest waves turned up to 20° clockwise (Figure 6e).

4.3. Sediment granulometry analysis

The granulometry of the material collected directly from the beach was carried out to determine the D_{50} and the fine content (<0.063 mm). In Levante Beach the material is distributed more evenly. The thickest sediments are found in the western sector of the beach with a mean value of 0.279 mm, while the finest are found in the centre and east of the beach with a D_{50} of 0.24 mm and 0.248 mm, respectively (Figure 7b–g). At Poniente Beach, the sediment size distribution is more irregular. Within the same sector we find that sample S03 (0.347 mm) is 42% bigger than S01 (0.245 mm). Also, D_{50} is bigger on this beach, being 0.293 mm, 0.287 mm, and 0.262 mm in the western, central and eastern sectors.

This uniformity is also justified by the obtained textural parameters (Figure 7j,k). Skewness (Sk) measures the relative importance of the fines and coarser particle tails in relation to the median diameter of the size distribution (Tascón 2018). Levante Beach samples are finely skewed, as up to 7 of the 12 samples collected have a skewness > 0.10. However, the samples from Poniente Beach do not show the uniformity that the other beach does, since there are greater variations of skewness between samples.

Table 3. Rate of mL/year for each period in Poniente Beach and Levante Beach.

	Poniente Beach		Levante Beach	
	Western zone	Eastern zone	Western zone	Eastern zone
1956–1990	−0.24	−0.60	−0.10	−0.06
1990–1992	5.53	35.61	1.58	0.13
1992–2007	0.77	−2.09	−0.36	−0.15
2007–2021	0.24	−0.11	0.12	−0.16
1956–2021	**0.28**	**0.27**	**−0.06**	**−0.10**

Subsequently, the behaviour of the material was analysed against the accelerated wear test. The impact of particles, the dissolution of carbonates and the separation of particles are factors that influence the decrease in sample size. Poniente Beach reached a size of <0.063 mm after 8 cycles, while Levante Beach reached this value after 10 wear cycles (Figure 8a). The material from Poniente showed progressive wear until Cycle No. 6, where it lost 12% of its total weight compared to the previous cycle. In case of Levante, this progressive decrease lasted until cycle 9, where 10% of the weight was lost after the previous cycle. These results certify a greater resistance to wear produced by the wave force in favour of Levante Beach.

Carrying out a statistical analysis gives us some information, although the amount of data is somewhat reduced so that the results can be significant. Before starting a multivariate study, it is interesting to visualize the distributions of values, detect possible errors and perform normality tests on the data. In the case under study, the Kolmogorov–Smirnov (K–S) test shows that none of the variables under study follow a normal distribution. As for the multivariate analysis as such, the correlation analysis shows the same result as the multiple regression analysis for beach width as the dependent variable. In this case, it is obtained that the most relevant factor is H_{max}, which explains 47%, followed by height $H_{s,12}$, which explains 39.1%, and wear, which explains 33.6%. However, the direction variables of H_{max} and wear show statistical significance, height H_{max} is at the limit of significance and the rest of the variables do not have any statistical significance.

5. Discussion

5.1. Historical evolution of the shoreline

The width change that occurs in the shoreline affects flooding in the backshore of the beach, as well as the use and enjoyment of it. Therefore, both coastal managers and owners must adapt to the new situation. For this, it is necessary to know the scope of the problem and the possible protection (Jin, Hoagland, and Ashton 2022). In the study carried out we find, like Poniente Beach, there are areas where its width (depending on the period) has ceased to be functional (Figure 4 and Table 3). This functionality ranges between 18

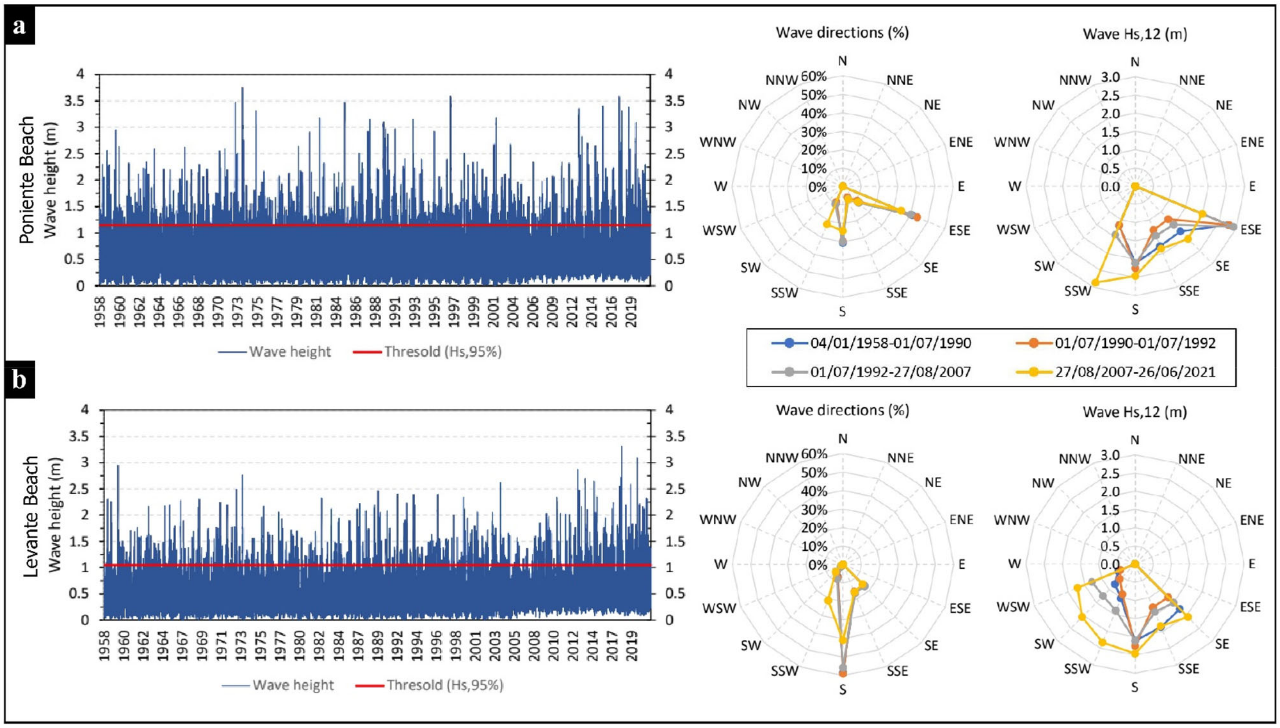

Figure 5. (a) Wave height with storm threshold for the entire study period, wind roses, and waves in Poniente. (b) Wave height with storm threshold for the entire study period, wind roses, and waves in Levante.

Table 4. Beach orientation (BO) and average wave flow (AF) for each sector and for each period studied.

	Poniente Beach						Levante Beach					
	West		Center		East		West		Center		East	
	BO	AF	BO	AF	BO	AF	BO	AF	BO	AF	BO	AF
1958–1990	136°	**133°**	152°	**160°**	178°	**177°**	171°	**171°**	186°	**180°**	197°	**193°**
1990–1992	134°	**132°**	154°	**160°**	177°	**178°**	171°	**172°**	186°	**179°**	196°	**192°**
1992–2007	135°	**133°**	155°	**166°**	179°	**178°**	173°	**172°**	187°	**179°**	198°	**197°**
2007–2021	135°	**136°**	153°	**166°**	180°	**181°**	171°	**177°**	186°	**177°**	198°	**198°**

Table 5. Frequency of incoming storms to the study beaches with respect to the total waves, considering the presence or absence of the island of Benidorm.

	Without considering the influence of the island		Considering the influence of the island	
	Poniente (%)	Levante (%)	Poniente (%)	Levante (%)
4/1/1958–1/7/1990	63.16	36.12	62.05	32.52
1/7/1990–1/7/1992	58.40	31.92	57.49	28.79
1/7/1992–27/8/2007	61.89	36.21	60.79	32.73
27/8/2007–4/10/2021	56.34	37.55	55.22	32.19
TOTAL	61.20	36.33	60.10	32.38

m and 46 m depending on the authors (Morgan 1999; Parsons, Massey, and Tomasi 1999; King 2006).

The future position of the shoreline (and associated beach width) is not as predictable as has often been assumed in many studies (Jin, Hoagland, and Ashton 2022). It is enough to analyse Poniente beach, where, according to the period analysed, this position depends on the affectation of *P. Oceanica* (Aragonés et al. 2015), the lack of predictability as a consequence of the change in the direction and wave height (Figure 5), the storm frequency (Figure 6), and the type of sediment (Figure 7).

Poniente and Levante beaches are located between rocky promontories and have a concave shape, although more pronounced in the first one. Levante Beach presents a straight line in the centre of the beach. Conversely, Poniente beach has a greater curvature as a result of a more defined shaded area (Klein et al. 2010; Mathew, Davidson-Arnott, and Ollerhead 2010).

Most of the research on beach morphodynamics focuses on sediment exchange along the shoreline (Trenhaile 2004; Short and Jackson 2013; Feal-Pérez et al. 2014). However, the analysed beaches have significant geological elements with rocky outcrops (such as Benidorm Island) or reefs formed by *P. Oceanica*. These outcrops are determining the limits, morphology, morphodynamics, and evolution throughout the study period (Figure 1), as well as other studies (Jackson, Cooper, and Del Rio 2005; Short and

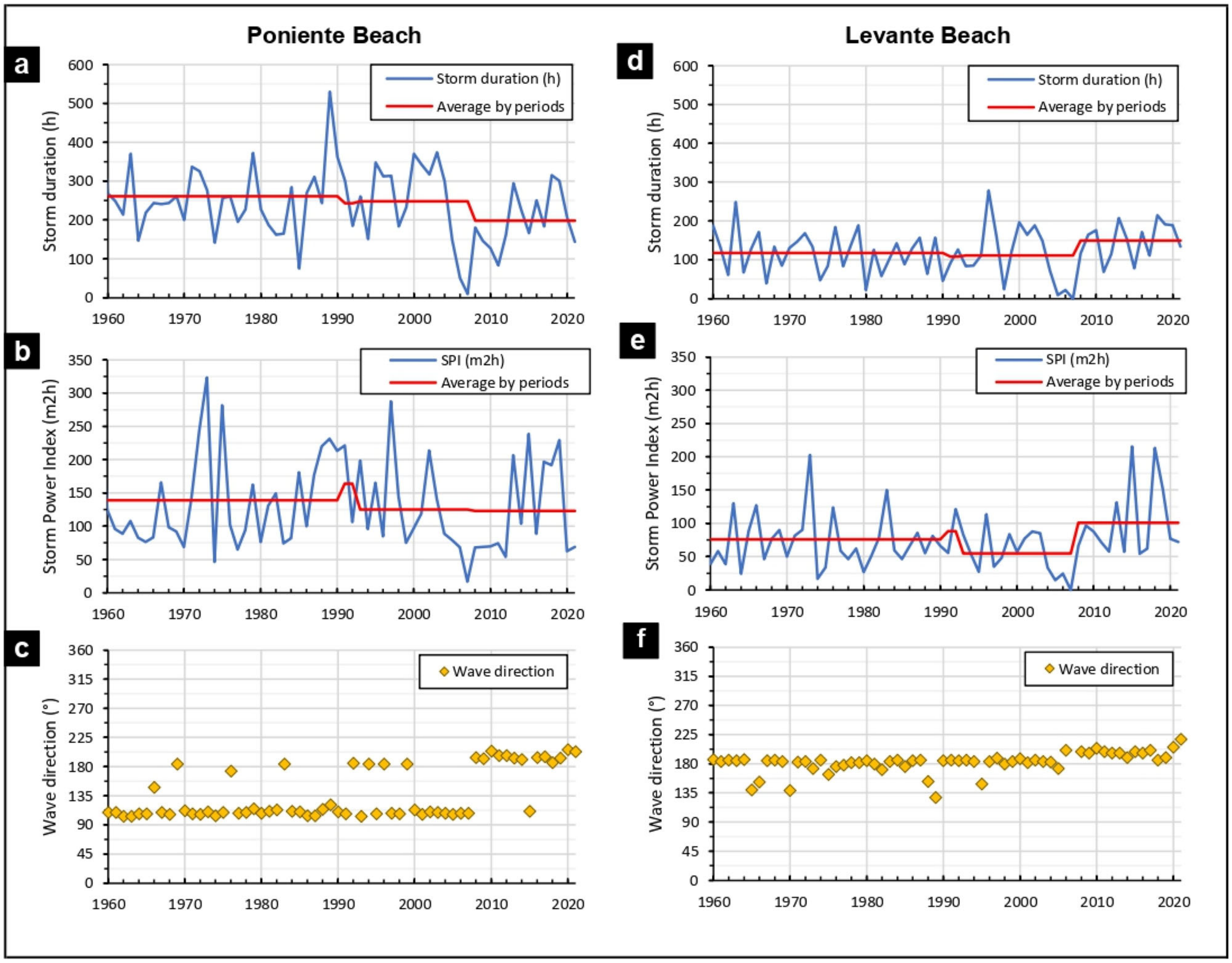

Figure 6. Evolution of storms in the study areas. (a) Poniente duration. (b) Poniente Storm Power Index. (c) Poniente wave direction. (d) Levante duration. (e) Levante Storm Power Index. (f) Levante wave direction.

Jackson 2013). From the study of the analysed beaches, a clearly different behaviour is observed in both beaches (Figure 3). On one hand, we have a beach with an erosive tendency (Poniente Beach), which meant that in the 1980s the promenade of the Playa de Poniente suffered considerable damage (Tros De Ilarduya Fernández 2013), and on the other hand, one in equilibrium (Levante Beach). The degree of stability of bay beach planform can be static, dynamic, or unstable (Klein et al. 2010). We could affirm that Levante Beach has a static equilibrium planform since there is almost no longshore transport that brings or removes sediment from the beach. Benidorm Island causes the incident waves to refract and diffract within its shadow area, so that the waves break simultaneously on the periphery of the beach. However, Poniente Beach cannot even be considered in dynamic equilibrium, since there is a continuous loss of sediments and its surface area decreases over the years. This instability is a consequence of the change in the cross-sectional profile generated as a result of the death of *P. Oceanica* during the 1991 nourishment (Aragonés et al. 2015) and the lack of sediment contributions from the ravines, as in Marineta Cassiana beach (Pagán et al. 2016).

Therefore, from the study carried out by periods a simple solution cannot be reached, given the radical change produced in Poniente Beach (Figure 4). In which in the last period analysed (2007–2021), erosion rates moderated, causing gross surface losses up to 10 times lower compared to the previous period (Tables 2 and 3). That is why traditional erosional models are not directly applicable.

5.2. Maritime climate

The maritime climate is for some authors the main cause of sediment transport (Bakhtyar et al. 2009; Yoshikawa and Nemoto 2010). From their analysis, it can be stated that it is one of the key factors that affect the beach width (Figures 5 and 6). The study beaches face south and are protected by the promontory of Sierra Helada, which protects them from storms coming from the east (Figure 1). However, they present a high risk of deterioration in the face of southern storms (Tros De Ilarduya Fernández 2013).

Benidorm Island is another fundamental element to understand the morphology of both beaches, since it also reduces the entrance of waves. Considering all the waves generated in the western Mediterranean, only 60% and 32% of them affect Poniente and Levante beaches, respectively (Table 5).

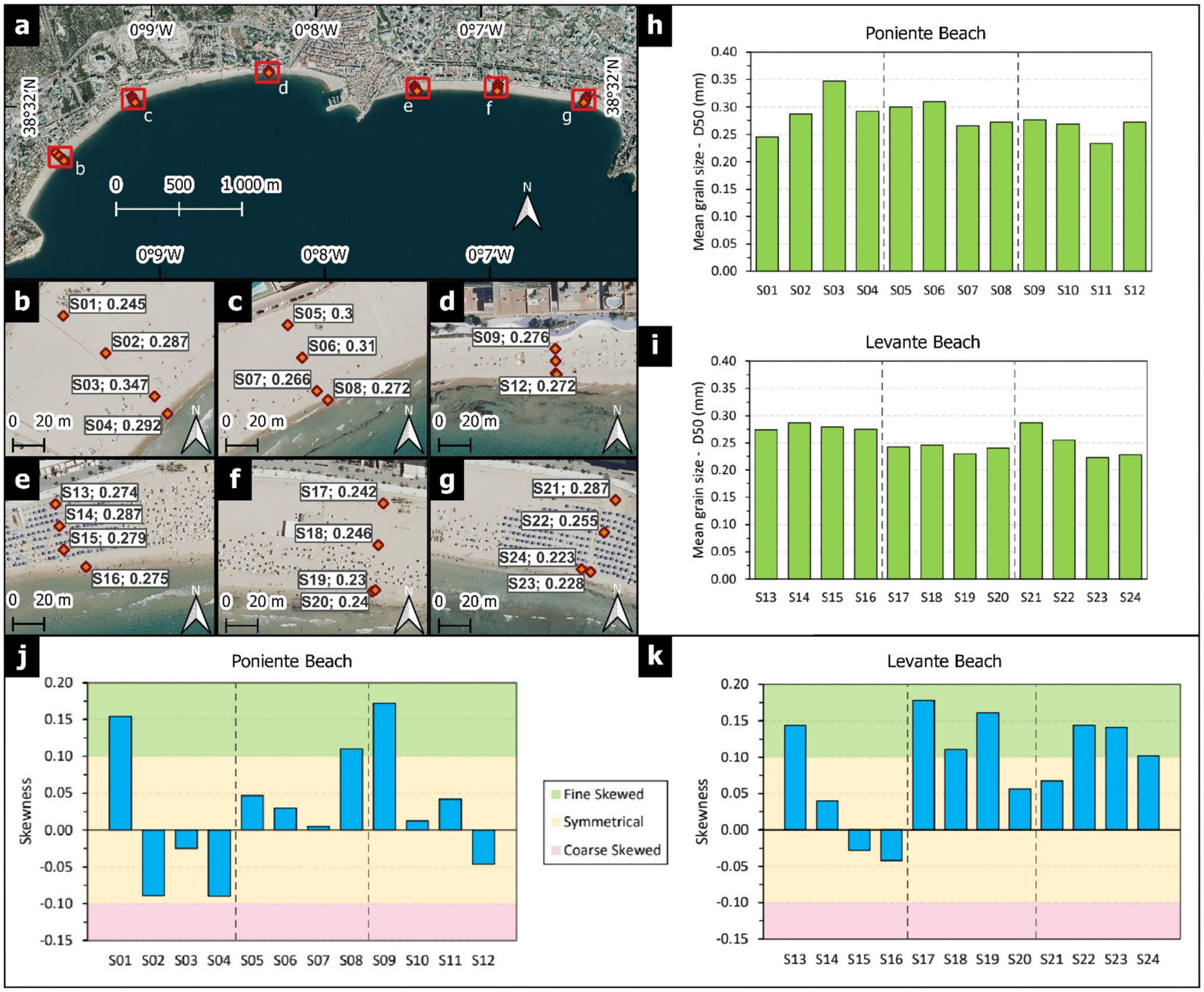

Figure 7. (a) Location of sediment samples. (b–g) Detail of the location and Median grain size (D_{50}) in mm. (h) D_{50} in mm Poniente. (i) D_{50} in mm Levante. (j) Poniente Skewness. (k) Levante Skewness.

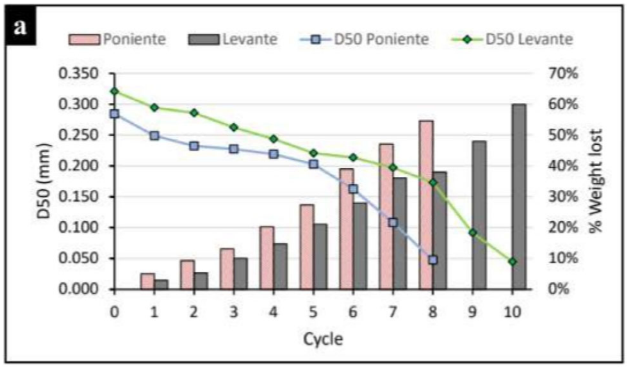

Figure 8. Evolution of the median sediment size (D_{50}) and weight loss during the accelerated particle wear (APW) test on Poniente and Levante beaches.

The stability that Levante Beach enjoys may be due to the protection provided by Sierra Helada, reducing waves by half compared to Playa de Poniente, which is more exposed to them due to its greater distance (Figure 1). But, the presence of Benidorm Island also influences reducing incoming waves in Levante by more than 10%, something that does not happen in Poniente (Table 5).

The wave frequency has not only decreased in the last analysed period, but its orientation has changed, which has generated greater stability of the studied beaches. For this reason, the interruption of the longshore sediment transport in the last period at Poniente Beach is caused by a change in the frequency of incoming waves from the year 2007 (Figure 5). In both beaches, the frequency of entry of waves from the west (SSW and SW) has increased significantly, while the frequency of those from the east (ESE and SE) and south have decreased. The waves coming from the east favour the tilting of the beach (erosion in the east zone and accretion in the west zone), while those from the west interrupt the transport of sediments (Figure 4). However, Levante Beach does not experience such tilting because the ESE direction is not contained in the range of wave incident sectors.

Analysing the storms in depth, the shorter duration of the storms coming from the SSW with respect to the storms from the ESE can be attributed as the cause of the reduction in the erosion produced during the last period in Poniente Beach (Figure 6a). The reduction in erosion in the last period can be attributed to a reduction in the frequency of incoming waves between the periods 1992–2007 and 2007–2021, where they went from 60.8% to 52.2% (Table 5). As a general rule, the difference in the behaviour between both beaches is related to the intensity of the storms, where in Poniente they are clearly more energetic than in Levante (Figure 6c). This difference in waves can partly explain the higher rates of erosion of Poniente Beach compared to Levante Beach.

Thus, strong feedback loops are observed on the analysed sandy beaches, where a change in a single driver, such as wave period and height or the storm frequency, has led to an adjustment in the form of the beach (Figure 5). This interaction was named morphodynamics (Wright and Short 1984).

5.3. Sediment granulometry analysis

Regarding the coastal sedimentology in the study area, we are in an anthropic stress area. The qualitative and quantitative changes in the sediments transported by the sea indicate serious difficulties in the sediment balance rates in Poniente Beach, but not in Levante (Table 3), as well as other studies (Engstrom and Wright 1984; Vaalgamaa 2004).

The natural tendency is to think that a beach with a larger sediment size D_{50} will present a better behaviour against erosion (Dean 1998; Gayo et al. 2004). In the case at hand, the smallest sediment sizes are located in Levante Beach, where there are fewer losses (Figure 7h,i). This is also justified by the obtained textural parameters, where Levante shows a great uniformity in the D_{50} of the sediment.

Conversely, on Poniente beach the distribution of D_{50} is more irregular (Figure 7j,k). In addition, the 1991 feeding caused an increase in D_{50} throughout Poniente Beach, especially in the western area. Much of the discharged material came from the eastern sector due to the longitudinal transport of sediments, making this lack of uniformity evident throughout the beach (Figure 7j). In fact, before nourishment, Poniente had a sediment D_{50} very similar to that of Levante (Aragonés et al. 2015).

In terms of wear resistance, Levante Beach presents a greater resistance to the APW test than Poniente Beach, and consequently, a greater resistance to global erosion of the beach (Figure 8). The case of the beaches that are the object of investigation can be compared to that of other beaches in the Province of Alicante, in which, having similar orientations, lengths and D_{50} of sediment, they behaved very differently, as is the case of Guardamar Beach and San Juan Beach (Pagán et al. 2018). In that case, the analysis of the maritime climate was not decisive in the results, but the sedimentology was. As in the area studied, the beach with the highest erosion rates showed worse behaviour in the APW test compared to the beach with the lowest erosion rates.

Benidorm is one of the main beach tourism cities in the world (Femenia-Serra and Ivars-Baidal 2021). The situation that occurs in some profiles of the Poniente beach leads to a beach status that prevents the desirable recreational use by tourists, during the high season, and increases the risk of flooding under the maritime climate that affects that beach. The construction of detached breakwaters or jetties to improve tourism capacity and solve the problem of coastal erosion (Paraná 2015) does not seem like a sustainable solution for an area of such ecological value as Benidorm. That is why it is of great importance to take measures to mitigate and protect the coastal zone and preserve the environment (Patrício et al. 2014). One of these measures could be the transfer of sediments from W to E. This would allow maintaining a minimum functional beach width of 40 m (Magrama 2016), which would maintain the operational conditions of the beach both to provide a defence of the coast, as well as for recreational use.

6. Conclusion

After analysing the natural factors that affect two beaches with similar characteristics, a different morphological behaviour against erosion has been detected. This behaviour is related to the period analysed (1956–2021). Therefore, it is concluded that:

- The beach width at Poniente Beach is currently at its functional limit.
- Levante beach is in static equilibrium and Poniente beach shows a historical erosive trend except in the last period analysed.
- There is a change in the frequency and direction of the waves in the last period studied.
- The wave height and the storm duration increase in Levante. However, despite the increase in the wave height, the storm duration decreases in Poniente.
- The quality of the sediment makes the sand behave better against erosion, even with lower D_{50}.

It is of great importance to take measures to mitigate and protect the coastal zone and preserve the environment. One of these measures may be the transfer of sediments from west to east.

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