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Long-Term Monitoring and Morphological Response to Repeated Beach Nourishments in a Critical Coastal Sector: Lido di Dante Beach, Emilia-Romagna, Italy †

Enrica Vecchi [1,*], Stefano Gandolfi [2], Nunzio De Nigris [3], Filippo Elia Pizzera [3] and Flavia Sistilli [3]

1 Department of Civil, Environmental Engineering and Architecture (DICAAR), University of Cagliari, 09123 Cagliari, Italy
2 Department of Civil, Chemical, Environmentaland Materials Engineering (DICAM), University of Bologna, 40136 Bologna, Italy; stefano.gandolfi@unibo.it
3 Regional Agency for Prevention, Environment and Energy in Emilia-Romagna (Arpae)—Technical Department, 40122 Bologna, Italy; fpizzera@arpae.it (F.E.P.); fsistilli@arpae.it (F.S.); ndenigris@arpae.it (N.D.N.)
* Correspondence: enrica.vecchi@unica.it

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Abstract

Among low-lying sandy coasts, where erosion represents a major challenge, artificial beach nourishment is widely used as a mitigation strategy. This study investigates the long-term morphological evolution of Lido di Dante beach in northern Emilia-Romagna, Italy, where three regional nourishment interventions (Progettoni 2, 3, and 4) were carried out between 2007 and 2025. The dataset comprises twelve topo-bathymetric surveys covering the complete monitoring sequences (PRE, POST, M1, and M2). Sediment budgets, DEMs of Difference, cross-shore profiles, and beach slopes were analysed within three sectors (I, II, and III) characterized by different coastal-defence configurations. All interventions produced marked beach widening, with local elevation increases. However, substantial sediment redistribution occurred during the subsequent monitoring phases. During POST–M1, losses relative to the supplied volumes were 12% and 82% in Sectors I and II after P2 (Sector III was not nourished), 62%, 99%, and over 100% after P3, and 3%, 45%, and 43% after P4. These results indicate a spatially heterogeneous response associated with nourishment distribution, coastal-defence configuration, and local morphodynamic conditions. The recurring post-nourishment losses demonstrate that sediment placement in this area produces substantial short-term recovery without ensuring long-term stability, thus supporting the need for repeated interventions and accurate multi-temporal topo-bathymetric monitoring.

Keywords: beach nourishment; coastal monitoring; topo-bathymetric survey; Emilia-Romagna; Lido di Dante; RGC; sediment volume

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1. Introduction

Coastal areas worldwide are increasingly exposed to erosion as a result of the combined effects of climate change, sea-level rise, land subsidence, and anthropic pressures [1,2]. Consequently, coastal protection strategies have gained increasing attention, gradually evolving from localized hard protection measures, such as groynes and breakwaters, towards artificial beach nourishment [3]. This soft defence measure has been extensively implemented along sandy coasts, providing well-established short-term benefits, although its long-term effectiveness is highly site-specific and depends on local hydrodynamic conditions, sediment characteristics and availability, and coastal boundary constraints, including the configuration of rigid defence structures [4–8]. In particular, previous studies have shown that nourishment lifespan may range from a few months to several years depending on local conditions related to the equilibrium beach profile. In most cases, a significant portion of the placed material undergoes redistribution shortly after placement due to natural cross-shore and alongshore transport processes [9,10].

For these reasons, beach nourishment is generally viewed as a temporary measure rather than a permanent solution to coastal erosion and should be therefore integrated within long-term coastal management strategies, requiring periodic sediment placement together with regular monitoring to support future planning [9,10]. Within this framework, systematic post-nourishment surveys are essential to quantify morphological adjustments and sediment redistribution patterns. In particular, repeated topo-bathymetric campaigns provide a fundamental basis for assessing the beach evolution and evaluating nourishment effectiveness over different temporal scales [10,11].

The Emilia-Romagna coastline, located along the Northern Adriatic Sea in Italy, represents a paradigmatic example of a coastal system where long-term erosion mitigation strategies have been progressively implemented. Extending for approximately 110 km from Cattolica to the Po di Volano River mouth, together with the barrier-lagoon system of the Sacca di Goro in the northern sector, the regional coast has experienced a progressive shift from rigid protection measures towards integrated management approaches [12,13]. Since the 1970s, after decades characterized by the widespread construction of coastal defence structures, the region has progressively adopted large-scale beach nourishment strategies, locally known as "*Progettoni*", formalized within the Coastal Plan (Piano Costa) introduced in 1981 [14]. Specifically, over the last decades, more than 4.3 million m^3 of sand, mainly dredged from offshore deposits, have been placed along the regional coastline to restore and maintain beach sediment volumes [15–17]. Despite these long-term management efforts, the regional coastline remains a highly vulnerable system, with low-lying sandy beaches affected by natural sediment deficit due to reduced fluvial sediment inputs, ongoing land subsidence, and increasing anthropogenic pressures [18–20].

In this regional context, Lido di Dante represents one of the most critical sectors, characterized by high subsidence rates, and the presence of different configurations of coastal defence structures [21]. Previous site-specific studies at Lido di Dante investigated the evolution of the protected beach and nearshore-bar dynamics using ARGUS video observations collected between 2003 and 2009 [22,23]. More recently, repeated geophysical surveys conducted in 2020–2021 provided further insights into the temporal variability of submerged-beach morphology and sediment distribution [24].

However, previous investigations at Lido di Dante have generally focused on specific and relatively limited observation periods or individual morphological processes. Although recent regional-scale studies have reconstructed the long-term shoreline evolution [7], an integrated site-specific assessment of the three-dimensional morphological response of Lido di Dante to successive nourishment interventions throughout their complete monitoring phases is still lacking.

To address this gap, the present study investigates the morphological evolution of Lido di Dante and its response to three major nourishment interventions carried out between 2007 and 2022. The analysis uses 12 topo-bathymetric datasets acquired by Arpae (the Agency for Prevention, Environment and Energy of Emilia-Romagna) between 2007 and 2025, covering the complete PRE, POST, M1, and M2 monitoring sequences of *Progettone* 2, *Progettone* 3, and *Progettone* 4. The three sequences are compared within common spatial domains by integrating sediment budgets, DEMs of Difference, cross-shore profile evolution, and beach-slope analysis. This approach enables short- and medium-term nourishment responses to be compared among adjacent sectors characterized by different sediment inputs and coastal-defence configurations.

The results contribute to understanding nourishment performance in a highly subsiding and structurally constrained coastal system and provide information for adaptive coastal management in the Mediterranean region.

2. Study Area

Lido di Dante beach is located along the northern portion of the Emilia-Romagna coastline, between the mouths of the Fiumi Uniti and the Bevano River, within the Po Delta Regional Park (Figure 1). The area is included in the Natura 2000 site IT4070009 "Ortazzo, Ortazzino, Foce del Torrente Bevano," characterized by high ecological value and sensitive dune and backshore environments [25]. From a coastal management perspective, the study area has been classified within the SICELL system [26], encompassing cells 70 (Bevano Centro Nord), 71 (Bevano Nord), and 72 (Lido di Dante).

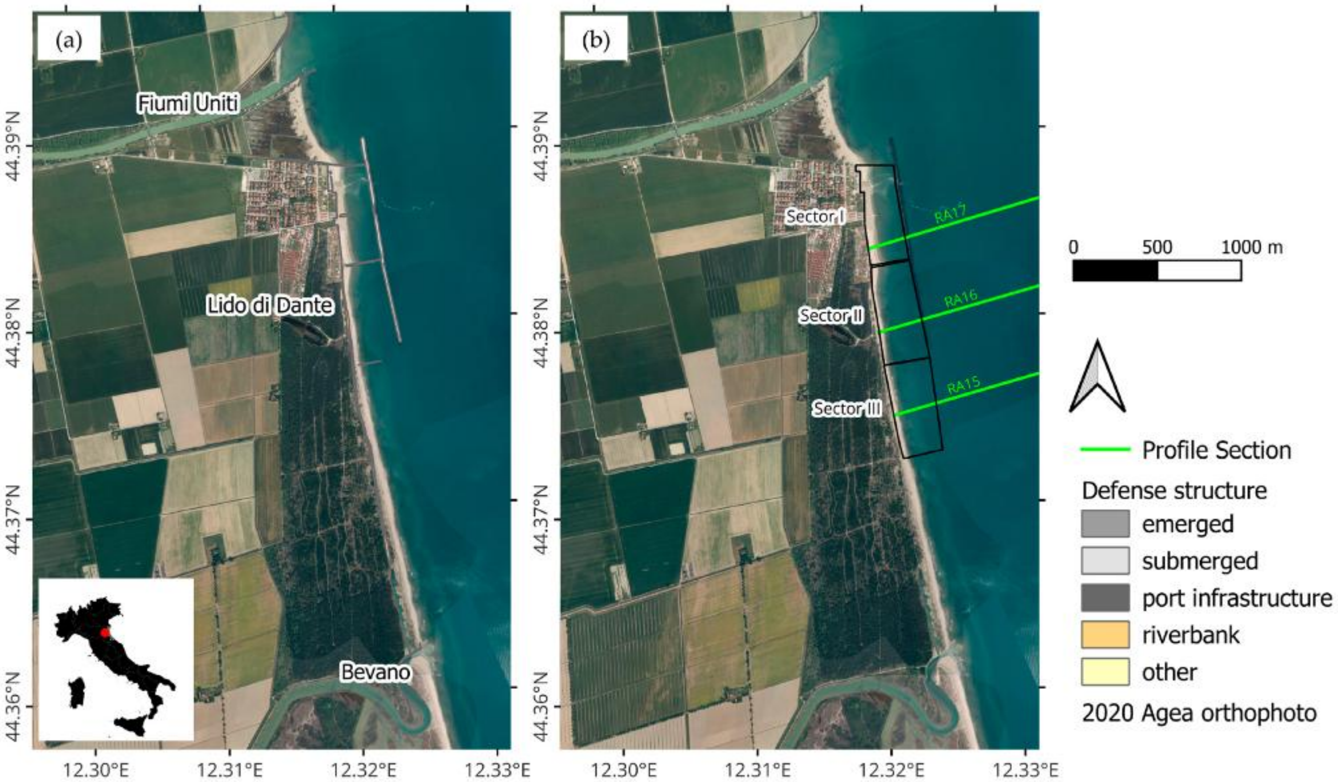

Figure 1. Lido di Dante beach, located along the northern Emilia-Romagna coast (Italy), showing the coastal defence structures and the locations of the Fiumi Uniti and Bevano River mouths (**a**). The three sectors adopted for the analysis and the representative monitoring profiles (RA15, RA16, and RA17) (**b**). Grid coordinates are aligned to the WGS84 coordinate system.

According to the latest available regional coastal indicators (ASE and ASPE), Lido di Dante experienced accretional conditions during the 2012–2018 period, due to the presence of coastal defence structures (ASE = A), whereas it would have been close to an unstable equilibrium without these interventions (ASPE = P) [12].

Since the late 1970s, the Lido di Dante sector has been protected by a complex system of rigid coastal structures, including groynes and detached or semi-submerged barriers. Initial interventions focused on groyne construction to reduce longshore sediment transport.

As erosion persisted, a 770 m long low-crested breakwater, parallel to the shoreline, was subsequently constructed in 1995 [27] to dissipate wave energy and enhance sediment retention [28]. Further modifications to the coastal defence system were carried out in the southern sector in 2020–2021, including the construction of a submerged breakwater and a wooden groyne.

The coastal morphology of Lido di Dante is typical of low-energy, sandy, dissipative beaches, with one or more submerged bars and an active nearshore zone [23]. Beach width varies significantly alongshore, from an almost absent emerged beach in erosional stretches to an extent of more than 80 m near the Bevano River mouth. Maximum beach elevations generally do not exceed 1–1.5 m above mean sea level [12].

A defining characteristic of the area is its high rate of land subsidence. Since the late 1990s, Lido di Dante has recorded some of the highest subsidence rates along the regional coast, with long-term values approaching 2 cm/year and more recent rates of approximately 17 mm/year. Official regional sources provide subsidence rates averaged over five-year intervals [29,30]. The specific rates available for the study area are reported in Table 1 to provide context for the morphological analysis.

Table 1. Subsidence rates in Lido di Dante [12].

Period	Rate (mm/y)
1999–2005	−19
2005–2011	−21
2011–2015	−17

The progressive lowering of the ground surface associated with subsidence can influence sediment budgets and should therefore be considered when evaluating morphological changes and volumetric balances. Over time, the reduced elevation of the coastal profile relative to mean sea level may increase the exposure of the beach system to ordinary wave action and extreme events, thereby promoting sediment losses and potentially reducing the long-term retention of nourished material [31–33].

The spatial subdivision adopted in this study differs from the SICELL classification and reflects the current configuration of the coastal defence system. Three alongshore sectors were identified: Sector I (northern sector), protected by three groynes and a low-crested breakwater; Sector II, protected by a low-crested breakwater and bounded to the south by a wooden groyne separating it from the southern Sector III, which has no additional defence structures (Figure 1). This classification enabled the assessment and comparison of morphological evolution, sediment dynamics, and nourishment response under different coastal defence configurations. In addition, three Arpae monitoring profiles (RA15, RA16, and RA17; Figure 1b) are located within the study area. Each profile is representative of one sector and was adopted for the subsequent analyses.

3. Materials and Methods

This section describes the nourishment interventions and associated topo-bathymetric survey campaigns carried out at Lido di Dante between 2007 and 2025, together with the altimetric reference framework adopted for their multi-temporal comparison. The methods used for data processing and for assessing sediment-volume changes and morphological evolution are subsequently presented.

3.1. Nourishment Interventions and Monitoring Plans

The critical morphological conditions of Lido di Dante beach have led to several nourishment interventions over time, as the site has been identified as a priority area within the regional coastal defense strategy [12]. Three regional large-scale beach nourishment projects involved this coastal stretch: *Progettone* 2 (2007), *Progettone* 3 (2016), *Progettone* 4 (2022). Unlike previous interventions that used quarry-derived sand, these projects employed offshore sediments dredged from designated borrow areas and selected for their granulometric compatibility with the native beach sediment (Figure 2) [16]. The available information allowed for the estimation of the sediment volumes supplied during each nourishment campaign for the three identified sectors and for the entire beach stretch (Table 2). It should be noted that, during the analysed period (2007–2025), additional sediment placements of generally smaller magnitude were also carried out within the study area and in other sectors of the Emilia-Romagna coast. However, these interventions were not systematically included in the analysis because consistent official documentation on their implementation, including exact dates, supplied volumes, and associated monitoring activities, was not always available. Where sufficiently documented, these inputs were explicitly considered in the analysis of sediment balances (Section 4.1).

Table 2. Summary of the sediment volumes supplied during each regional nourishment intervention for the three beach sectors (S I, S II, and S III) and the entire study area (Total). The table reports the sector area (Area, m^2), the alongshore length of the nourished stretch (L, m), the total supplied sediment volume (V_T, m^3), and the unit volume normalized by the alongshore length (V_U, m^3/m).

Sector		*Progettone* 2			*Progettone* 3			*Progettone* 4		
	Area (m^2)	L (m)	V_T (m^3)	V_U (m^3/m)	L (m)	V_T (m^3)	V_U (m^3/m)	L (m)	V_T (m^3)	V_U (m^3/m)
S I	126,220	600	53,550	89	600	34,700	58	600	29,080	48
S II	151,680	550	53,550	97	550	86,400	157	550	76,150	138
S III	145,850	/	/	/	50	1000	20	550	71,050	129
Total	423,750	1150	107,100	93	1200	122,100	102	1700	176,280	104

The standard monitoring protocol adopted by Arpae consists of a sequence of topo-bathymetric survey campaigns for each nourishment intervention, structured as follows [17]:

- Pre-nourishment survey (PRE): conducted shortly before sediment placement to document the initial morphological conditions of the beach system;
- Post-nourishment survey (POST): performed immediately after the intervention to quantify the initial morphological response and the effectively placed nourished volume;
- First monitoring survey (M1): first follow-up survey to assess the medium-term morphological evolution after nourishment;
- Second monitoring survey (M2): second follow-up survey to evaluate medium-term adjustments.

The present study consistently adopts this terminology to distinguish the different phases associated with each nourishment intervention. Twelve topo-bathymetric datasets were analyzed, covering the period from 2007 to 2025 and including the complete monitoring sequence (from PRE to M2) for each of the three *Progettoni* (Table 3).

Table 3. Summary of the topo-bathymetric survey datasets analysed in this study, including nourishment project, survey phase, and acquisition date. For P4-M2, the complete area was surveyed on separate dates, as indicated by the reported date range.

Nourishment Intervention	Survey Campaign	Date
Progettone 2	P2-PRE	02/2007
	P2-POST	05/2007
	P2-M1	10/2008
	P2-M2	07/2009
Progettone 3	P3-PRE	05/2016
	P3-POST	06/2016
	P3-M1	11/2017
	P3-M2	11/2018
Progettone 4	P4-PRE	03/2022
	P4-POST	04/2022
	P4-M1	11/2023
	P4-M2	02–04/2025

For clarity, each dataset is identified by the nourishment project code (P2, P3, or P4) followed by the corresponding survey phase (PRE, POST, M1, or M2). For example, P4-PRE, P4-POST, P4-M1, and P4-M2 identify the four survey datasets associated with *Progettone* 4.

Figure 2. Lido di Dante beach during the *Progettone* 4 nourishment intervention.

3.2. Altimetric Reference

When dealing with multi-temporal comparisons of spatial datasets, particular attention must be paid to the geodetic reference adopted during data acquisition and processing [34]. This aspect is especially critical in subsiding coastal environments, where vertical ground movements can introduce significant biases in volumetric estimates. Without a stable and homogeneous geodetic reference, apparent elevation changes may partly reflect inconsistencies in the vertical referencing of successive surveys rather than actual sediment redistribution, leading to systematic overestimation or underestimation of erosion and accretion volumes [17].

The present analysis was not intended to quantify or correct the absolute lowering induced by land subsidence or to provide orthometric elevations continuously updated at each survey date. Instead, it was designed to evaluate relative morphological changes associated with erosion and sediment redistribution, particularly through volumetric differences, within a common local vertical reference framework.

During the P2 monitoring period, successive surveys were harmonized through local vertical adjustments based on overlapping portions of the surveyed area assumed to be morphologically stable and unaffected by significant erosion or deposition processes. This procedure allowed successive DEMs to be aligned for relative morphological comparisons, although it did not provide a stable and reproducible geodetic framework. The limitations of this procedure were among the reasons for establishing a dedicated coastal geodetic network in Emilia-Romagna.

Indeed, in 2016, Arpae, in collaboration with the Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM) of the University of Bologna, established the Coastal Geodetic Network (Rete Geodetica Costiera, RGC) [35]. The RGC was specifically designed to provide a stable and homogeneous geodetic network for coastal monitoring activities, ensuring centimeter-level accuracy for both horizontal and vertical components. Benchmarks coordinates are consistently aligned with the official national reference system ETRS89–ETRF2000 (2008.0 epoch). Since RGC benchmarks support both GNSS and high-precision levelling measurements, their elevations are provided as both ellipsoidal and orthometric heights. The network currently represents the primary geodetic infrastructure supporting topo-bathymetric surveys and coastal monitoring activities throughout the region, with uniformly distributed benchmarks ensuring spatial continuity along the Emilia-Romagna coastline. Locations and technical information for the RGC benchmarks are available through the official Arpae webpage [36].

In 2023, a high-precision geometric levelling campaign was carried out along the Emilia-Romagna coastline to update the orthometric heights of all RGC benchmarks [37]. The campaign also connected the RGC network to the existing tide-gauge stations of Porto Garibaldi and Marina di Ravenna, and to the new stations installed in Cervia and Cattolica within the AdriaClim project [38]. In particular, the coastal levelling network was vertically referenced using the GNSS/tide-gauge station of Porto Garibaldi, with the nearest RGC benchmark, PGFV0100, adopted as the starting reference point for the levelling line [37].

From 2016 onwards, the surveys used in this study were referenced to the RGC. For morphological-monitoring purposes, the coordinates and elevations assigned to the benchmarks at the adopted reference epoch were fixed throughout the multi-temporal comparisons and were not updated to the epoch of each survey. Accordingly, no time-dependent correction for land subsidence was applied. Moreover, because each RGC benchmark is located close to its corresponding monitored coastal area [36], the GNSS positioning approach, referenced to a local RGC master benchmark, assumes that the benchmark and the surrounding beach undergo approximately the same vertical displacement. Under this assumption, their common vertical displacement is not expressed in the relative DEM differences, which isolate the effects of erosion and sediment redistribution processes.

This methodology provides a consistent vertical reference for long-term morphological comparisons without requiring a separate subsidence correction for each dataset. Conversely, alternative positioning solutions, such as real-time positioning services (with ellipsoidal heights converted to orthometric heights through geoid models), may introduce inconsistencies with respect to RGC-based datasets over decadal time scales if the effects of ongoing vertical ground movement are not properly considered. Given the subsidence rates characterizing the study area (Table 1), vertical differences of several centimetres may accumulate over approximately ten years, potentially biasing the interpretation of morphological changes.

3.3. Topo-Bathymetric Surveys

This section briefly outlines the surveying standards adopted for the topo-bathymetric measurements analysed in this study and carried out after the establishment of the RGC network. These methodologies are based on Arpae's long-term experience in coastal monitoring within the Emilia-Romagna region and provide a detailed representation of both the emerged and submerged beach.

The emerged beach was surveyed using GNSS instruments in Real-Time Kinematic (RTK) mode, with the master station positioned on the closest RGC benchmark. Kinematic surveys were conducted along both longitudinal and cross-shore transects perpendicular to the shoreline. Cross-shore transects were generally spaced 100–200 m apart. Both cross-shore and alongshore transects were designed to adequately capture spatial variability, particularly near rigid coastal structures and nourishment boundaries, as detailed in [17].

Bathymetric surveys of the nearshore and inner shelf were conducted along the seaward extensions of the emerged beach transects using single and multi-beam echo sounders (SBES, MBES) mounted on small vessels and integrated with an IMU (Inertial measurement Unit) platform and GNSS receiver operating in RTK mode. Surveys typically extended to water depths of approximately 7 m, covering the active morphodynamic zone and allowing for a partial assessment of offshore sediment redistribution processes.

To minimize measurement uncertainty during the acquisition phase, the surveys were conducted under favourable sea-state conditions, with wind speed not exceeding Beaufort force 2 (4–6 knots) and significant wave height not exceeding Douglas Sea state 2 (0.10–0.50 m), consistently with the regional monitoring protocols described in [12,17,39]. Further details on the topo-bathymetric monitoring methodology, including survey design, transect configuration, instrumentation, data-acquisition procedures, measurement accuracy, instrument calibration, quality control, and uncertainty assessment, are provided in the relevant technical literature [12,17,39].

Referencing the GNSS surveys to RGC benchmarks enabled the direct integration of emerged and submerged point datasets, achieving centimeter-level accuracy in both planimetric and vertical components.

3.4. Volumetric and Morphological Analysis

The topo-bathymetric datasets were processed using a combination of GIS-based operations and custom Python (v. 3.13.9) scripts. Following quality control and outlier removal, the elevation points acquired over the emerged and submerged portions of the beach were combined and interpolated using a Triangulated Irregular Network (TIN) to generate continuous Digital Elevation Models (DEMs) with a common grid-cell size of 10×10 m for all survey campaigns. The grid-cell size represents the spatial resolution adopted for the analysis and should not be interpreted as the vertical measurement accuracy. The latter was assessed under comparable survey conditions in [17] and is used to quantify the uncertainty of the volume changes presented below.

DEM of Difference (DoD) analysis was performed between consecutive surveys to generate elevation-change maps and assess the morphological evolution during each monitoring interval. To ensure spatial consistency, sediment-volume changes were calculated within the same three fixed sector polygons for all survey comparisons (Sectors I, II, and III; Figure 1b). The corresponding sector areas are reported in Table 2.

The DEM-derived shoreline position was extracted as the contour corresponding to zero orthometric elevation (H = 0 m) at the reference epoch of the adopted framework. This contour represents the intersection between the emerged and submerged portions of the reconstructed topo-bathymetric surface.

Consecutive shoreline positions were compared to provide a spatial assessment of shoreline advance and retreat associated with the nourishment interventions and subsequent sediment redistribution. This analysis was used to support the interpretation of the DoD maps and cross-shore profiles.

The cross-shore profile analysis was performed along the three regional monitoring transects defined by Arpae, selecting one representative profile for each Sector: RA15, RA16, and RA17 for Sectors III, II, and I, respectively (Figure 1b).

Two different methods were adopted to estimate beach profile slopes. Method I evaluates the nearshore slope between the shoreline and the closure depth, following the approach proposed by Athanasiou et al. (2019) [40]. For this method, the closure depth was estimated using the empirical formulation proposed by Hallermeier [41]:

$$D_c = 2.28H_{12} - 68.5\frac{H_{12}^2}{gT_p^2}, \tag{1}$$

where H_{12} is the significant wave height exceeded for 12 h per year, T_p is the associated wave period, and g is the acceleration of gravity. Wave parameters were derived from records collected by the Nausicaa regional wave buoy, managed by Arpae, and available through the Dexter platform [42,43]. The calculation was based on ten years of available data between 2013 and 2023. For each year, H_{12} was identified from the corresponding exceedance percentile of the annual distribution. The annual estimates were then averaged, resulting in a depth of closure of approximately 5.7 m.

Method II, based on the approach of Doran et al. (2015) [44], estimates the beach profile slope by linear regression of the cross-shore elevation data, together with the associated coefficient of determination (R^2). For this computation, no fixed elevation band was adopted for the three analyzed profiles. Instead, the regression for each profile was calculated over the submerged portion extending seaward to the position of the local defence structure, resulting in variable horizontal and elevation ranges.

The temporal evolution of the slope values obtained using both methods was then analyzed to assess the profiles response to sediment redistribution processes during accretional and erosional phases.

4. Results

This section presents the results of the multi-temporal analysis of topo-bathymetric datasets, describing sediment redistribution patterns, morphological evolution, cross-shore profile changes, and beach slope variations associated with the nourishment interventions.

4.1. Sediment Budgets and Morphological Evolution

Figure 3 shows the sediment volume changes associated with the three nourishment interventions during the POST–M1 and M1–M2 intervals. Consistent colours are used for the three sectors to facilitate comparison of their responses to P2, P3, and P4, with numerical labels reporting sediment loss (red) and accretion (green) volume in m^3 displayed above each bar. The volume uncertainty $\sigma_{\Delta V}$ per square metre (m^3/m^2) was calculated following the approach described in [17]. This provides a conservative estimate of the uncertainty associated with the volumetric analysis, accounting for both measurement errors and potential systematic biases. At the 68% confidence level, the values are consistent with those reported in [17], ranging from 1.18% to 1.20% across the three sectors.

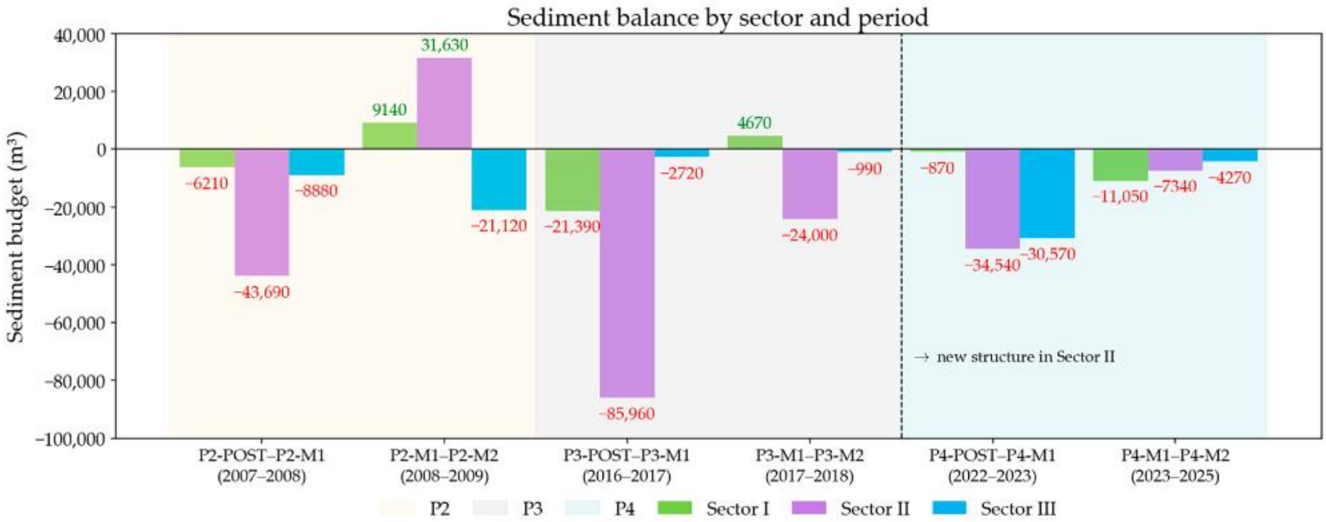

Figure 3. Sediment volume changes during the POST–M1 and M1–M2 intervals for the three nourishment campaigns (P2, P3, P4).

As previously observed in Table 2, Progettone 2 involved the placement of approximately 107,100 m^3 of sediment, evenly distributed between Sectors I and II, with no sediment supply in Sector III. During the first monitoring interval, the comparison between the P2-POST and P2-M1 surveys revealed significant sediment redistribution and erosion within the nourished area. The largest sediment losses occurred in Sector II, which lost approximately 82% of the initially placed volume, whereas Sector I experienced a more limited reduction of about 12%. Moreover, erosion also affected the adjacent, non-nourished Sector III, suggesting alongshore sediment redistribution beyond the area directly involved in sediment placement.

Between the P2-M1 and P2-M2 surveys, Sector III exhibited persistent erosion, with a sediment loss exceeding 21.000 m^3, while the response of the northern sectors changed markedly. Indeed, both Sectors I and II experienced sediment gains, although associated with different processes. The positive balance observed in Sector I can be partly attributed to the additional sediment input of approximately 10,000 m^3 from quarry-derived material supplied between M1 and M2, which was not included in the official P2 nourishment volumes. Conversely, the accumulation detected in Sector II may be related to a natural recovery process occurring during the P2 period, when no rigid coastal defence structures were present in this sector.

Accounting for the additional 10,000 m^3 of material supplied during the M1–M2 interval, the adjusted net sediment volume in Sectors I and II at the end of the P2 monitoring sequence was approximately 87,970 m^3, corresponding to 82% of the official P2 nourishment volume. This value represents the net sediment balance within Sectors I and II, which may include the effects of sediment exchanges with adjacent areas.

The *Progettone* 3 nourishment was mainly concentrated in Sector II, which received approximately 71% of the placed material. Sector I received 28%, whereas only 0.8% (approximately 1000 m^3) was placed along a limited portion of Sector III (Table 2).

Between P3-POST and P3-M1 surveys (2016–2017), substantial volumetric losses occurred throughout the study area, reaching approximately 110,000 m^3 overall. The volumetric pattern shown in Figure 3 indicates substantial sediment redistribution following placement, with particularly pronounced erosion in Sector II and more limited losses in Sector I and III. Normalizing the observed losses by the nourishment volume supplied to each sector reveals markedly different relative responses. Sector I experienced a net sediment loss equivalent to approximately 62% of the supplied volume, whereas the loss in Sector II, the main recipient of the intervention, was equivalent to approximately 99%. Sector III recorded an apparent loss of approximately 2700 m^3, exceeding the volume initially supplied to this sector. The observed behaviour likely reflects erosion of pre-existing material and sediment exchanges across the sector boundaries.

During the subsequent interval between P3-M1 and P3-M2 (2017–2018), sediment dynamics showed a partial attenuation of the high erosional trend observed immediately after nourishment. Sector I experienced a moderate sediment gain, although its cumulative balance over the entire POST-M2 period remained negative. Sector II was again the most dynamic sector in terms of sediment redistribution, experiencing further substantial losses. Sector III showed only minor changes; however, its overall balance cannot be directly compared with the northern sectors (I, II) due to the limited initial sediment supply and the lack of consistent baseline for volumetric accounting.

The last nourishment intervention involved the largest sediment volumes among the three regional projects, with a total of 176,280 m^3 distributed across the three Sectors. Different from the previous interventions, the placed material was supplied to the entire study area: 16% in Sector I, 43% in Sector II, and 41% in Sector III. As observed for the previous nourishment campaigns, the first monitoring interval, between POST and M1 (2022–2023) surveys, revealed significant sediment redistribution and renewed erosional processes. Sediment losses mainly affected Sectors II and III, which lost approximately 45% and 43% of the initially supplied volumes, respectively. Conversely, the volume of Sector I, which received the smallest nourishment volume, remained almost stable, indicating comparatively greater sediment retention, likely favoured by the protection of its rigid coastal defence structures.

Between the P4-M1 and P4-M2 surveys (2023–2025), erosional processes continued across the entire study area, although with lower magnitudes in Sectors II and III compared to the first monitoring interval. In contrast, Sector I experienced a more pronounced sediment loss during this period, which may be related to a delayed response compared with the other sectors. Consequently, the cumulative sediment budget relative to the initial nourishment volumes for *Progettone* 4 remained negative in all sectors.

Overall, the sediment budget analysis reveals a recurring morphodynamic pattern characterized by sediment losses during the first monitoring interval after nourishment, followed by progressively lower erosion rates and more stable morphological conditions in subsequent years. Moreover, the response shows marked spatial variability, likely associated with the different coastal defence configurations: Sector II experiences the highest sediment losses, whereas Sector I consistently exhibits comparatively greater stability and sediment retention capacity.

DEM of Difference (DoD) maps for P2, P3, and P4 spatially illustrate the same patterns identified in the previous volumetric analysis, and are shown in Figures 4, 5 and 6, respectively. Each figure follows the same temporal sequence: (a) PRE–POST, (b) POST–M1, and (c) M1–M2.

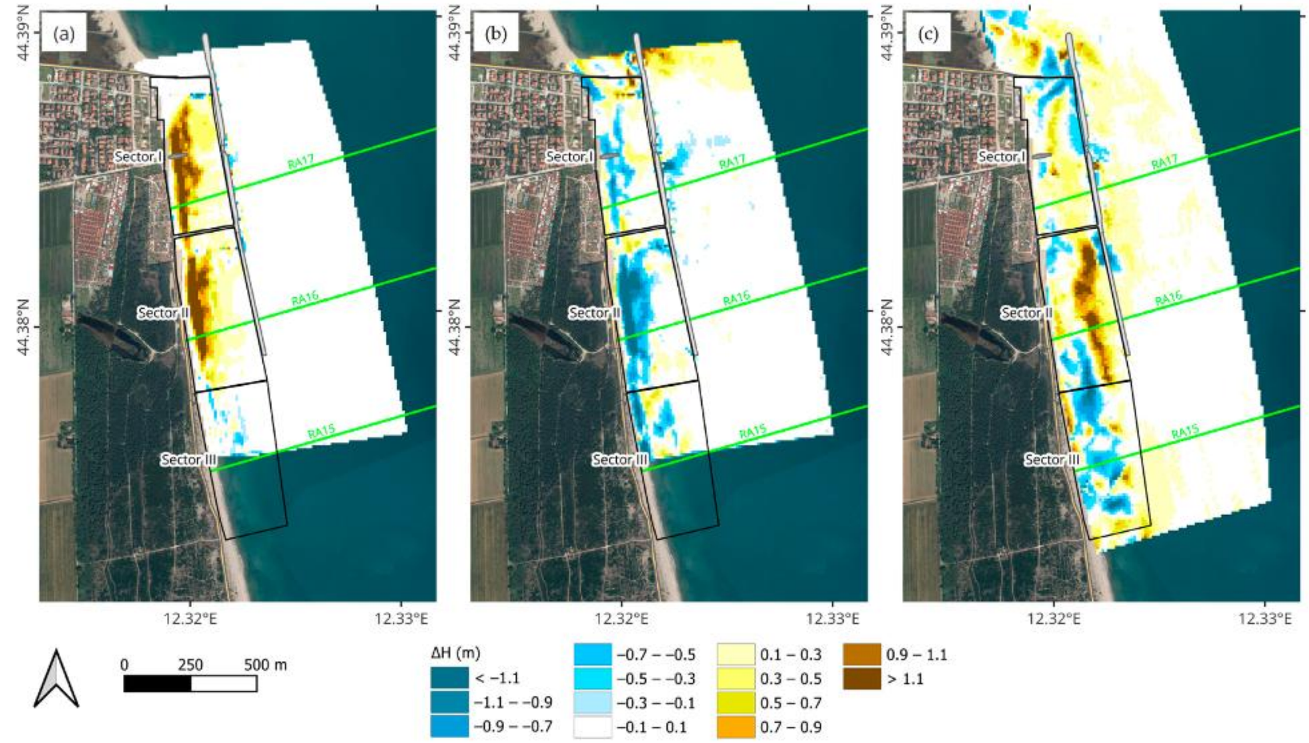

Figure 4. Elevation difference maps of P2 for the P2-PRE–P2-POST (**a**), P2-POST–P2-M1 (**b**), and P2-M1–P2-M2 (**c**) intervals.

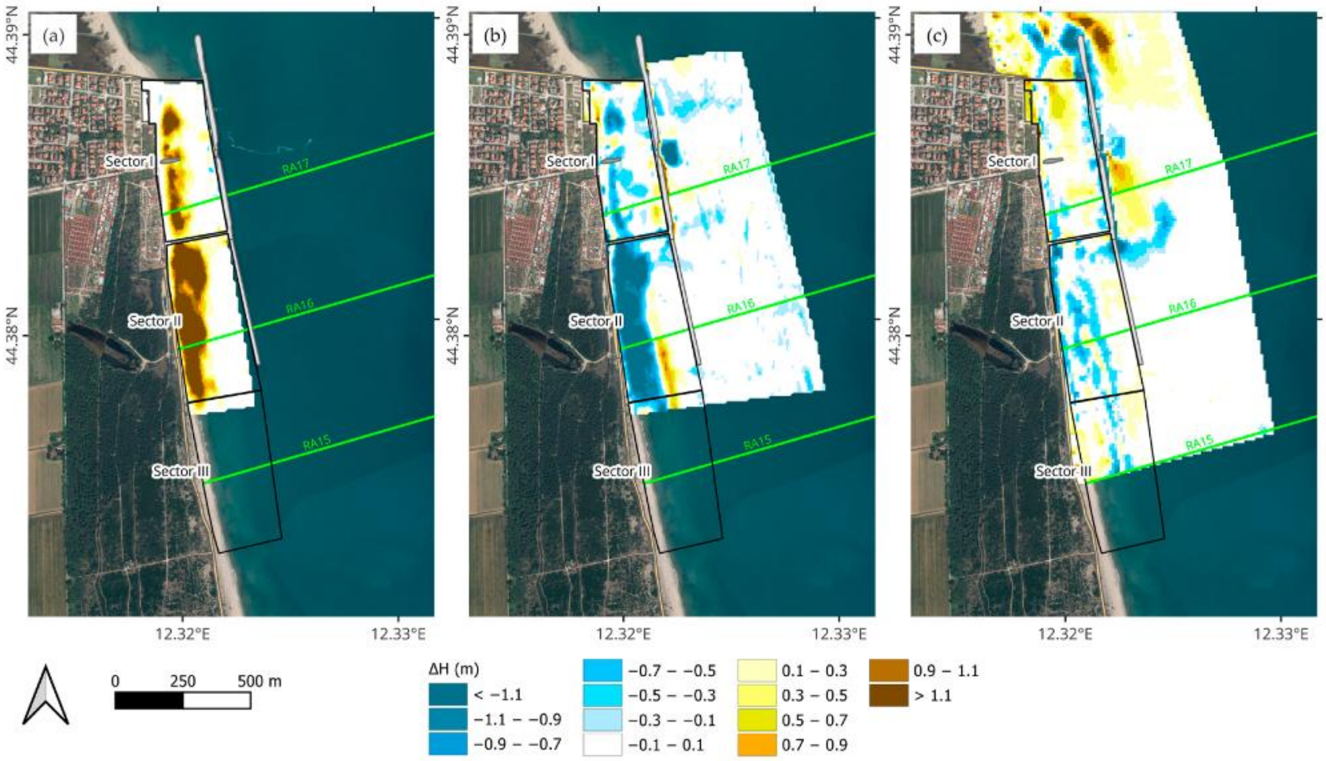

Figure 5. Elevation difference maps of P3 for the P3-PRE–P3-POST (**a**), P3-POST–P3-M1 (**b**), and P3-M1–P3-M2 (**c**) intervals.

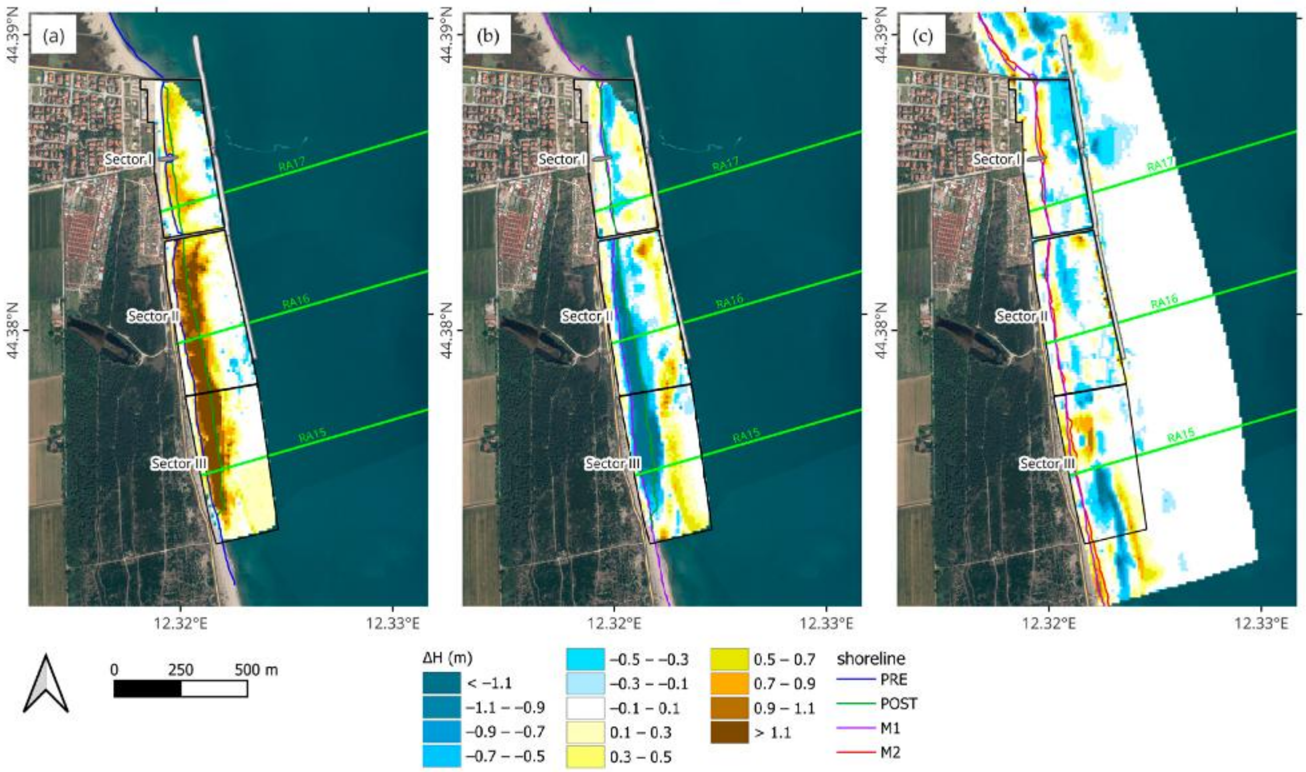

Figure 6. Elevation difference maps of P4 for the P4-PRE–P4-POST (**a**), P4-POST–P4-M1 (**b**), and P4-M1–P4-M2 (**c**) intervals.

Figures 4a, 5a and 6a clearly illustrate the effects of the three nourishment interventions and the different spatial extents of sediment placement. In all cases, the nourished sectors exhibit positive elevation changes locally exceeding 1 m, accompanied by shoreline advancement consistent with their respective sediment allocation.

The different morphological responses of the three sectors became evident in Figures 4b, 5b and 6b, corresponding to the POST–M1 intervals of P2, P3, and P4, respectively. Sector I consistently exhibits relatively limited elevation changes, generally not exceeding −0.5 m, whereas the highest erosional patterns are observed in Sector II, where elevation losses locally exceed 1 m and are associated with pronounced shoreline retreat, locally reaching approximately 55–60 m. Erosional trends in Sector III following *Progettone* 4 are also evident in Figure 6b.

The most relevant evidence, however, comes from the M1–M2 DoD maps (Figures 4c, 5c and 6c). Since the M1 and M2 surveys generally cover a wider area than the strictly nourished sector, these maps also document morphological changes outside the original nourishment footprints. For example, the P4-POST–P4-M1 map (Figure 6b) highlights sediment accumulation landward of the low-crested breakwater in Sector II and farther south in Sector III. These patterns become more evident in the subsequent M1–M2 map (Figure 6c), suggesting sediment circulation influenced by the coastal defence structures. Overall, the M1–M2 (c) DoD maps indicate that sediment redistribution occurred primarily through cross-shore transport, accompanied by secondary alongshore exchanges.

4.2. Profile Evolution

For clarity, the cross-shore profile analysis is presented only for the P3-M2–P4-M2 period (2018–2025). As described above, the beach profiles were extracted along the three Arpae monitoring transects (RA15, RA16, and RA17; Figure 1b) and are presented in Figure 7.

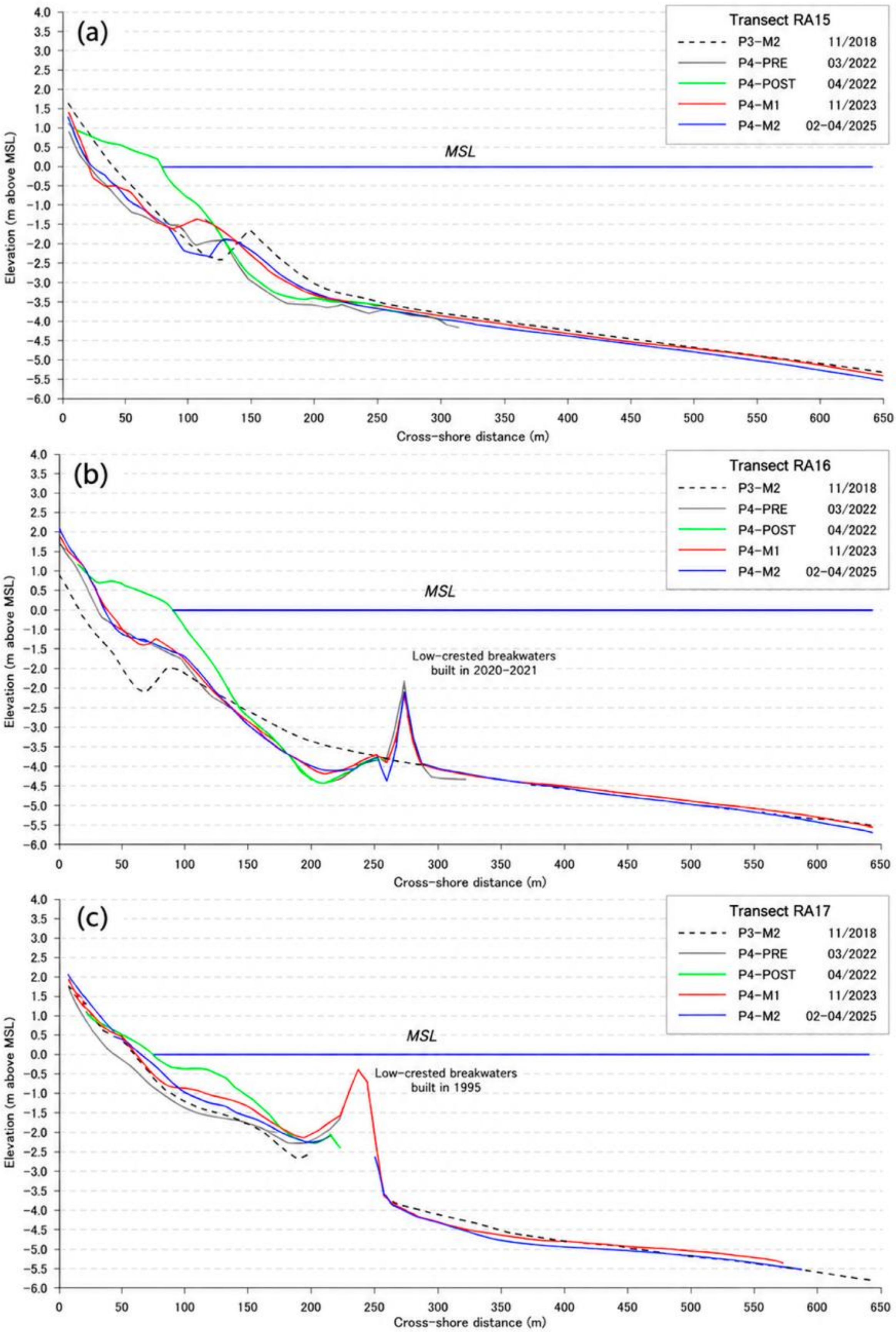

Figure 7. Cross-shore beach profiles extracted along the Arpae monitoring transects RA15 (**a**), RA16 (**b**), and RA17 (**c**).

This analysis provides additional insight into the morphological evolution occurring between the last survey campaign of *Progettone* 3 (P3-M2) and the subsequent nourishment intervention (P4-PRE). In particular, the period between P3-M2 and P4-PRE (2018–2022) was characterized by significant erosion and shoreline retreat at profiles RA15 and RA17 (Figure 7a,c). In contrast, profile RA16 in Sector II shows marked shoreline advancement over the same interval (Figure 7b), suggesting localized sediment placement within the inner portion of the profile that was not part of the regional nourishment interventions. At the same time, RA16 exhibits erosional patterns landward of the low-crested breakwater, consistent with the expected morphological adjustment during the interval between two major nourishment campaigns.

Comparison of the P4-PRE and P4-POST profiles clearly shows the immediate effects of the nourishment intervention, with local beach-elevation increases of approximately 1 m and shoreline advances ranging from 30 to 60 m, depending on the sector. At RA15 (Figure 7a), the P4-POST profile also indicates partial smoothing of the submerged bar previously located approximately 100 m seaward of the shoreline.

During the first monitoring interval (P4-POST–P4-M1), the profiles show renewed erosion. At RA15 and RA16, shoreline retreat reached approximately 50 m, with elevation losses of up to 1.5 m and the development of a new submerged bar along RA15 transect. In contrast, RA17 in Sector I experienced comparatively limited erosion and only minor elevation changes.

Overall, the profile analysis confirms the greater morphological stability in Sector I (RA17), whereas the unprotected or partially protected sectors exhibit more pronounced shoreline and elevation changes.

4.3. Beach Slopes

The beach slope analysis, performed on the same profiles discussed in Section 4.2, highlights both the temporal evolution of profile slopes and the differences between the two calculation methods (Figure 8).

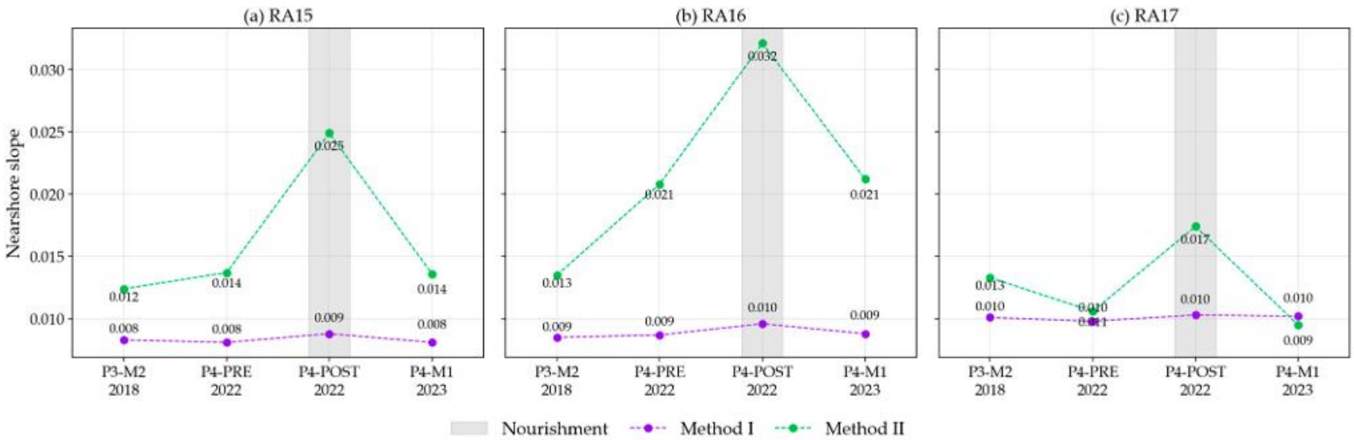

Figure 8. Temporal evolution of beach slope values obtained using Method I (violet) and Method II (green) along the Arpae monitoring profiles RA15 (**a**), RA16 (**b**), and RA17 (**c**).

Method I, which characterizes the overall nearshore profile, produced relatively stable slope values of approximately 1% throughout the analysed period. Conversely, Method II systematically produced higher slope values, typically exceeding 1% and reaching values of up to approximately 3%. Moreover, Method II also captured the temporal variability, reflecting its higher sensitivity to local-scale morphological changes.

The linear regressions adopted in Method II resulted in coefficients of determination (R^2) close to 0.9 at profiles RA15 and RA16 and approximately 0.8 for RA17. The slightly lower R^2 value obtained for RA17 may be related to its greater geometric complexity, associated with the break in slope at the toe of the low-crested breakwater.

In general, the temporal evolution of beach slopes is consistent with the alternation of accretional and erosional phases that emerged from the previous analysis. The increase in slope observed at profiles RA15 and RA16 during the interval between the two nourishment campaigns (P3-M2–P4-PRE) suggests localized sediment accumulation. This change may also be associated with modifications to the coastal-defence configuration (new structure) in Sector II.

Immediately after nourishment, sediment placement produced the largest increase in slope, reflecting the artificial placement of sediment and the resulting increase in beach width and elevation, consistent with the findings reported by previous studies [10]. These changes were particularly evident at profiles RA15 and RA16, consistent with their more dynamic response dominated by cross-shore sediment transport.

During the first monitoring phase (P4-POST–P4-M1), all three profiles experienced progressive flattening, with marked reduction in slope. Overall, the lower slope variability observed at RA17 is consistent with a possible short-term stabilizing effect of the coastal defense structures.

5. Discussion

5.1. Effectiveness of Nourishment Interventions in a Complex System

Despite differences in the volumes and spatial distribution of the supplied sediment among *Progettoni* 2, 3, and 4, a consistent morphodynamic response was observed across all monitoring campaigns. The periods between two successive interventions (e.g., the P3-M2–P4-PRE interval highlighted by the cross-shore profile analysis) was generally characterized by shoreline retreat, except where locally counteracted by additional sediment inputs not included in the official regional nourishment projects. The nourished material produced substantial beach widening and elevation increases during the PRE–POST intervals; however, a large portion of the placed sediment was subsequently redistributed during the POST–M1 periods.

The observed cross-shore and alongshore redistribution, extending from the subaerial and intertidal beach towards the nearshore zone, was likely associated with the increased availability of mobile sediment and the placement of the nourishment material in a configuration differing from the local equilibrium beach profile.

For all three nourishment interventions, cumulative sediment-volume changes during the post-nourishment monitoring sequences remained negative. This indicates that the beach system did not reach a stable morphological equilibrium within the monitored periods and continued to evolve through repeated erosion-recovery cycles.

It should be noted that the PRE, POST, M1, and M2 surveys represent predefined phases of the monitoring protocol: PRE and POST document the conditions immediately before and after sediment placement, whereas M1 and M2 represent successive monitoring stages (Table 3). Sediment-volume changes were therefore evaluated over the original survey intervals and were not converted into annualized rates, as this would imply an approximately linear evolution between surveys.

Although regional wave time series reconstructed by combining buoy observations and reanalysis data are available [7], deriving site- and interval-specific hydrodynamic-exposure indices and relating them to the observed morphological changes would require a dedicated analysis beyond the scope of this study. The reported sediment budgets should therefore be interpreted as integrated responses to the combined effects of post-nourishment adjustment, hydrodynamic forcing, sediment inputs, and boundary conditions.

5.2. Role of Coastal Defence Structures

It should first be noted that the coastal defence configuration was not constant throughout the three nourishment campaigns. The submerged breakwater extension and the wooden groyne constructed in 2020–2021 were present during the P4 intervention but not during the previous ones (P2 and P3) (Section 2). Consequently, the morphological response observed after P4 reflects the combined influence of nourishment, the modified structural configuration, and other environmental and morphodynamic factors.

The interpretation of the responses observed across the three sectors also requires consideration of the different nourishment volumes supplied. For example, during P4, Sector I received a substantially lower unit volume (48 m^3/m) compared with Sectors II and III (138 and 129 m^3/m, respectively) (Table 2). The post-nourishment response was therefore assessed not only in terms of absolute sediment-volume changes but also by expressing the relative changes as percentages of the volume initially supplied to each sector. This normalization accounts for differences in the initial sediment inputs when comparing sector behaviours.

Within this context, the analyses revealed a spatially heterogeneous morphodynamic response among the three sectors. Hard defence structures, such as the breakwaters and groynes in Sector I, may locally promote shoreline stabilization and short-term sediment retention while also modifying cross-shore and alongshore sediment-transport pathways and potentially limiting natural sediment redistribution and onshore accumulation [7,45].

This dual effect is consistent with previous DELOS studies conducted at Lido di Dante, which showed that low-crested structures can reduce incident wave energy while modifying local circulation and generating current acceleration and erosion near gaps and roundheads [45,46]. The lower relative sediment loss observed in Sector I during P4 may therefore be partly related to its defence configuration.

These spatially differentiated responses may contribute to the overall instability of the beach system and affect the long-term performance of nourishment interventions by altering natural sediment-redistribution and recovery processes.

5.3. Implications for Adaptive Coastal Management

The persistent sediment losses observed at Lido di Dante and the consequent need for repeated nourishment interventions highlight the importance of adopting adaptive coastal management strategies. The Emilia-Romagna region has a well-established monitoring framework that includes a dedicated stable geodetic infrastructure (the RGC), ensuring consistency among multi-temporal datasets, regular topo-bathymetric surveys conducted according to well-defined protocols, and a wave monitoring system supporting the analysis of hydrodynamic forcing.

6. Conclusions

This study investigated the long-term morphological evolution of Lido di Dante beach, located in a highly subsiding area and erosion-prone coastal sector of northern Emilia-Romagna, Italy. The analysis was based on multi-temporal topo-bathymetric datasets associated with three large-scale regional nourishment interventions. Twelve survey campaigns covering the period 2007–2025 were analysed, including pre-nourishment (PRE), post-nourishment (POST), first monitoring (M1), and second monitoring (M2) phases for *Progettone* 2 (P2), *Progettone* 3 (P3), and *Progettone* 4 (P4).

The adopted methodology combined sediment budget calculations, cross-shore profile evolution analysis, and slope evaluation, providing a comprehensive characterization of the nourishment performance and morphodynamic response. The integrated analyses revealed recurring similarities in the post-nourishment response following the three interventions, while highlighting marked spatial variability mainly related to the local configuration of coastal defence structures. Effective beach recovery and shoreline advancement consistently followed sediment placement, whereas subsequent monitoring phases documented progressive sediment reworking from the subaerial and intertidal beach towards the nearshore zone.

The results highlighted the intrinsic vulnerability of Lido di Dante and its limited long-term capacity to retain artificially supplied sediment. Under the current coastal setting, periodic nourishment interventions remain necessary to compensate for the persistent natural sediment deficit and maintain long-term stability.

However, the monitoring phases associated with the three interventions differ in seasonal timing and hydrodynamic exposure; consequently, the observed morphological changes represent integrated responses to multiple forcing factors. Future work will focus on integrating topo-bathymetric surveys with records of meteo-marine conditions associated with each monitoring interval and investigating their relationship with the observed morphological changes. Comparing the measured profiles with theoretical equilibrium configurations could also help a more detailed assessment of post-nourishment adjustments of the beach system.

Overall, this case study highlights the complexity of evaluating nourishment performance in coastal environments where defence structures interact with natural sediment dynamics. At the same time, it demonstrates the value of consistent, long-term topo-bathymetric monitoring for identifying spatial and temporal differences in nourishment response. In this context, the adoption of a well-defined geodetic reference framework was essential to ensure reliable comparisons among successive surveys.

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