

Integrating multidisciplinary approaches to assess beach dynamics and erosion susceptibility



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Short Note

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ABSTRACT

This work presents the methodological framework developed within the BERMS project, designed to integrate sedimentological, geomorphological, geophysical, compositional, and ecological approaches for assessing beach dynamics and erosion susceptibility. The primary aim is to establish a standardised, transferable protocol for monitoring wave-dominated sandy beaches in Mediterranean settings affected by increasing anthropogenic pressures and climate-driven changes.

Field activities focus on three sites in Southern Italy—Torre Guaceto (Adriatic Sea) and Porto Cesareo (Ionian sea) located in Apulia, and Sibari by the Ionian sea in Calabria—each characterised by distinct sediment dynamics, geomorphological features, and ecological sensitivities. The study combines high-resolution topographic surveys with subsurface imaging techniques (Sub Bottom Profilers, Ground Penetrating Radar, resistivity models), supported by numerical simulations using Delft3D.

The key innovation of the project is the methodological framework based upon monitoring techniques. By combining traditional field-based approaches with advanced modelling and ecological indicators, BERMS aims to balance environmental conservation with socio-economic development needs. Special attention is also given to identifying primary sediment sources and understanding sediment–ecosystem interactions, which are essential for sustainable coastal management.

The resulting methodology provides scalable tools and protocols for long-term beach monitoring across the Mediterranean, contributing to more informed decision-making processes in coastal planning and climate resilience strategies.

KEYWORDS: coastal erosion, sediment dynamics, sandy beaches, coastal management, geomorphological and geophysical monitoring.

INTRODUCTION

Assessment of beach evolution dynamics requires the integration of diverse monitoring techniques from multiple scientific disciplines, each addressing specific aspects of beaches. Since the 1960s, industrialisation and urban growth have driven progress in sandy beach studies, leading to new sedimentological, geomorphological, ecological, and geophysical approaches. Essential works include: i) analyses of sand movement (Ingle, 1966); ii) sedimentary textures indicating the health state of the beach (Dal Cin, 1969), iii) modelling of the equilibrium profile (Dalrymple & Thompson, 1977), and iv) morphodynamic classifications (Wright et al., 1979; Wright & Short, 1984). Modern research employs topographic surveys for shoreline variation (Pranzini, 2008; Anfuso et al., 2011; Nordstrom et al., 2015; Karkani et al., 2017) and beach profiling (Thom and Hall, 1991; Almeida et al., 2010; Riazi & Türcker, 2017), using GPS RTK, LiDAR, TLS, and video monitoring. Modelling tools simulate wave dynamics (Lesser et al., 2004) and sediment transport (Fredesøe & Deigaard, 1994; Trouw et al., 2012). GPR techniques, initially applied in archaeology and environmental studies, are used to investigate beach and dune systems (Leatherman, 1987; Bristow et al., 2000; Neal & Roberts, 2000; Neal, 2004; Hugenholtz et al., 2007; Guillemoteau, 2012; Shukla et al., 2013; Guillemoteau, 2012). Offshore, marine geophysical tools like multibeam sonar

and sub-bottom profilers provide insight into sediment thickness and seafloor features (Morang et al., 1997; Lubis et al., 2017; De Giosa et al., 2019; Kim et al., 2020).

Despite technological advancements, only a few research works integrate biological (van Loon et al., 2017; Lapietra et al. 2022a, b, c), sedimentological (Moretti et al., 2016), and ecological data (De Falco et al., 2003; Satta et al., 2013; Lisco et al., 2017), such as studies on *Posidonia oceanica* (Short et al., 2007), bioclast production (Gaglianone et al., 2017; Simeone et al., 2018), and banquette dynamics (De Falco et al., 2002, 2008).

Grain size studies (Gao & Collins, 1994; Dawe, 2001) and sediment transport analyses (Poizot et al., 2008) remain central, especially when supported by granulometric statistics (Folk & Ward, 1957; Visher, 1965; Friedman, 1967; Edwards, 2001).

Although interdisciplinary methods have improved beach management (Van der Salm & Unal, 2003; Nicoletti et al., 2006; APAT-ICRAM, 2007; Targusi et al., 2019; Tortora, 2020a, b), the effective integration across scientific disciplines is still not extensive (Gunn et al., 2006; Buosi et al., 2017; De Falco et al., 2015; Buosi et al., 2017).

In this context, the BERMS project aims to develop a standardised and interdisciplinary methodology for monitoring sandy beaches dominated by wave action and assessing their susceptibility to erosion, building upon the integrated framework proposed by Lapietra et al. (2022a). The approach integrates the majority of active physical and biological processes affecting beach dynamics, overcoming the limitations of previous sectoral or thematic studies. By employing advanced and innovative technologies, such as terrestrial laser scanners, marine geophysical instruments, and remote-operated vehicles, BERMS provides reliable quantitative and semi-quantitative data within a comprehensive, holistic framework. The integration of diverse methodologies is a key innovation that addresses the scientific challenge of producing a unified understanding of beach morphodynamics.

Furthermore, BERMS contributes to the emerging strategic theme of sustainability and natural resources protection by supporting sustainable human activities, including tourism, fishing, and coastal management, in sensitive coastal environments. The detailed knowledge of the interactions between physical and biological components enables informed decision-making and promotes responsible use of marine areas, avoiding blanket prohibitions. Overall, the project aligns with broader goals of biodiversity preservation and ecosystem restoration on land and at sea, fostering innovation and improved knowledge for effective coastal zone management.

STUDY AREA

The selected study areas include three sandy coastal sectors (Fig. 1a,b)—Torre Guaceto (TGU), Porto Cesareo (PCE), and Sibari (SIB)—which span a broad section of Southern Italy's coastline along the Adriatic Sea (TGU) and the Ionian Sea (PCE and SIB). These locations exhibit notable differences in beach dynamics, particularly concerning sediment composition, morphology, and wave climate. SIBs sediments are mainly siliciclastic terrigenous,

derived from nearby river systems, while Porto Cesareo is characterised by bioclastic carbonate sands due to limited terrigenous input, and Torre Guaceto shows a hybrid sediment composition, intermediate between the other two sites. TGU and PCE represent two pocket beaches characterised by a relevant importance from a naturalistic and socioeconomic point of view. The wave climates vary among the sites, each reflecting the distinct conditions of their coastal sectors, with differences in prevailing wave directions and wind intensities affecting sediment transport and beach morphology. From economic, social, and environmental viewpoints, these beaches are significant as popular tourist destinations generating substantial revenue. Notably, TGU and PCE are situated within marine protected areas, and Sibari lies within a regional natural reserve, helping to mitigate human impacts and preserving local habitats. The selection of these areas also benefits from comprehensive previous research on their geomorphology, sedimentology, and ecological features, providing a strong basis for the ongoing study.

Torre Guaceto (TGU)

Torre Guaceto (TGU) is a pocket beach located along the Adriatic coast of Southern Italy (Fig. 1c). Sediments along the shoreline exhibit a hybrid composition, consisting of siliciclastic and bioclastic-carbonate fractions derived from extra-basinal and intra-basinal sources, respectively (Lapietra et al., 2022b). TGU's morphology consists of a 1 km coastline, bordered by well-developed coastal dunes and a seabed varying between rocky and sandy substrates. The coastal profile is characterised by a narrow beach-dune system and a compact backshore, as is common for many beaches in this region. The wave climate is governed by prevailing wave directions and wind intensities consistent with the southern Adriatic Sea, significantly impacting sediment transport and beach dynamics. During the winter season, wind distribution is primarily concentrated around the 330°, 300°, and 180° sectors (approximately 12%), with velocities exceeding 17 knots. In contrast, the summer season is dominated by winds from 330° (approximately 23%), which also represent the highest recorded speeds.

As a designated Marine Protected Area, TGU benefits from legal protections that effectively reduce human pressure, ensuring the preservation of its habitats and maintaining ecosystem integrity through biodiversity conservation. The area has been extensively studied in terms of its geomorphology, sedimentology, and ecology, providing a comprehensive dataset that supports ongoing research activities (Lapietra et al., 2022a,b).

Porto Cesareo (PCE)

Porto Cesareo (PCE) is situated along the Ionian coast of the Salento Peninsula (Fig. 1d) and is characterised by predominantly bioclastic carbonate sands, due to the limited input of terrigenous sediments facing onto a karst area. Morphologically, PCE consists of narrow pocket beaches confined by carbonate headlands, a typical feature of the Ionian Salento coastline. The beach stretches along a relatively small shoreline with a

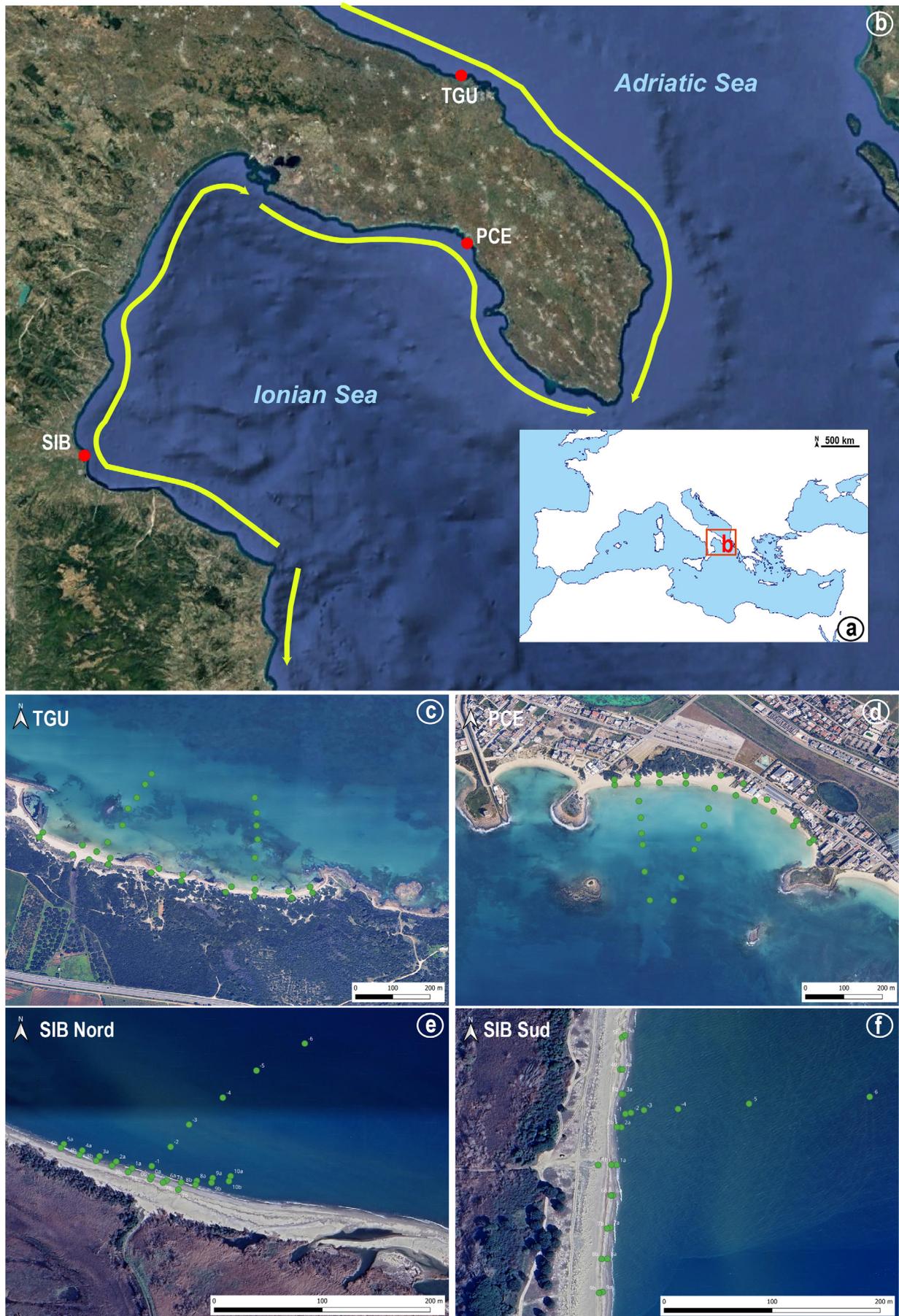


Fig. 1 - a) General map; b) Location of the three study areas - Torre Guaceto (TGU), Porto Cesareo (PCE) and Sibari (SIB) - where the yellow arrows represent the main longshore drift (Pinardi et al., 2016); c) Torre Guaceto sampling area; d) Porto Cesareo sampling area; e) Northern and f) Southern Sibari sampling area.

marine seabed primarily composed of carbonate substrates. Wave climate conditions at PCE reflect the typical Ionian Sea environment, with prevailing wave directions and wind intensity patterns influencing sediment transport and beach morphology. The historical series from [Milli et al. \(2017\)](#) show that ~36% of winds derive from 0° and 270° directions. The fastest winds are less frequent (approximately 17%) and come from 180° and 150°. Data from the Taranto station show that winds from 330° and 210° are the most frequent throughout the year, while those from 150° tend to be stronger. In contrast, north-easterly winds are generally weak and have little impact on the coastal area. PCE is included within a marine protected area, which helps reduce human impacts and preserve the coastal ecosystem. This site has been the focus of numerous studies on its sedimentological and ecological characteristics, providing a strong data foundation for ongoing research initiatives ([Lapietra et al., 2022b,c](#)).

Sibari (SIB)

Sibari (SIB) is located along the Ionian coast of Calabria (Fig. 1e,f) and is mainly characterised by terrigenous sediments derived from the nearby river systems typical of this region. The beach is extensive both longitudinally and in cross-shore direction, offering a broad sandy littoral zone. Morphologically, SIB differs from the pocket beaches of PCE and TGU by its wider and more continuous beach profile. The wave climate reflects typical Ionian Sea conditions, which, in the northern sector, are marked by high spatial variability and waves coming from a wide range of directions, associated with a generally high total wave-energy content. However, in the innermost portion of the Gulf of Taranto, where SIB is located, the most energetic wave motion predominantly arrives from the south-east, due to the limited fetch from other directions ([Foti et al., 2022](#)). These marine dynamics play a key role in modulating sediment transport and beach morphology. Unlike the other two areas, SIB is situated within the northern sector of the regional natural reserve of “Foce Fiume Crati,” which provides environmental protection aimed at limiting anthropogenic pressures and preserving local habitats. The site has been extensively studied in terms of geomorphology, sedimentology, and ecology, contributing valuable data to support the broader research efforts.

METHODOLOGY

The study employs a comprehensive, multidisciplinary approach integrating sedimentological, geomorphological, petrographic, geophysical, hydrodynamic, and biological analyses (Fig. 2). The combined use of classical field sampling techniques alongside advanced technological instruments allows a detailed characterisation of the sandy beach systems, their sediment dynamics, and ecological features. Seasonal monitoring and multiple survey campaigns ensure temporal variability, providing a robust dataset to evaluate beach morpho-dynamics and erosion susceptibility.

The methodological framework consists of:

- Beach sand analysis: Sampling along the backshore, foreshore, and shoreface from foredunes to 6 m depth, followed by grain-size analysis using standardized sieving procedures and statistical processing. Compositional and bioclastic analyses include petrographic point counting and identification of siliciclastic-terrigenous, bioclastic, and anthropogenic components to assess provenance and sediment dynamics.
- Topographic surveys: Terrestrial Laser Scanning (TLS) is used for detailed 3D mapping of the emerged beach sector, with repeated surveys capturing seasonal morphological changes. Video monitoring combined with Optical Total Station measurements verify and refine bathymetric data in the foreshore and shoreface.
- Geophysical surveys: Ground Penetrating Radar (GPR) profiles reveal sediment thickness and stratigraphy in the emerged beach. Sub-Bottom Profiler (SBP) surveys quantify sand layers in submerged shoreface sectors. Electrical Resistivity Tomography (ERT) complements these by imaging subsurface structures along the entire beach profile.
- Wave climate and sediment transport modelling: Delft3D software models hydrodynamic conditions, including wave-current interactions and sediment transport, integrating bathymetric and climatic datasets to simulate beach response under storm events.
- Biological surveys: Habitat mapping and biocenosis analysis involve ROV-assisted underwater observations and scuba diving to characterize ecological communities across supralittoral to infralittoral zones. This evaluates biological influences on sediment dynamics, including the role of seagrass meadows in coastal stability.

RESULTS

Torre Guaceto (TGU)

The morpho-sedimentary investigation of Torre Guaceto beach revealed marked seasonal and spatial variations across both emerged and submerged sectors. Digital Terrain Model (DTM) comparisons, both between winter and summer seasons and among different zones of the beach system, indicated distinct patterns of sediment gain and loss. The central-northern portion of the beach experienced significant sediment accumulation (gain), while the southern sector, particularly near dune bases, underwent notable erosion (loss). Furthermore, sediment-volume calculations derived from cross-shore topographic transects clearly reflected these dynamics, revealing localised accretion of up to 43 m³/year and erosion exceeding 14 m³/year. In the submerged zone, seasonal bathymetric profiles obtained through Optical Tracking System (OTS) revealed the formation of bars and troughs during winter months, indicative of active sediment reworking under more energetic conditions. Summer beach profiles were more regular and gently sloped. Sediment loss in the submerged zone between the two seasons reached up to 34 m³. Granulometric analyses showed main characters of medium, well-sorted sands. Alongshore and depth-related trends highlighted decreasing mean grain size and

ON-SITE AND LABORATORY ANALYSIS PROCEDURES

to assess beach dynamics and erosion susceptibility

ON-SITE

LABORATORY

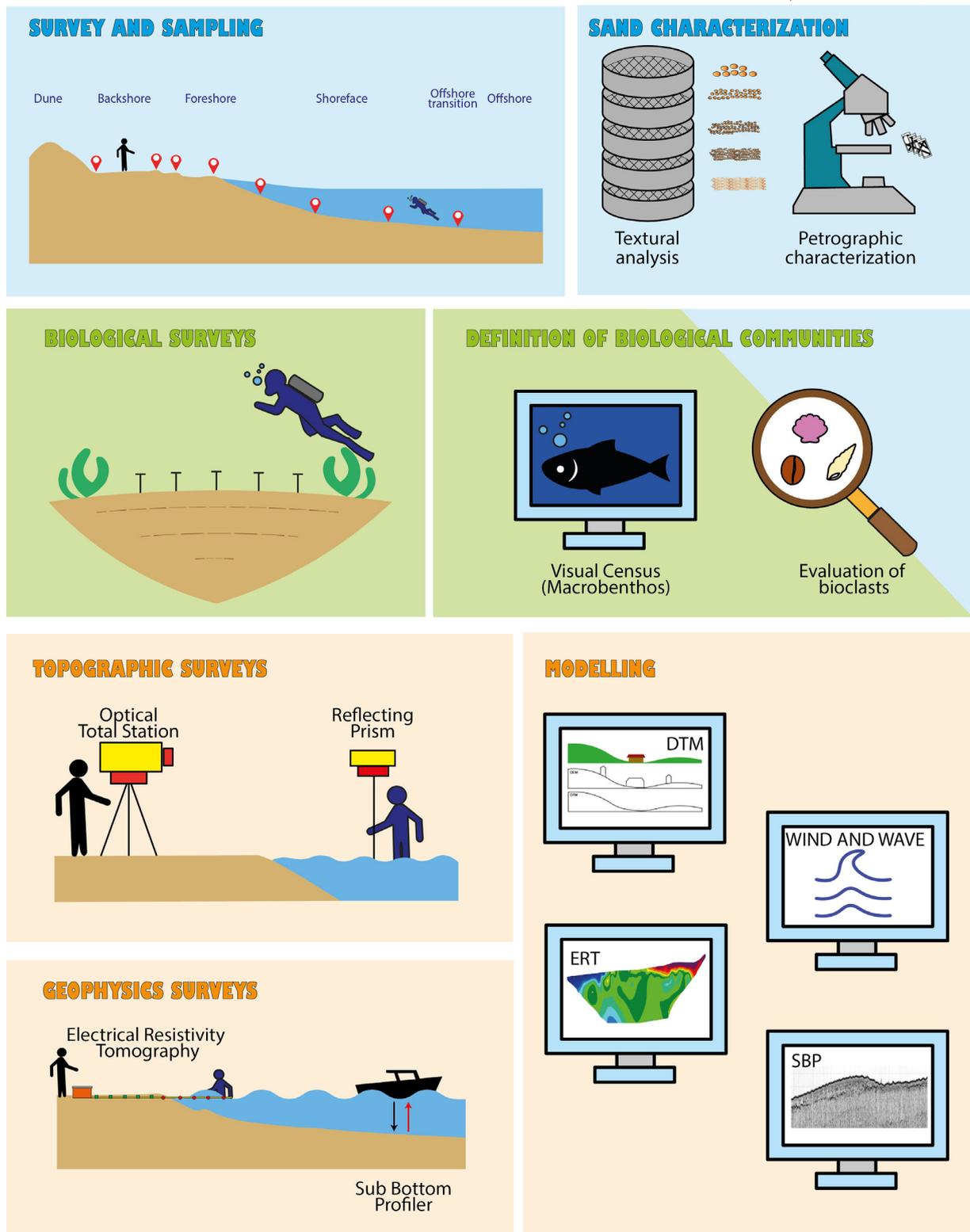


Fig. 2 - Schematic representation of all methodological procedures applied both in the field (left side) and in the laboratory (right side). From top to bottom, the figure illustrates the methods used for sediment sampling longshore-perpendicular transects (field), followed by the textural and compositional analyses (laboratory). Below, the procedures for biological data analysis are shown, including image acquisition using a GoPro camera, in situ macrobenthos sampling, and the counting of bioclasts in sediment samples. Further down, the figure shows the topographic surveys (field) performed with a total station, and the geophysical–geoelectrical surveys that allowed the creation of a continuous land–sea transect, which was integrated with offshore sub-bottom profiling data. These datasets provided the basis for laboratory modeling aimed at defining the physical model of the studied beaches.

increased sorting towards offshore. Petrographic results classified the beach deposits as hybrid sands, composed of both bioclastic and siliciclastic materials (Fig. 3). Bioclast content was highest in the northern foreshore (up to 80%), decreasing progressively southward. Shoreface sediments maintained relatively constant bioclastic percentages, though some variability was observed with depth and location.

Hydrodynamic models under simulated extreme events revealed strong seasonal contrasts. Winter waves (up to 4 m offshore) led to high-energy dissipation, especially over submerged rocky outcrops between 2 and 5 m depth. This geological feature played a key role in wave attenuation and sediment dynamics, acting as a natural breakwater that dissipates wave energy and limits sediment resuspension nearshore. A slight longshore transport from south-east to north-west (Fig. 1b) was consistently observed, shaping sediment redistribution across the beach system.

The macrozoobenthic organisms identified by biological surveys as the main responsible for sediment production were bivalve and gastropod molluscs, tube-dwelling polychaete annelids, and foraminifera, present in greater numbers and with greater biodiversity values between 4 and 6 meters deep.

Porto Cesareo (PCE)

Le Dune beach at PCE presents a consistent sedimentological framework that reflects the combined influence of wave dynamics,

sediment dispersion, and biological productivity. Across the emerged and submerged beach sectors, the sediments are generally composed of moderately to well-sorted medium to coarse sands, with variations in grain size and sorting that reflects long-term exposure to high-energy marine processes. The shoreface area, especially between 1 and 3 meters depth, is particularly dynamic. In fact, the frequent breaking waves induce selective transport and deposition of sediments, resulting in finer, better sorted sands with symmetrical and leptokurtic grain size distributions in deeper zones.

Grain morphology across the beach shows a dominance of blade-shaped and oblong grains on the foreshore, while oblate forms are more common in the submerged areas. These patterns suggest a consistent hydrodynamic sorting mechanism that redistributes sediment shapes according to energy gradients along the profile.

Le Dune beach sands are strongly dominated by carbonate bioclasts, such as shell fragments and foraminifera, with minimal siliciclastic input, limited primarily to well-rounded quartz grains. The sands can be classified as hybrid intrabasinal sands (*sensu* Zuffa, 1980), with bioclast content consistently exceeding 85% and often reaching over 95% in the shoreface (Fig. 3).

The bioclastic assemblage is taxonomically diverse and persistent across seasons and zones, with a clear contribution of molluscs and benthic foraminifera, accompanied by echinoderms,

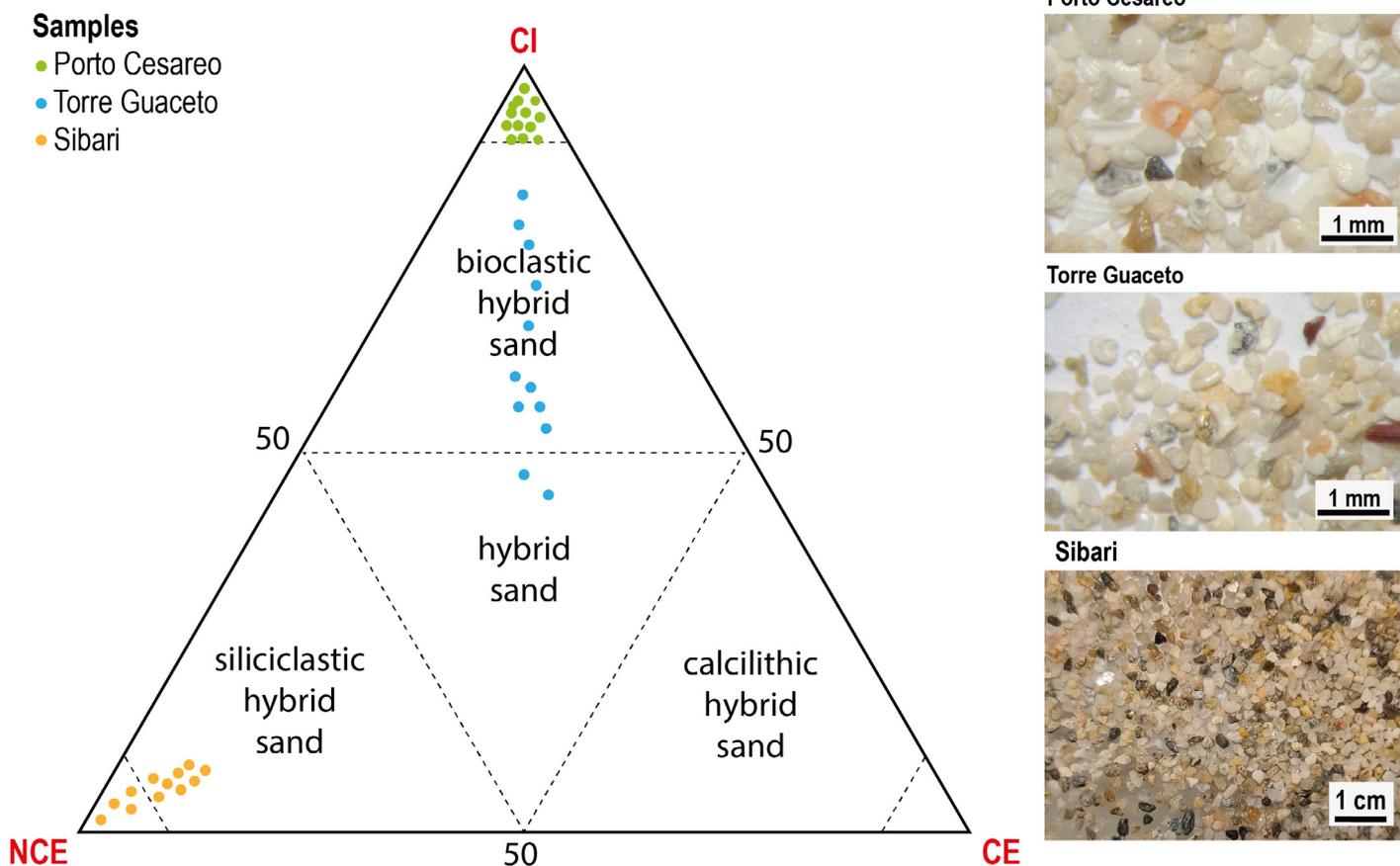


Fig. 3 - Classification of sands with the triangular diagram proposed by Zuffa (1980) for hybrid sand. NCE Non carbonate extrabasinal; CE- carbonate extrabasinal; CI-carbonate intrabasinal; green - samples from Porto Cesareo; blue - samples from Torre Guaceto; orange - samples from Sibari.

red algae (Rhodophyta), bryozoans, sponges and arthropods. This biological imprint reinforces the natural origin and ongoing contribution of in situ carbonate production to the beach sediment supply. Overall, Le Dune beach exhibits a general trend of sediment redistribution influenced by wave energy and biogenic input, with a stable petrographic composition dominated by carbonates and a consistent morpho-textural structure. These features reflect a naturally high-energy, carbonate-rich coastal system that remains compositionally stable despite localised erosional or depositional changes depending on both their location and seasonal variations in currents. Biological sampling aimed at characterizing the macrozoobenthos allowed the identification of 24 bivalve and 14 gastropod taxa, as well as 3 foraminifera taxa, these latter present with high abundance values especially between 3 and 6 meters of depth.

Sibari (Sib)

The beaches located north and south of the Crati River mouth have granulometric characteristics typical of wave-influenced coastal systems, with noticeable variations between transects perpendicular to the coastline and different sectors parallel to the coast. Across the sampling southern sector (Fig. 1f), samples from transect A range from very fine gravel to coarse sand, with grain-size distributions shifting from unimodal in the northern part of transect A, to bi- and tri-modal trends towards the southern part. Sorting is variable in the northernmost samples but becomes more homogeneous southwards, where sediments are consistently poorly sorted. Kurtosis values are generally mesokurtic, although leptokurtic and platykurtic distributions also occur. Skewness is predominantly asymmetrical, with curves enriched in finer fractions. Samples from transect B (Fig. 1f) in the same sector range from very coarse to medium sands. These sediments are uniformly unimodal, mostly moderately well-sorted, in some cases they show well-sorted features. Their grain-size distributions are mainly mesokurtic and symmetrical, with enrichment in fine and coarse fractions limited to a few samples. In the northern sector, sediments from transect A (Fig. 1e) vary from very fine gravel to very coarse sand, with a predominance of bimodal distributions, though unimodal and trimodal trends are also present. Sorting decreases from north to south, ranging from moderately to poorly sorted, and kurtosis values span from platykurtic to leptokurtic. Distributions are mostly symmetrical, with some coarser tails. Samples from transect B, in contrast, are dominated by medium sands, in some cases coarse sands. These sediments are moderately well- to well-sorted, mesokurtic to leptokurtic, and show skewness patterns enriched towards finer fractions. When comparing beach profiles south and north of the river mouth, a general trend emerges: both areas exhibit granulometric features such as mean, mode, and kurtosis, characteristic of beach environments, but with subtle differences in sorting and symmetry. South of the river, foreshore samples show less uniformity and asymmetric distributions enriched in finer particles, whereas backshore samples are more uniform, mesokurtic, and better sorted. North of the river, grain size decreases from foreshore (fine gravel) to backshore (coarse sand), with sorting improving landward. Here, distributions range from

platykurtic to mesokurtic and from symmetrical to asymmetrical, with enrichment in finer sediments.

Overall, beaches around the Crati River mouth reflect dynamic coastal settings influenced by waves, tides, and currents, with moderate erosive capacity. Both northern and southern sectors show skewed distributions enriched towards fine fractions, highlighting the role of selective transport and deposition processes. The compositional characteristics of these deposits are the low contribution of bioclasts and the prevalent presence of siliciclastic materials that sometimes show signs of recycling (Fig. 3). The beach deposits originate from the Crati river which erodes magmatic, metamorphic and sedimentary rocks from the Calabria Alpine chain. In particular, a mafic component such as pyroxenes and metavolcanites prevails, but high-grade micaschists, granitoids and some limestone fragments are also widespread. Bioecological surveys have locally ruled out the presence of seagrass meadows within 6 meters of depth, with sporadic traces of *Cymodocea* sp. on the seabed south of the Crati mouth. Sediment sampling conducted by diving allowed the identification of a limited number of species of sedimentological interest, primarily bivalves and tube-dwelling polychaetes, primarily concentrated at depths between 3 and 6 meters. Overall, north of the river mouth the assemblage was even more sparse than on the southern side, with the sole exception of polychaetes, which showed slightly higher abundance values. At all the depths investigated, only a few dead gastropod shells were found and a total absence of foraminifera.

DISCUSSION AND CONCLUSIONS

By combining traditional field-based approaches (Dal Cin et al., 1984; Leont'ev, 1985; Depountis et al., 2023) with advanced geophysical techniques (Leucci, 2006), ecological assessments (Vacchi et al., 2017), and numerical modeling (Bonardo et al., 2019), the BERMS project introduces a novel and integrated methodology for coastal erosion monitoring. This multidisciplinary approach offers a comprehensive understanding of beach system dynamics, which is essential for the development of effective coastal planning and climate resilience strategies (Masselink & Hughes, 2003; Cowell et al., 2003; Vousedoukas et al., 2020). The project's findings are intended to support policymakers, environmental agencies, and local communities in making informed decisions that align ecological sustainability with socio-economic development. The BERMS project is expected to deliver a set of scalable tools and protocols for long-term beach monitoring and erosion risk assessment. These outputs will enhance our capacity to identify vulnerable areas, prioritize conservation actions, and inform adaptive management strategies. By linking physical processes with ecological conditions, the project also provides insights into how beach ecosystems respond to sedimentary changes, which is crucial for maintaining ecosystem services. The applicability of the BERMS methodology is demonstrated through analyses at different Mediterranean sites. As a case study, sediment analyses highlight how prevailing coastal currents influence beach sand composition. The sands of Torre Guaceto exhibit a mixed origin, resulting from siliciclastic materials transported from the northwest and intra-

basin bioclasts. In contrast, the beach sands of Porto Cesareo show an exclusively local contribution of carbonate and bioclastic materials, while the sands and gravels of Sibari are characterised by siliciclastic sediments derived from the Calabrian crystalline chain.

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