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To cite this article: Marco Porta, Carla Buosi, Daniele Trogu, Angelo Ibba & Sandro De Muro (2021) An integrated sea-land approach for analyzing forms, processes, deposits and the evolution of the urban coastal belt of Cagliari, Journal of Maps, 17:4, 65-74, DOI: [10.1080/17445647.2020.1719441](https://doi.org/10.1080/17445647.2020.1719441)

To link to this article: <https://doi.org/10.1080/17445647.2020.1719441>



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An integrated sea-land approach for analyzing forms, processes, deposits and the evolution of the urban coastal belt of Cagliari

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ABSTRACT

Using a comprehensive cartographic product, this paper aims to illustrate the evolution of the urban geomorphological setting of the urban coastal belt of Cagliari (southern Sardinia, Italy, western Mediterranean Sea). The geomorphological map (1:14,000) presented herein summarizes different data (e.g. urban development, anthropogenic features, geomorphological elements, recent deposits, sedimentological distribution, hydrodynamics and ecological components) acquired through an integrated sea-land approach and a multidisciplinary-multitemporal investigation.

The main significant environmental changes are linked to urbanization, the development of port infrastructures (embankments along the shoreline and the construction of the canal harbour), remediation work and filling activities, and the hardening of dune and beach systems and cliffs. These man-made interventions have increased the vulnerability of the shore zones to flood hazards and risks, which are linked to sea-level rises and global warming.

ARTICLE HISTORY

Received 20 August 2019
Revised 19 December 2019
Accepted 18 January 2020

KEYWORDS

Urban geomorphology; geomorphological evolution; coastal management; coastal city; Gulf of Cagliari; Mediterranean sea

1. Introduction

Urban coastal belts are complex, narrow transition areas that connect terrestrial and marine environments. They are characterized by dynamic interactions between biophysical, human and socio-economic forces, and are among the world's most productive and valued ecosystems (Blumberg & Bruno, 2018; Crossland, Kremer, Lindeboom, Crossland, & Le Tissier, 2005). These environments are consequently exposed to pressures and hazards from both land and sea (Cummins et al., 2014). Properly managing these complex zones requires an understanding of the interactions between physical processes, eco-geomorphological settings and urbanization, and can be crucial when it comes to reducing vulnerability and planning appropriate interventions. In this context, the mapping of urban geomorphology in coastal areas is a relatively recent research field that requires constant updating (Brandolini, Faccini, Paliaga, & Piana, 2018; Coates, 1976; Diao, 1996). However, despite the growing interest in urban geomorphology (Bathrellos, 2007; Brandolini, Faccini, Paliaga, & Piana, 2017; Brandolini et al., 2019; Cooke, 1976; Del Monte et al., 2016; Faccini, Piccazzo, Robbiano, & Roccati, 2008; Reynard, Pica, & Coratza, 2017; Thornbush, 2015), there are a limited number of cartographic products that use an integrated sea-land approach to identify, understand and describe static and dynamic processes in an urban coastal area, including in relation to sea-level rises and

increasingly common extreme events linked to global warming. In fact, due to its tectonic stability, Sardinia can be viewed as a 'sentinel island' for the evaluation of these changes in sea-levels in the future.

Using a comprehensive cartographic product, this paper aims to illustrate the evolution of the urban geomorphological setting of the coastal city of Cagliari (southern Sardinia, Italy, western Mediterranean Sea). Ever since the Punic period (Buosi, Del Rio, et al., 2017), the city and its surroundings, including a wide range of natural and man-modified environments, have progressively grown to reach their current extent. In the last few decades, the coastal areas of Cagliari have experienced intense urbanization with the expansion of the city and its hinterland (about 500,000 inhabitants). Residential developments, in addition to industrial activities, have placed significant human pressure on the two beach systems of Giorgino and Poetto, which are, respectively, located to the west and east of the metropolitan area of Cagliari. In particular, recent economic development (with the coexistence of industry and fishing, touristic and recreational activities) has almost completely reshaped the original coastal morphology and modified the fluvial and lagoonal systems, increasing the vulnerability to coastal risks, especially flooding and erosion (Brambilla, van Rooijen, Simeone, Ibba, & De Muro, 2016; De Muro, Ibba, Simeone, Buosi, & Brambilla, 2017; De Muro, Porta, et al., 2018; Ruju

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Supplemental map for this article is available online at <https://doi.org/10.1080/17445647.2020.1719441>

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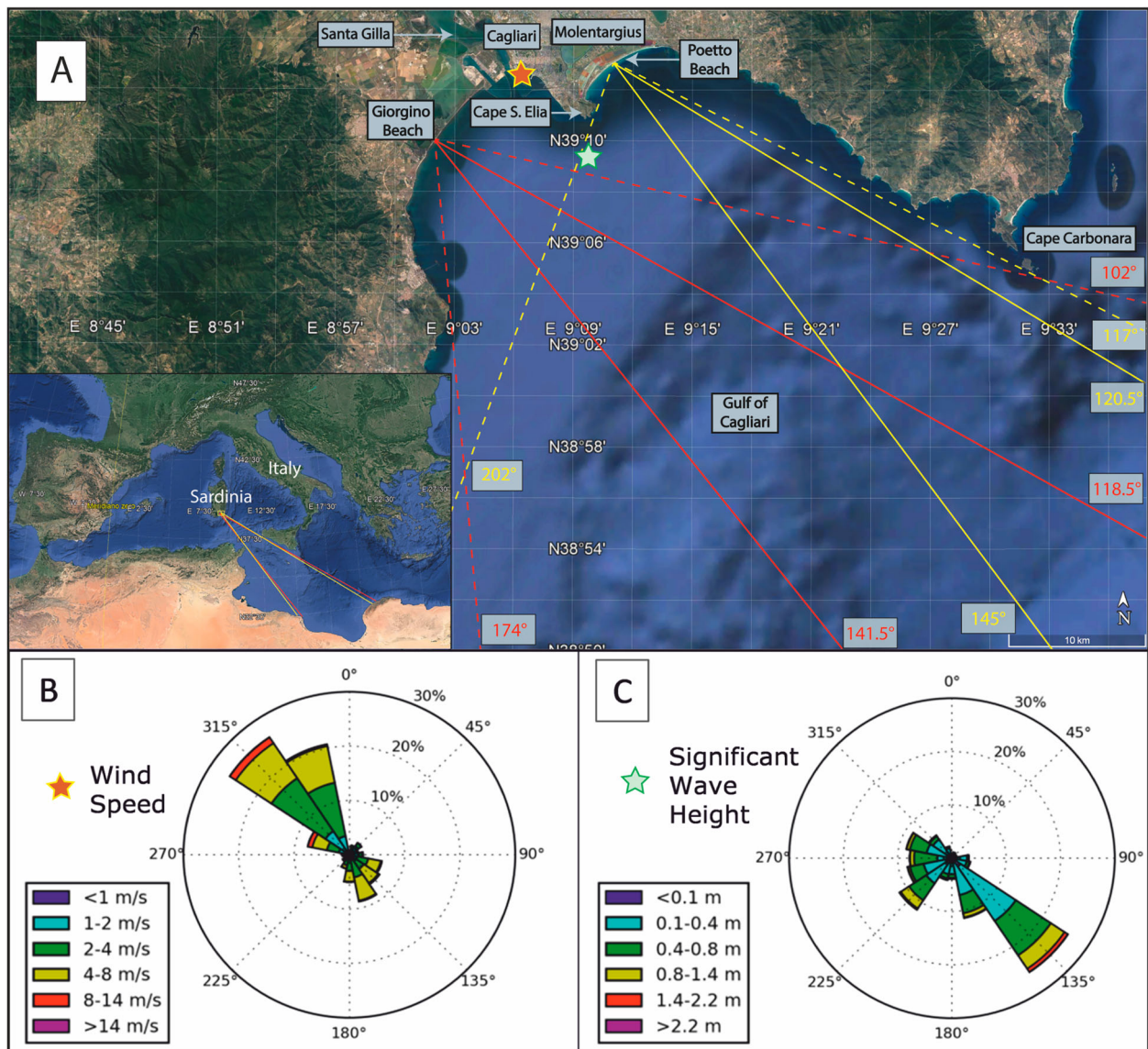


Figure 1. Geographical setting of the study area, located in the Western Mediterranean Sea, Gulf of Cagliari (A), including the wave exposure angles (referred to the N = 0°) and fetch of Poetto (yellow lines) and Giorgino (red lines) beaches. Wind speed and direction (B) from Cagliari station of the national tidal monitoring network (location: orange star); significant wave height and direction (C) at the NOAA hindcast dataset point (location: green star).

et al., 2019). The geomorphological map presented herein summarizes different data (e.g. urban development, anthropogenic features, geomorphological elements, recent deposits, sedimentological distribution, hydrodynamics and ecological components) acquired through an integrated sea-land approach and a multidisciplinary-multitemporal investigation. The map contains an analysis of the main natural and man-made forms, processes and deposits of the urban belt of Cagliari, taking into account a varied landscape characterized by: hilly zones; several fluvial systems; lagoons (Santa Gilla); ponds (Molentargius); and coastal-marine settings (Giorgino and Poetto beaches) separated by a rocky promontory and cliffs (Cape S. Elia; Figure 1). When combined in a unique cartographic product focusing on the transitional environment, these data can easily be used by policy-makers to assess territorial and marine features and locate vulnerable areas.

Understanding the interactions between urban development, landforms, environmental evolution, geomorphological processes, human impact and climate forcing can be crucial for local managers when it comes to sustainable management, risk prevention and urban planning (Buosi, Tecchiato, et al., 2017).

2. Study area

2.1. Regional setting

This paper focuses on the geomorphology of the urban coastal belt of Cagliari (southern Sardinian, Italy, western Mediterranean; Figure 1). Currently, the city of Cagliari, which faces the Gulf of Cagliari, stretches over several hills about 80–100 m in height and is surrounded to the east, north and west by wet environments, namely marshes, ponds and lagoons. In

particular, on the western side, the Lagoon of Santa Gilla covers an area of about 15 km². This is an elongated, NW-SE-orientated depression, which is roughly deltoid in shape and is connected to the Mediterranean Sea through a narrow channel located in the south, with a long sandy bar (Giorgino beach) separating it from the sea. On the northern shore, the lagoon has two major freshwater inflows from the Fluminimannu and Cixerri rivers. A second wet, saline environment, called the Molentargius pond, and a wide system of saltworks extend east of Cagliari (Figure 1).

The study area includes two urban beaches, Poetto and Giorgino. These are, respectively, located to the east and west of Cape S. Elia (Figure 1) and are classified as microtidal, wave-dominated systems. Poetto beach is sandy, 8 km long and has a maximum width of about 100 m. Its dune systems appear to be very threatened by human activities. In particular, erosion processes have been triggered by the construction of a pedestrian/cycling route along the shoreline on the foredunes, while embryo dunes reveal cross-shore fragmentation as a consequence of pedestrian access to the beach. A nourishment project was carried out in 2002 on the western side to limit erosion. The coarser and bioclastic sediments used for the nourishment have significantly modified the textural, compositional and morphological features of the backshore, shoreline and shoreface (De Muro, Ibba, et al., 2017; Lai, 2008). The coastal sector of Giorgino is characterized by a complex system of lagoonal mouths, which are periodically dredged, and the sediment transported away from the beach system. A road limits the beach amplitude landwards in this sector. The canal harbour (Figure 1) was built close to the city of Cagliari in 1970 and currently extends to 2500 m, with 1600 m of the quay providing berths for transshipment and ship cargo. The seabed in front of the canal harbour pier is repeatedly subjected to dredging and is characterized by muddy sediment and turbidity (De Muro, Porta, et al., 2018). The Main Map herein reports on a 5.8 km portion of the urban beach of Poetto and 4.5 km of the Giorgino coastal area.

From a geological point of view, the Cagliari Gulf, which is located between two Paleozoic tectonic blocks (Appendix 1), contains both the extreme eastern edge of Cenozoic structures related to the Oligo-Miocene graben-system (Casula, Cherchi, Montadert, Murru, & Sarria, 2001; Cherchi & Montadert, 1982) and the NW-SE Plio-Quaternary Campidano graben. The calcareous Cape S. Elia (horst) promontory divides two Pleistocene-Holocene beach systems (Giorgino – La Maddalena to the west and Poetto to the east).

2.2. Wave climate and hydrodynamics

The main geographical fetch at Poetto beach is between 120° and 145°, while the possible directions

for approaching storms range from 117° to 202° (Figure 1A; De Muro, Ibba, et al., 2017); at Giorgino beach, the dominant geographical fetch is between 118.5° and 141.5°, with the directions of approaching storms ranging from 102° to 174° (De Muro, Porta, et al., 2018). The tidal range is low (less than 20 cm), reaching a maximum of about 40 cm (Brambilla et al., 2016).

The prevalent winds recorded in the study area (Figure 1B) come from the NW (27% of occurrence), but the winds that give rise to the principal wave events come from southern directions: SE (40% of the occurrence), SW (20%) and SSE (10%; Figure 1C; De Muro, Porta, et al., 2018). This is because the beach system is naturally protected by Cape Carbonara to the east and Cape Spartivento to the west (Brambilla et al., 2016; De Muro, Porta, et al., 2018; Passarella, 2019).

In general, wind from SE generates opposite longshore currents that develop on the Poetto beach. The convergence of these currents produces a main rip current flowing offshore for about 400 m and is located about 1 km eastwards of the western limit of the beach (Brambilla et al., 2016; De Muro, Ibba, et al., 2017). Meanwhile, at Giorgino, a northwards longshore current (Map 1) flows with a magnitude in the order of 0.5 m/s along the entire coastline. A rip current flows along the port pier in the northern-most part of this beach, near the canal harbour.

Wind from SW produces several cells that are active on the shoreface of Poetto (Brambilla et al., 2016; De Muro, Ibba, et al., 2017). These cells produce various longshore currents running from the south west to the south east and several rip currents (Map 1). Meanwhile, in the western sector of the Gulf of Cagliari, a weak northeast-oriented longshore current (Map 1) develops during SW events in shallow waters feeding a weak rip current that flows along the embankments of lagoonal mouths in the eastern-most sector of Giorgino (De Muro, Porta, et al., 2018).

3. Methods

The geomorphological map of the urban coastal area of Cagliari (Map 1; scale 1:14,000) is based on a detailed geomorphological study and multitemporal analysis of orthophotos, satellite images and topographic maps. One supplementary map (Map 2) focuses on topographic and morphobathymetric surveys (routes and sampling point) and side-scan sonar cover (1:50,000 scale, right-bottom part of Main Map). The data reported in the Main Map were collected and analyzed following the methodological protocols developed by the Coastal and Marine Geomorphology Group (CMGG, University of Cagliari; Batzella et al., 2011; De Muro, Batzella, Kalb, & Pusceddu, 2008; De Muro, Ibba, & Kalb, 2016; De Muro, Pusceddu, & Kalb, 2010; Pusceddu et al., 2011).

The elements reported on the map and in the legend are based on: (1) the Geomorphological Map of Italian Guidelines at a scale of 1:50,000 (VV.AA., 1994); (2) the Italian Geological 1:50,000 Scale Map (VV.AA., 2009) and (3) the Geomorphological Map of the Italian Coast (Chelli et al., 2018; Mastronuzzi et al., 2017); also integrated with recent maps on a detailed scale (e.g. Buosi et al., 2019; De Muro et al., 2016; De Muro, Turchiato, Porta, Buosi, & Ibba, 2018).

3.1. Man-made modifications and evolution

The chronological reconstruction of the geomorphological evolution of the urban coastal area (long-term impact such as reclaimed areas and lagoons, port zones) is based on the interpretation of orthophotos, satellite images and historical cartography.

Specifically, the analysis was conducted on: (1) orthophotos from 1945 to 2016 provided by the RAS (Regione Autonoma della Sardegna) using a GIS (Geographic Information System) and WMS (Web Map Service); and (2) a digitized and geo-referenced IGM (Istituto Geografico Militare) topographic map of 1885 (Sheet n. 234 of the 'Map of Italy') and its updates (until 1919) at a scale of 1:25,000.

3.2. Coastal zone

3.2.1. Backshore

Forms, processes and deposits of the backbeach-backshore were acquired from topographical surveys carried out along 26 transects, which were spaced 400–500 m apart and extend from the backbeach-backshore up to a depth of 1 m (Map 2). The data were collected using a DGPS (Differential Global Positioning System) in a GNSS (Global Navigation Satellite System) and/or StarFire (Navcom SF3040) system (frequency of 1 Hz).

Thirty-six sediment samples (about 200 g in weight) were collected using a bailer along transects from the backbeach – backshore (Map 2).

The mapping of the backbeach-backshore morphologies is based on topographic surveys, satellite images, orthophotos and immersive images (Figure 2), aerial-photogrammetric surveys carried out by drone (Figure 3).

A video monitoring station, installed on the top of the hill on the headland that bounds Poetto beach on the south-western side (Cape S. Elia) was used to: (1) assess human impact; and (2) measure and evaluate mass water movements (e.g. swash, run ups, flooding areas, the timing of flooding and the return to a state of equilibrium).

3.2.2. Shoreface

The forms, processes, and shoreface and inner-shelf deposits described are based on single-beam bathymetry acquired using an Ecosounder/DGPS system

interfaced with navigation software (sampling frequency of 5 Hz). The shoreface survey was carried out by extending the 26 shoreline-shoreface transects from a depth of 1 m to the inner shelf at an approximate depth of 20 m (Map 2).

Eighty-eight sediment samples from the shoreface to the inner shelf were collected using a Van Veen grab (5 dm³ capacity) along the transverse transects (Map 2).

The mapping of the benthic habitat, rocky substrate and shoreface morphologies is based on data acquired by side-scan sonar, single-beam acquisitions, satellite images, scuba diving and underwater videos.

3.2.3. Sediment analysis

The grain-size analyses were performed on a >63 µm fraction. Each sediment sample was dry sieved through a battery of sieves spaced at ¼ phi (ϕ) per unit (Wentworth, 1922). The pipette sedimentation method (Folk, 1974) was used to analyze the <63 µm fractions. Textural parameters (median, mean diameter and sorting) were calculated following the Folk and Ward (1957) protocols.

The percentages of quartz, feldspars, micas, other minerals, lithoclasts and skeletal grains in each sample were established under an optical microscope (Lewis & McConchie, 1994).

Sedimentary facies were identified based on the grain-size and mineralogical/petrographical composition of the sediment (De Muro, Batzella, De Falco, & Porta, 2010; De Muro et al., 2016; De Muro, Kalb, Ibba, Ferraro, & Ferrara, 2010; De Muro, Pusceddu, et al., 2010; VV.AA., 2013, 2016).

4. Results

4.1. Geomorphological evolution and man-made modifications

The analysis of historical maps shows that the urban area of Cagliari in 1885 was constituted of a single nucleus close to the port infrastructures. A wide system of wet environments (lagoon, saltmarshes and saltworks) extended to the west of the city and was separated from the sea by a continued longshore sandy bar. Six lagoonal mouths connected this wet environment with the sea. A small island (Sa Illetta) was located in the lagoon at approximately 1500 m from the coastline northwards. On the south-west side of the Cape S. Elia promontory, south of the urban nucleus, a small gulf was bordered by ancient saltworks. At the east of the city, Poetto beach was constituted of a longshore sandy bar with a wide dune system. Residential areas and marinas were not present.

In 1945, the urban surface stretched to northern, eastern and southern areas, and several urban nuclei and a network of roads were built in the promontory of Cape S. Elia. The saltworks located in the

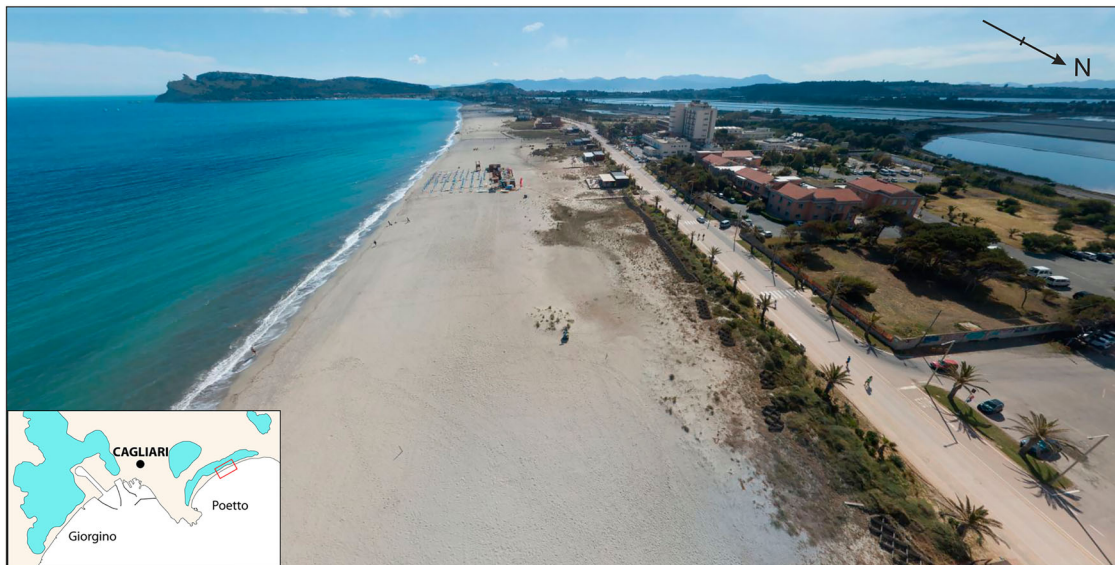


Figure 2. Immersive image of a section of Poetto beach (location: red rectangle) acquired by drone.

promontory at the south of the city were reclaimed and filled by man-made materials. The dune systems of the two beaches narrowed (by up to 80%) due to the construction of hard structures (like roads) landwards.

Coastal embankments and the development of harbour infrastructures (piers and breakwaters) were the most significant morphological modifications between 1945 and 2016. In particular, lagoonal mouths were

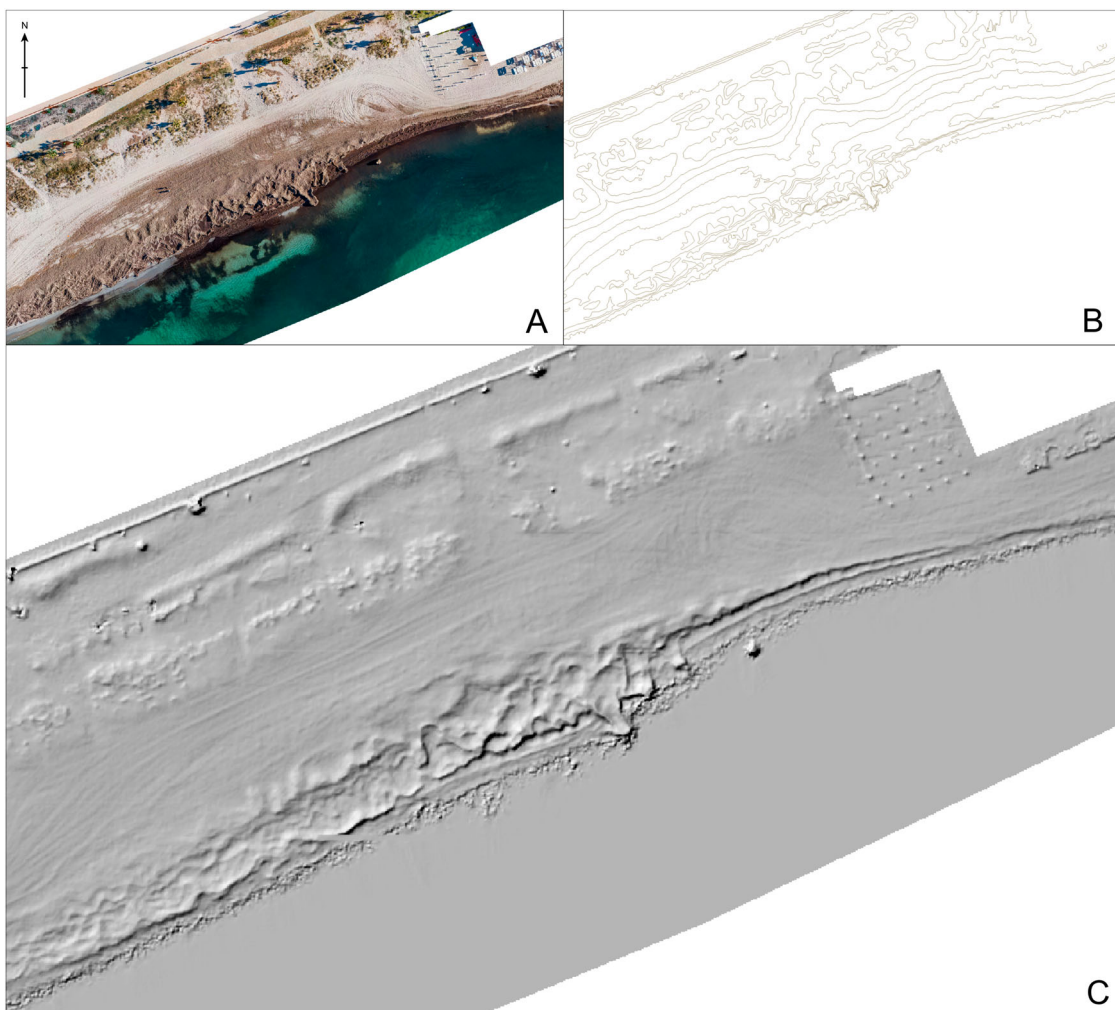


Figure 3. Example of aerial-photogrammetric survey. (A) orthophoto; (B) topographic contour line (10 cm interval); (C) Digital Terrain Model (DTM).

hardened and deviated in the Giorgino coastal stretch, and the beach extent was diminished by 2.5 km due to the construction of the canal harbour, which altered the water circulation. On the landwards side of Poetto beach, new residences and a pedestrian road were built following the development of tourism. A marina, artificial reefs and coastal defence structures were constructed on the north-east side of Cape S. Elia. In the promontory, urban expansion has modified the former geomorphological setting due to the excavation of several limestone quarries, affecting the slope morphology. The promontory, which is constituted of marly-limestone at the base ('Pietra Cantone' Auct.), overlaid by biocalcarenes ('Tramezzario' Auct.) and biohermal limestones ('Pietra Forte' Auct.), was affected by karst processes, resulting in the development of superficial morphologies (sinkhole, solution pan), cliffs, pocket beaches (rocky/gravelly), wave-cut notches and platforms, erosion scarps, stacks, arches and caves.

4.2. Geomorphological processes, forms and deposits of the beach systems

4.2.1. Shoreface geomorphology and benthic habitats

The bathymetric profiles reveal a complex system of submerged sand bars alternating with troughs located 250–300 m from the shoreline and up to 3 m deep at Poetto. Further offshore, the sea-bottom slopes down to –10 m (about 1000 m from the shoreline). At Giorgino beach, the shoreface gently slopes down to –8 m isobaths in the central sector and to –4 m in the eastern-most side, with a system of submerged bars developing on the shoreface between 50 and 250 m from the shoreline.

Four main benthic habitats and substrate types have been identified: (1) uncolonized sediment substrates that dominate the seafloor in the intermattes and between the shoreline and the upper limit of the seagrass meadow; (2) a well-developed and dense meadow, mainly *P. oceanica*, which only occurs in some areas at depths between –15 and –20 m in Giorgino; (3) a wide, discontinuous seagrass meadow (mainly *Caulerpa prolifera*, *Cymodocea nodosa* and *P. oceanica* – between –4 and –20 m) with numerous intermattes (from –10 m to –15 m), which is mainly recognized at Giorgino. This discontinuous meadow appears to have been greatly affected by human activities (e.g. dredging, dumping, fishing, mooring, maritime traffic); (4) beach-rock, which is mapped along the coastline in the north-eastern sector of Poetto at a depth of 2 m; and (5) rocky outcrops, which are located near the Cape S. Elia promontory.

4.2.2. Sediment facies

Six sediment facies were identified in the coastal area of Cagliari: (1) facies 1 is mixed siliciclastic-bioclastic

sand from the backshore/beachface; (2) facies 2 includes siliciclastic sand from the shoreface; (3) facies 3 encompasses mixed bioclastic-siliciclastic sandy-muddy sediment that is linked to the transition zone from the shoreface to the seagrass meadow's upper limit; (4) facies 4 is composed of mixed bioclastic-siliciclastic sand and mud from the inner shelf; (5) facies 5 comprises sand and gravelly sand with calcilithic and terrigenous components. This facies is found at the bottom of the cliffs of the Cape S. Elia promontory in parallel strips between the shoreline and the upper limit of the *P. oceanica* meadow (Cape S. Elia calcilithic facies; Lecca, De Muro, Cossellu, & Pau, 2005); (6) facies 6 includes biogenic gravelly sediment linked to the seagrass meadow (intermattes).

5. Discussion and conclusions

The analysis of the data and the comparison of historical maps and orthophotos has enabled the identification and mapping of the most relevant natural and human-induced changes that have occurred in the urban coastal area of Cagliari. These changes were moderate between 1885 and 1945, but thereafter the urban coastal area was altered by several modifications linked to the increase in urbanization in a system where waves and littoral currents are the dominant coastal processes for the transport and deposition of sediment. For example, the construction of the canal harbour and other port infrastructures diminished the coast, changing the water circulation by modifying the natural sediment-accumulation processes and altering the continuity of the *Posidonia oceanica* meadow. In particular, the urbanization has caused the narrowing and hardening of the Poetto and Giorgino beaches due to the building of roads and temporary and permanent structures in dynamic zones. These activities have interfered with natural processes and indirectly influenced the erosion of the dune system. In fact, human infrastructure appears to be more vulnerable to direct damage due to wave collision and long-term flooding in Poetto beach. The infrastructure could interfere with the maximum run-up, causing erosion of the scarp and scours on the areas where a collision between run-up/up-rush and man-made structures occurs (De Muro, Ibba, et al., 2017; Passarella, De Muro, Ruju, & Coco, 2018). The coarsening of sediment, from natural siliciclastic to a coarser version with a higher carbonate content (Lai, 2008), during the beach nourishments has led to another crucial imbalance in Poetto beach. In addition, beach-cleaning operations, which are regularly carried out mainly in spring and summer, flatten and lower the backshore level, compacting the sediment and making this zone more vulnerable to overwash (De Falco et al., 2008; Simeone, De Falco, Como, Olita, & De Muro, 2008; Simeone, De Muro, & De Falco, 2013). Prior to the

development of the city of Cagliari (twentieth century), the Poetto and Giorgino beaches were connected by a continuous aeolian, cross- and along-shore sediment supply (De Muro, Porta, et al., 2018). After 1945, urban development and the reclamation works on the wetlands located south of the city interrupted this sediment input, which is now: mainly siliciclastic from the Santa Gilla lagoon towards the inner shelf of Cagliari Gulf; and mainly carbonate and siliciclastic from the cliff erosion of the Cape S. Elia promontory. However, the defence structures at sea (attached and parallel breakwaters), and slope-stabilization in the cliffs (e.g. reinforced geogrids and pinned nets) located at the eastern and western bases of the cape, limit the carbonate and siliciclastic sediment-supply originating from cliff erosion. Today, an important authigenic bioclastic sediment input comes from the *Posidonia oceanica* meadow (VV.AA., 2013, 2016), which also plays a key role in protecting the beach system from erosion (De Muro, Kalb, et al., 2010; De Muro, Porta, Passarella, & Ibba, 2017; Gómez-Pujol, Orfila, Álvarez-Ellacuría, Terrados, & Tintoré, 2013). In fact, the seagrass meadow attenuates hydrodynamic forces, increasing sediment retention and reducing sediment resuspension (De Muro, Pusceddu, Buosi, & Ibba, 2017; Ruju et al., 2018; Tecchiato, Buosi, Ibba, Ryan, & De Muro, 2016). A recent study (De Muro, Porta, et al., 2018) showed a wide area of degraded and discontinuous *P. oceanica* and dead meadow in front of Giorgino beach (from -4 to -20 m). Reflecting the poor ecological state of the seabed (Map 1; De Muro, Porta, et al., 2018), low biodiversity values of the benthic foraminiferal assemblages and the high abundance of opportunistic and stress-tolerant foraminiferal species have been documented (Buosi et al., 2013; Schintu et al., 2016). At Poetto, even though the dune system appears to be influenced by major human pressure, the benthic foraminiferal assemblages do not seem to be affected and the ecological status (Map 1) appears to be good (De Muro, Ibba, et al., 2017).

The geomorphological map of the urban coastal area of Cagliari enables us to highlight the connections between historical urban development, man-made transformations, geomorphological processes and human impact on coastal ecosystems. These findings are relevant, not only in relation to the management and maintenance of the beaches and wetlands, but also with respect to decisions about future measures concerning risk-mitigation, sea-level rises and erosion.

The applications of this urban cartography to coastal management include: (1) facilitating the assessment of the vulnerability of coastal areas to severe natural events linked to climate change; (2) easy access to up-to-date digital geospatial data and mapping products; and (3) a baseline study for the future assessment and monitoring of environmental changes.

Software

Single beam and DGPS data were acquired and expanded using Reson PDS2000 and the GNSS Solutions software, respectively. Google Earth GIS was used to calculate distances and angles of wave exposure and the fetch of the study area.

The textural data were obtained with the Gradistat software (Blott & Pye, 2001).

The grain-size and the side-scan sonar data were processed using Autodesk Map 3D to obtain the grain-size distribution and to identify the main benthic habitat.

The QGIS software was used to organize the entire dataset and to create the digital cartography. A land-sea DTM was produced by Global Mapper 14. The final map was created using the Adobe Illustrator CS5 software.

Acknowledgements

This study forms part of the TENDER NEPTUNE, NEPTUNE 2 and BEACH projects. The authors warmly thank Battellieri Cagliari and Sardegna Progetta. Daniele Trogu acknowledges the support by the University of Cagliari ('Borse di studio di Ateneo' - Dottorati di Ricerca XXXIV ciclo, voce CO.AN.A.06.01.01.01.02). The authors would like to thank the 'Coastal and Marine Geomorphology Group' of Cagliari University and the staff of 'Osservatorio Coste E Ambiente Naturale Sottomarino OCEANS' and the 'Deposito PolNato Marina Militare (Navy PolNato Depot)' of Cape S. Elia - Cagliari.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by: (1) Regione Autonoma Sardegna under L.R. 7/2007. 'Promozione della ricerca scientifica e dell'innovazione tecnologica in Sardegna' for NEPTUNE, NEPTUNE 2 and BEACH projects. (2) Fondazione Banco di Sardegna and Università di Cagliari under Contributo di Ateneo alla ricerca (Car) 2012–2013–2014, and under Progetti di rilevante interesse dipartimentale (Prid) 2015.

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Appendix 1. Geological map of the study area (from Carmignani, Oggiano, Funedda, Conti, & Pasci, 2016; adapted).

