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Holocene to near-future evolution of the southern Molise coast (Central Adriatic, Italy) under the influence of natural and anthropogenic controls

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ABSTRACT

Coastal areas are dynamic environments that easily change over time. To contribute to a better understanding of natural and anthropogenic factors that may have contributed in the past and/or control present-day and near-future coastline modifications, we have realised a chronologically arranged sequence of three geomorphological and geothematic maps focusing on the southern Molise coast (Adriatic coast, Italy). The first two maps concern the geomorphological and anthropogenic modifications that occurred respectively from the Holocene to the 1950s (Map 1), and from the 1950s to the Present (Map 2). The third map deals with the present-day conditions and near-future scenarios of coastal hazard considering the period from the Present to the year 2050. Results obtained and comparative observations of the three maps highlight the elevated shoreline mobility of the Biferno River alluvial coastal plain sector, and its high susceptibility to further coastal hazard due to erosion and inundation.

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1. Introduction

Coastal areas are among the most dynamic environments undergoing deep and frequently rapid modifications over time that may deeply alter their morphological setting. At the same time, thanks to their resources and facilities, coastal areas are subject to growing anthropisation and progressive increase of already high population densities (Neumann et al., 2015). Therefore, the evaluation of coastal vulnerability, i.e. the degree to which littoral systems and communities are exposed and sensitive to coastal hazards, as well as their capacity to adapt and recover from related impacts (Anfuso et al., 2021; Benassai et al., 2015; Dolan & Walker, 2006; Gornitz, 1991; Mclaughlin & Cooper, 2010), is crucial for effective coastal management, adaptation planning, and the preservation of coastal ecosystems and livelihoods. Coastal vulnerability is influenced by a multitude of factors, among which topography and sediment dynamics are very relevant (Budillon et al., 2020, 2022). Coastal areas with low-lying topography, narrow beaches and limited sediment supply are often more vulnerable to erosion, storm surges and sea-level rise (Griggs & Reguero, 2021; Karle et al., 2021). In contrast, coasts with natural protective

features such as barrier islands, dunes and wetlands tend to exhibit higher resilience to coastal hazards. Climate change plays a significant role in increasing coastal vulnerability. Rising sea levels, higher frequencies, and intensities of storms as well as changes in precipitation patterns pose substantial risks to coastal communities and ecosystems. Sea-level rise threatens to inundate low-lying coastal areas, erode shorelines, and intrude into freshwater resources, exacerbating the vulnerability of coastal regions (Church et al., 2013; IPCC, 2021; Kopp et al., 2016). Human activities and population growth along the coast also contribute to coastal vulnerability. Urbanisation, industrialisation, and infrastructure construction alter natural coastal processes, disrupt ecosystems, and increase exposure to hazards.

When trying to deepen our understanding of the actual equilibrium/disequilibrium and potential future development of a coastal area, the reconstruction of its geomorphological and anthropogenic short to long-term evolution along with the assessment of possible future trends gets of crucial importance. This also to reconstruct a chronological frame of the identified events and modifications.

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Supplemental map for this article is available online at <https://doi.org/10.1080/17445647.2023.2243973>.

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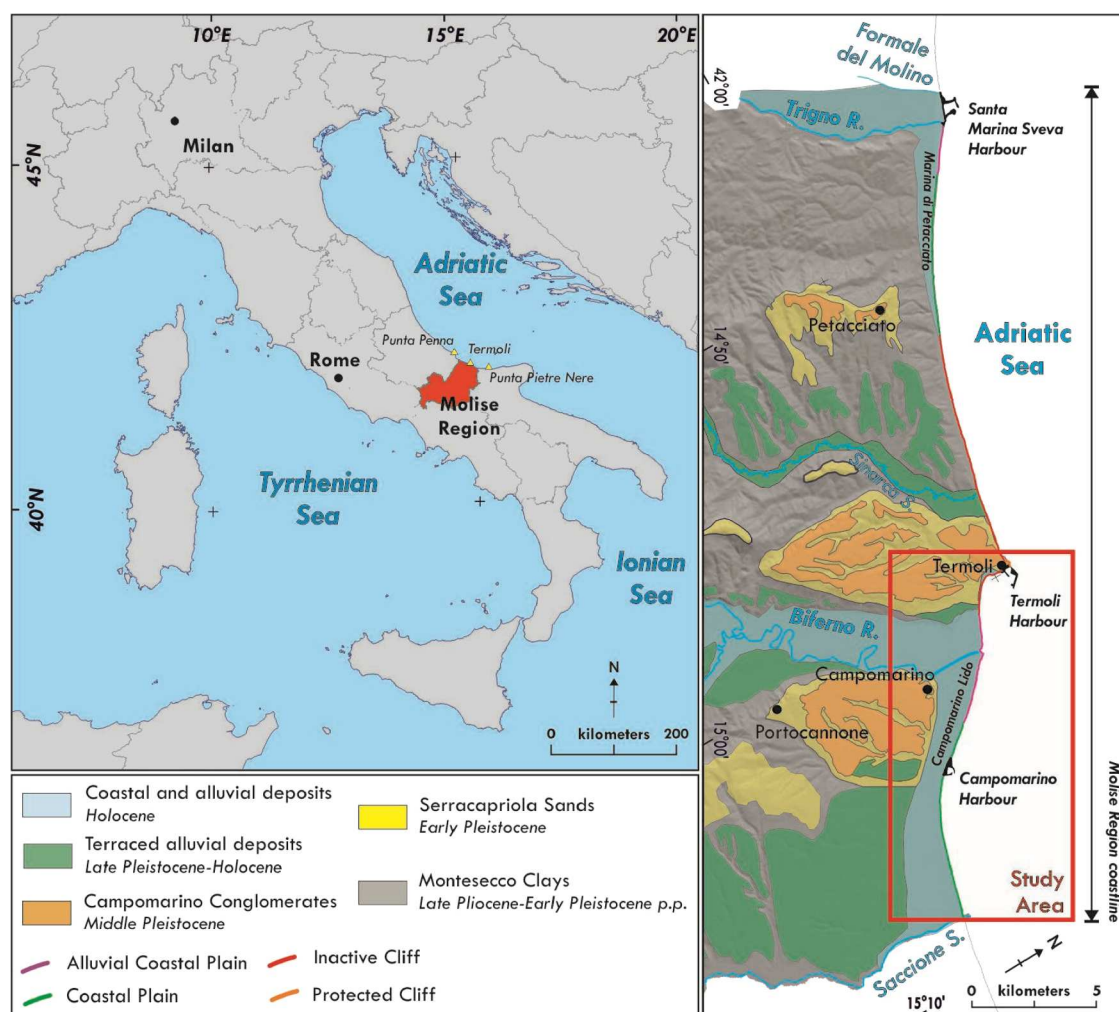


Figure 1. Geological sketch map of the Molise Region coastal area, with the characterisation of the coastline typology (after Bracone et al., 2012 and Rosskopf et al., 2018).

In this framework, the sector of the Molise Region coastline that is located south of the Termoli promontory (Figure 1), named the southern Molise coast, represents a typical example of low-lying sedimentary coast, suitable for this kind of studies thanks to the presence of numerous geomorphologic elements and dated archaeological traces.

The main aims of this study are: (1) to reconstruct the Holocene to Present geomorphological evolution of the southern Molise coast; (2) to understand its human occupancy over time in response to coastal modifications; (3) to recognise the relationships between areas prone to coastal dynamics and coastal defence structures; (4) to assess near-future trends of shoreline position and coastal inundation. To this purpose, we carried out a review of geological, geomorphological, and archaeological data, mostly extracted from literature, remotely sensed data, geographic and topographic maps, which we integrated with data coming from recent surveys and field observations. Furthermore, we added new data on actual to near future coastal vulnerability aspects.

Based on acquired data, we constructed a sequence of three, chronologically arranged, geomorphological and geothematic maps to illustrate the following aspects of the study coast: the geomorphological and anthropogenic evolution from the Holocene to the 1950s, considering with particular attention the period from Roman times onwards; the mid to short-term geomorphological and anthropogenic evolution from the 1950s onwards; the actual coastal vulnerability and the related near-future perspectives under the influence of ongoing climate changes and related trends to sea-level rise (period Present – 2040/2050).

2. Main features of the southern Molise coast

2.1. Geological and geomorphological background

The study coast is about 15 km long and coincides with the southern portion of the Molise Region coastline. The Molise coast falls entirely in the physiographic unit of Punta Penna (Abruzzo) – Punta

Pietre Nere (Apulia) and is split by the Termoli promontory (Figure 1) into two nearly independent sub-units with a WNW and NW-SE orientation, respectively, namely the northern and the southern Molise coast. As highlighted by previous studies (e.g. Aucelli et al., 2018; Roszkopf et al., 2018 and references therein), the Molise coastline is predominantly made of sandy low coast. A high coast sector is present in its central portion including the protected cliff of the Termoli promontory (Figure 1) and the adjacent coastal stretches characterised by inactive sea cliffs (Roszkopf et al., 2018) which are located few tens up to few hundreds of metres from the present shoreline. The beaches are therefore almost continuous along the Molise coast except in the river mouth areas of the Trigno, Biferno, Sinarca and Saccione rivers (Figure 1).

Along the sandy low coast sectors, beaches and associated dune systems are limited landwards by flat, low-lying areas underlain by prevalently fine and easily erodible, clayey to sandy sediments. These low-lying areas form the alluvial coastal plains built by the Trigno and Biferno rivers, and some coastal plains generated by Mid- to Late Holocene coastal progradation (Roszkopf et al., 2018). According to Roszkopf et al. (2018), three coastal morphotypes are identified along the southern Molise coast: the inactive cliff, which extends between the Termoli Promontory and the terrace peak Punta di Pizzo (Figure 1), the alluvial coastal plain of the Biferno River, limited landwards by paleo-sea cliffs and the terminal part of the Biferno valley, and the coastal plain that extends from Campomarino Lido up to the Saccione mouth. This coastal plain is limited landwards by rather well-preserved paleo-sea cliffs that are southwards replaced by degrading hilly slopes, both carved in the Plio-Pleistocene succession formed by the Montesecco Clays, Serracapriola Sands and Campomarino Conglomerates formations, which are partially covered by more recent alluvial terraced deposits (Figure 1). The up to 50 m high paleo-sea cliffs limit wide and gently degrading terraced surfaces towards the sea, part of which are the substratum of the city of Termoli and the small town of Campomarino (Bracone et al., 2012).

The southern Molise coast is rather anthropized and hosts two harbours (Figure 1): the Campomarino touristic harbour, which was built in the mid-1990s (Roszkopf et al., 2018), and the commercial Termoli harbour, built in 1937. The latter underwent several modifications since the 1970s, including the construction of the adjoining small touristic harbour of Marina di San Pietro at the end of the 2000s.

2.2. Archaeological background

The southern Molise coast hosts numerous human traces dating from the prehistoric period up to the

Renaissance (Bracone et al., 2016; Valente & Cozzolino, 2019), but mainly referring to the Samnite and Roman periods. Most of the findings consist of surface material of various ages, but there are also structures and artefacts related to a necropolis, isolated tombs, villas and farms, mostly of Samnite and Roman age. The distribution of archaeological sites and findings well reflect the need of humans to protect their settlements from foreign invasion and to control the territory around them. In fact, most of the archaeological elements are located on the terraced surfaces beyond the low-lying alluvial coastal plain and the coastal plain.

The most significant findings refer to the Roman site of Marinelle Vecchie (see Inset A of Map 1). This site is located in the Biferno alluvial coastal plain some hundreds of metres east of the Biferno channel and approximately 1.5 km from the coast. The archaeological excavations carried out between 2007 and 2010 (De Benedittis, 2008, 2013) have provided important data about the human frequentation of the southern Molise coast between the IV century BC and the VIII century AD. Traces of house structures (mosaic *tesserae*) and remnants of a necropolis have been found. The necropolis consists of tombs located at depths of up to 2 metres that are distributed in three different levels (Bracone et al., 2016), dating from the middle of the II century AD up to the VII century AD, when the Marinelle Vecchie site was definitely abandoned.

Geophysical surveys conducted in 2009, together with some geoarchaeological field surveys and the location of Roman findings via GPS carried out in recent years, have provided important data about the extension of the Marinelle Vecchie site (see Inset A of Map 1) and revealed the trace of a recent course or probably secondary channel of the Biferno River in a sub-superficial position (Bracone et al., 2016).

One of the most relevant local archaeological questions concerns the hypothesis of a Roman port located at the Biferno River mouth (De Benedittis, 2013), which is supported by various mediaeval documents including the *Cartula venditionis* (Martin et al., 2002) dated 828–832 AD and the Erisi, according to which both Termoli and Campomarino constituted port centres. This hypothesis has found strong support in the discovery, seawards of the necropolis, of abundant ceramic findings that document the intense and diversified commercial exchanges between the Marinelle Vecchie site and other Roman settlements located along the Adriatic coast and in the Mediterranean area (De Benedittis, 2008, 2013), giving moreover evidence of its proximity to the coast and/or to the river, but without this proximity having created negative impacts attributable to river dynamics and/or wave action.

Besides the Marinelle Vecchie site, only a few other archaeological elements have been found in the coastal

plain areas. Among these, several traces of a Roman road, three of which are located on the left of the Biferno River and one within its riverbed (see Inset A of Map 1). These traces allow supposing the route path of the *Via Inferior* that skirted the Adriatic joining *Histonium* (Vasto), Termoli, Campomarino and Teanum Apulum (Serracapriola) (Filangieri, 1970). This road connected the coast with other internal roads such as the one passing through *Larinum* (*Via Superior*).

Other important sites are the coastal tower of Campomarino and the ‘*scafa*’, an anchor place allowing ferries to pass from one side of the Biferno River to the other, for which, however, no archaeological data and literature documentation are available for a precise location. The tower of Campomarino (Figure 2 (A)) was built in 1568/69 (Marino, 1977) as part of the tower system erected to protect the coast from the invasions of the Saracens. It is reported in several geographical maps until the beginning of the nineteenth century AD, such as the Contado di Molise et Principato Ultra map (Magini, 1620), and the Atlante Geografico del Regno di Napoli (Rizzi Zannoni, 1808) (Figure 2(B,C)). The *scafa* is documented starting from 1594 AD (Marino, 1977) until the end of the eighteenth century AD (Rizzi Zannoni, 1792). The approximate location of both structures, lost before 1869 AD most probably due to divagations of the Biferno River, has been inferred based on historical maps and geomorphological considerations.

3. Methods

The constructed main map includes 3 chronologically ordered panels (i.e. Map 1, Map 2, and Map 3) and presents the synthesis and reinterpretation of available geological, geomorphological and archaeological data extracted from published literature and historical maps coupled with some new observations and data.

Map 1 shows the long-term geomorphological evolution of the study area, which is chronologically constrained between the Holocene and the 1950s. The base map is a hillshade derived by a DTM with a 5 m horizontal resolution. A view of the topography in the 1950s was obtained by constructing a DTM based on the interpolation of contour lines and elevation points of the 1:25,000 scale topographic map ‘Termoli’, published by the Military Geographic Institute (IGM) in 1957. Older shorelines were extracted from the two 1:50,000 scale sheets ‘Termoli’ published by IGM respectively in 1869 and 1909. These maps have been carefully georeferenced using fiducial marks identified both along natural and artificial structures, such as the Termoli promontory and the railway line, for which at most very limited modifications during the last 150 years can be assumed. Associated with Map 1 is the Inset A placed in the

left portion of the map that shows a detail of the Mar-inelle Vecchie archaeological area.

Map 2 provides information about the southern Molise shoreline evolution from the 1950s to the Present, and the increasing anthropisation of the coast over time due to the construction of coastal defence and harbour structures (Buccino et al., 2020; Paola et al., 2020). The topographic basis was extracted from a DTM with a 2×2 m cell size derived from a LiDAR survey performed in 2012 by the Italian Environment Ministry (MATTM, 2012). To analyse the recent shoreline migrations and anthropogenic changes, a morphometric analysis was carried out in a GIS environment by examining a set of six orthophotos and aerial photos taken in the following years: 1954 in light brown, 1985 in purple, 1992 in green, 2002 in red, 2012 in black, and 2019 in yellow. The photo-interpretation allowed the reconstruction of the shoreline positions and the implementation of a database containing information about the periods in which the coastal defence structures were constructed, modified or removed. The identified coastal defence structures are represented by adherent, submerged and emerged breakwaters, and by groynes. To ascertain changes in shoreline position over time, we employed the Digital Shoreline Analysis System (DSAS), a freely accessible add-on to ESRI’s ArcGIS (Himmelstoss et al., 2021). This software facilitates the automatic generation of evenly spaced transects, along which the shoreline positions of different ages were compared. By utilising a Linear Regression Rate of change statistic (LRR) applied to all shoreline points along each transect, we were able to calculate shoreline variations. In all, 274 transects were positioned at regular intervals of 100 m, enabling a comprehensive analysis.

Map 3 illustrates the future coastal hazard scenarios developed for the study area taking in account the potential Relative Sea-Level Rise (RSLR) projected in the latest IPCC report (2021). As significant vertical land movements are not recorded in the studied area (Aucelli et al., 2018; Bracone et al., 2012; D’Amico et al., 2013), the evaluation of RSLR considered only the eustatic sea-level rise estimated in the IPCC (2021). The latter assumes, considering the SSP5-8.5 scenario (NASA, 2022), an average rise of 0.22 m by 2050 for the investigated area. Starting from the consideration that the areas potentially prone to be inundated due to of the RSLR are those lying either below or slightly above the present mean sea level, a coastal inundation hazard analysis was carried out by investigating the topography of the study area (see info related to the DEM carried out for Map 2) by using the GIS-based ‘bathtub approach’ (Aucelli et al., 2018; Creach et al., 2015; Didier et al., 2018; Poulter & Halpin, 2007; Rowley et al., 2007; Xu et al., 2022). Certainly, the method is improvable, but it remains a valid tool both because it is straightforward to

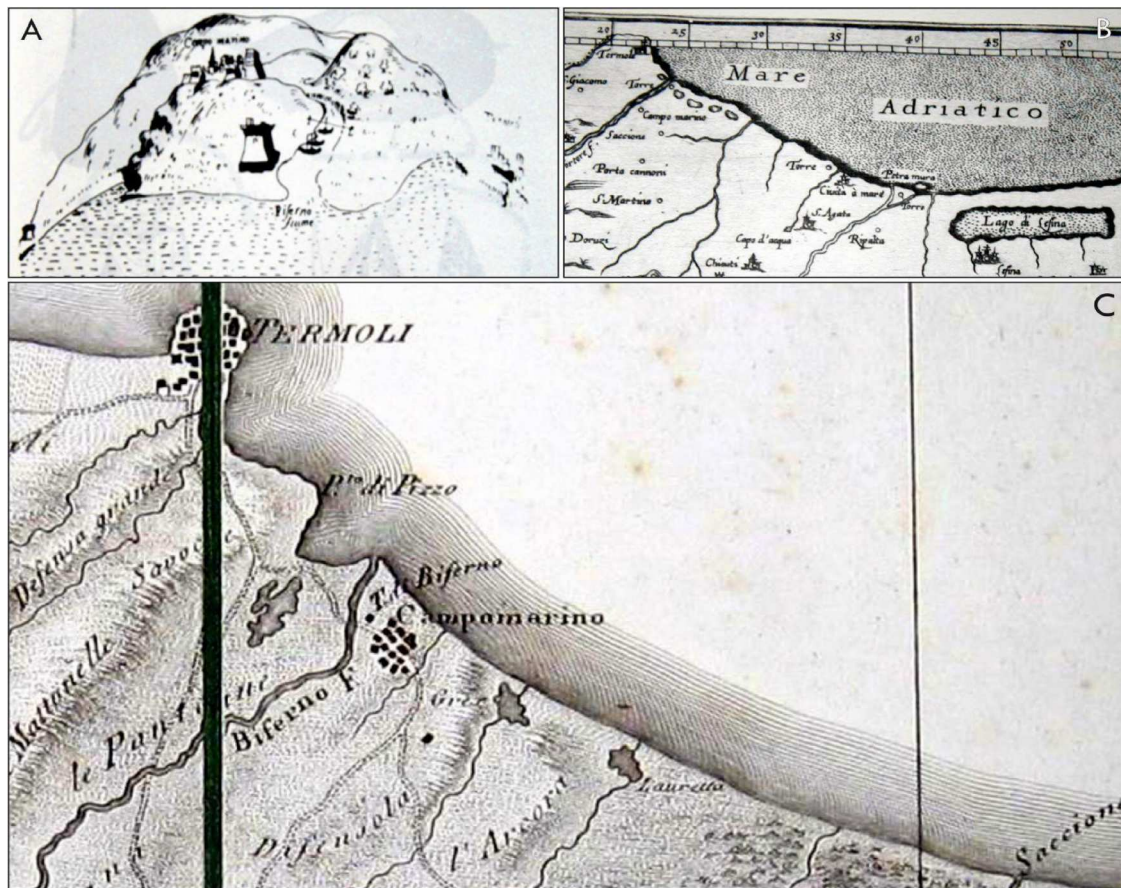


Figure 2. (A) View of the coast around the Biferno mouth in 1594 from the perspective of C. Gambacorta, Marquis of Celenza (Marino, 1977). (B) Map of the Contado di Molise et Principato Ultra (Magini, 1620); (C) Atlante Geografico del Regno di Napoli (Rizzi Zannoni, 1808).

apply and because it has been shown to be a reliable tool when compared to other much more complex methods (48–51%, Didier et al., 2018). Afterwards, inundation maps were generated for the projected scenario by using four hazard classes (from H1 to H4) based on different inundation proneness levels of the coastal territory (Di Paola et al., 2021). Class H1 includes the areas located above 1 m a.s.l., prone to be inundated only occasionally. Classes H2 and H3 respectively identify areas between 0.5/1 m a.s.l. and 0/0.5 m a.s.l., which are prone to frequent inundation events and permanent morphological changes, such as beach and dune erosion. Finally, class H4 identifies areas prone to be permanently inundated because already below the present mean sea level. The inland limit for the inundation analysis has been set at 5 m a.s.l., as proposed in the frame of the EUROSION Project (2004).

To identify the future shoreline in 2040, the DSAS was used which allows calculating a future shoreline position (20 years forward) based on historical shoreline position data. The shoreline forecasting calculation is based on the use of the Kalman filter (Kalman, 1960), as developed by Long and Plant (2012), to forecast future shoreline positions by combining observed shoreline positions with model-derived positions. The DSAS Kalman filter, which is initialised with the LRR

calculated by DSAS, estimates the shoreline position and the change rate for every 10th of a year, and provides an estimate of positional uncertainty at each time step. The methodology considers that a linear regression through past shoreline positions is a good approximation for future shoreline positions. This assumption appears to be valid for coastlines like this one studied, considering that each evaluated shoreline position in the past is the result of numerous factors, including sediment input from surrounding rivers, the presence of human structures, changes in wave action, and the recorded sea-level rise in recent decades. Clearly, this allows for modelling within a relatively recent timeframe, which cannot exceed twenty years (Abd-Elhamid et al., 2023; Chrisben & Gurugnanam, 2022; Ciritci & Türk, 2020; Hossen & Sultana, 2023). To limit related uncertainties, we used the shorelines dating from 1869 to 2019 reported in Maps 1 and 2.

4. Results

4.1. Integrating Holocene and historical human-induced geomorphological evolution of the southern Molise coast

Map 1 spans from the Early/Middle Holocene to 1957. The most ancient Holocene event documented in

literature concerns the lagoon that formed around 8100 BP in the innermost portion of the Biferno alluvial coastal plain (Amorosi et al., 2016). Its location allows supposing that the shoreline at that time was in alignment with the bases of the actual paleo-sea cliffs that border the terraced surfaces carved in Plio-Quaternary deposits, turning them active. The lagoonal deposits are covered by Middle Holocene fluvio-plustrine deposits dated at 5600 BP (Amorosi et al., 2016), which highlight a significant phase of coastal progradation that occurred after 8000 BP, even if the location of the shoreline at 5600 BP has not been clearly defined up to now. Some remnants of isolated dune ridges found near the base of the Campomarino paleo-sea cliff and referred to the Middle Holocene thanks to the local discovery of protohistoric cherty artefacts (see below), most probably are related to this shoreline.

From 5600 BP to 2500 BP, coastal progradation continued, although in an inhomogeneous manner, leading to the deactivation of the sea cliff. The seaward shift of the shoreline allowed human settlements to move from the top of the terraced surfaces to the Biferno valley floor and the coastal plain, leaving significant archaeological traces of Iron to Roman age in the southern portion of the coastal plain (Bonifica Ramitelli). Some remnants of isolated dune ridges preserved within the Biferno alluvial plain and in the coastal plain just near the foot of the Campomarino paleo-sea cliff most probably are connected to this shoreline. For them, a Middle Holocene age is inferred based on the local discovery of cherty artefacts of protohistoric age (oral communication of De Benedittis G.) on top of the dune ridge located just east of the Marinelle Vecchie site (see also Inset A of Map 1), suggesting an age of at least 3-4000 years for this dune ridge. The abundance of Roman Age pottery in front of the Marinelle Vecchie site bears witness to intense commercial activities (De Benedittis, 2008, 2013), and provides evidence of the easy access to the site, not conditioned negatively neither by marine nor by fluvial dynamics. This consideration allows hypothesising that the Roman shoreline was located no less than a few hundred metres in front of the Marinelle site. Unfortunately, its precise location is still unknown due to the lack of related surface and sub-surface evidence probably because of subsequent shoreline variations. Some dune ridge remnants for which a Late Medieval to Renaissance age is inferred thanks to the Renaissance pottery found on top of them, give evidence about the approximate position of a much younger shoreline that was, however, most likely located rather close to the Roman one.

As shown by the design of the Marquis of Celenza (Marino, 1977) and the comparison of historical maps, shoreline progradation gradually transformed the coastal area starting from the end of the sixteenth

century. Progressive shoreline advance led first to the formation of dune ridges closing several coastal ponds behind them, then to the growth of the Biferno River delta cusp. One of these ponds, called Pantanello, located on the left of Biferno River, survived at least up to 1869. The last phase of coastal progradation is documented by the comparison of topographic maps of 1869 and 1909. This phase led to a further slight growth of the Biferno delta cusp, the filling of the Pantanello pond, and the formation of the coastal stretch where afterwards the Campomarino Lido urban agglomerate developed. The coastal progradation along the southern Molise coast from 1600 onwards falls within a climate epoch characterised by cooler/wetter conditions and expanded glaciation, the Little Ice Age (LIA, Helama et al., 2021 and references therein), which is well documented for Europe and persisted with latest pulsations up to the first decades of the 1900s. In particular, the persistence in southern Italy of wetter conditions until the 1930s and consequent increased slope dynamics, above all landslide occurrence – moreover favoured by the massive deforestation operations between the first decades of the 19th and the 20th centuries – (Scorpio et al., 2015 and references therein), favoured flood events, high fluvial sediment loads (in the case of Biferno River also evidenced by a clear trend to channel widening between 1870 and the 1950s; Scorpio et al., 2015), and the increase of sediment delivery to the coast, promoting coastal progradation.

4.2. Recent shoreline changes and anthropogenic modifications of the southern Molise coast

The analyses of recent shoreline changes were conducted using 274 transects generated through the DSAS tool in ArcMap (Figure 3). Several time intervals were defined (Table 1), providing insights into long-term, medium-term and short-term shoreline variations (Figure 3(B–D)). Regarding 1957 to Present shoreline changes, the comparison between the oldest (1957 shoreline, light-brown line) and the youngest shoreline (2019 shoreline, yellow line) shows that the central portion of the investigated coast has been widely affected by shoreline retreat, while coastal progradation occurred both to the north and to the south of it.

To give a short view of the shoreline changes that characterised various segments of the southern Molise coast, we took into consideration six sectors for which both shoreline changes and annual shoreline rates were determined (Table 1 and Figure 3). Acquired data show that between 1957 and 2019 (Figure 3(A)) the Biferno mouth area underwent a total retreat of 358 m, corresponding to an annual shoreline retreat rate of 5.8 m/yr. In the same time span, most of the

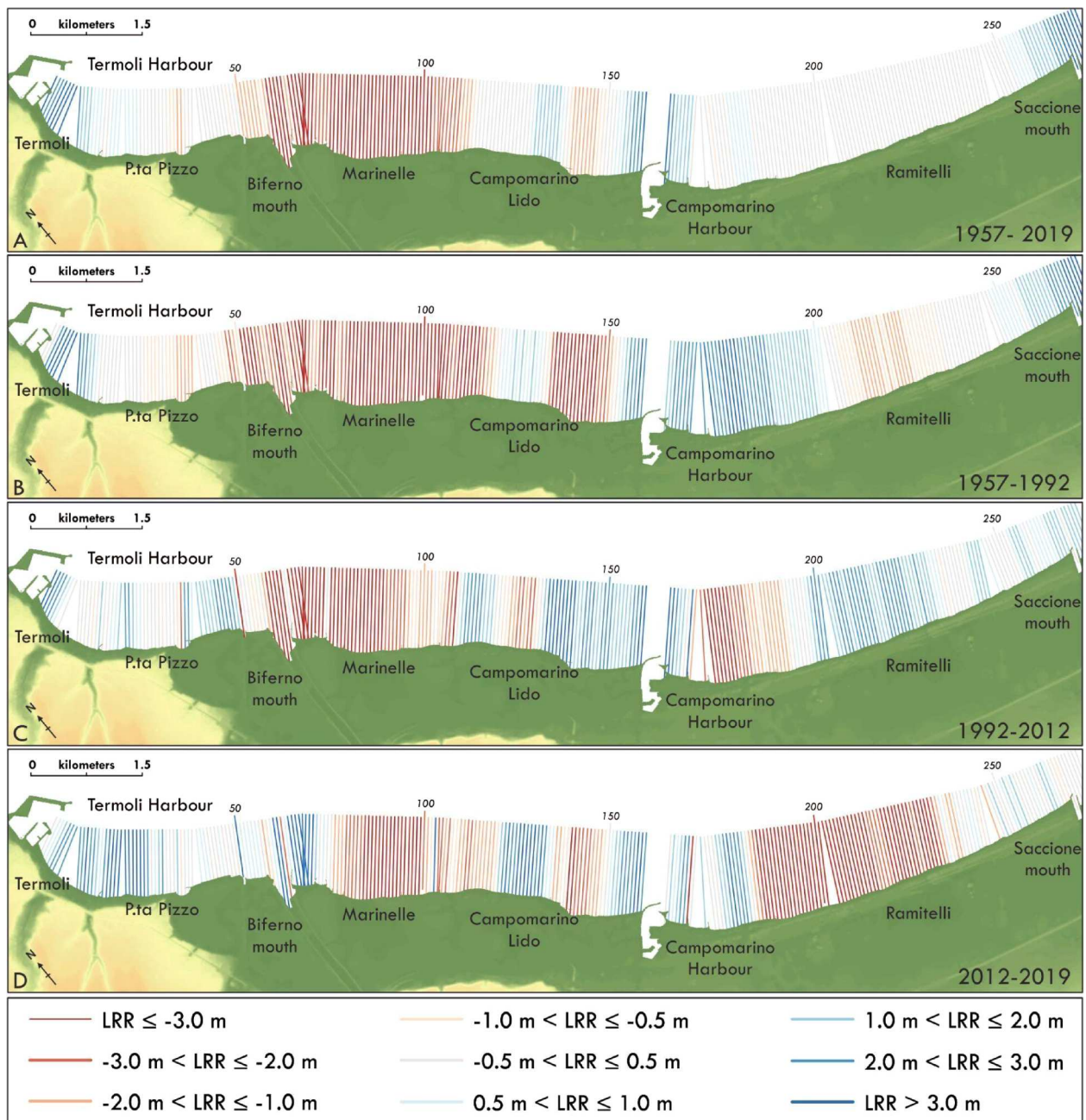


Figure 3. Annual shoreline rates (in m/yr) along the study coast, represented for the total period 1957–2019 (A) and main periods 1957–1992 (B), 1992–2012 (C) and 2012–2019 (D). The figure also shows the 274 DSAS transects.

Table 1. Shoreline changes (in m) and annual shoreline change rates (in m/yr) of southern Molise coastal sectors, calculated for the total period 1957–2019, for main periods 1957–1992, 1992–2012 and 2012–2019, and related sub-periods 1957–1985, 1985–1992, 1992–2002 and 2002–2012.

Location		Period							
		1957–1992	1957–1985	1985–1992	1992–2012	1992–2002	2002–2012	2012–2019	1957–2019
Punta Pizzo	m	–18	–7	–11	–13	–11	–2	17	–14
	m/yr	–0.5	–0.3	–1.6	–0.7	–1.1	–0.2	2.4	–0.2
Marinelle (Biferno mouth)	m	–254	–243	–11	–53	–35	–18	–51	–358
	m/yr	–7.3	–8.7	–1.6	–2.7	–3.5	–1.8	–7.3	–5.8
Campomarino Lido	m	–56	–124	71	35	–14	49	–15	–36
	m/yr	–1.6	–4.4	10.1	1.8	–1.4	4.9	–2.1	–0.6
Campomarino Harbour (South)	m	33	65	–32	–20	7	–27	–41	–28
	m/yr	0.9	2.3	–4.6	–1.0	0.7	–2.7	–5.9	–0.5
Bonifica Ramitelli	m	–46	–42	–4	37	15	22	–35	–44
	m/yr	–1.3	–1.5	–0.6	1.9	1.5	2.2	–5.0	–0.7
Saccione mouth	m	103	110	–7	27	6	21	3	133
	m/yr	2.9	3.9	–1.0	1.4	0.6	2.1	0.4	2.1

other sectors registered only slight shoreline retreats (between -14 m and -44 m), corresponding to annual rates between -0.2 m/yr and -0.7 m/yr (Table 1 and Figure 3(A)). Instead, the southernmost Saccione mouth sector was affected by consistent progradation, equal to a total of 133 m and an annual rate of 2.1 m/yr.

Observing the shoreline changes over time (Table 1), shows that only the Biferno mouth sector was affected in all periods by shoreline retreat, while other sectors were characterised by alternating periods of erosion and progradation. Important variations are observable for example in correspondence of the Campomarino Harbour and Bonifica Ramitelli sectors

(Table 1), whose total amount of shoreline retreat of respectively -28 m and -44 m (period 1957–2019) was deeply influenced by the amount of positive and negative shoreline changes during the first, nearly thirty-year period 1957–1985 (65 m and -42 m, Table 1). During the last years (period 2012–2019), both sectors registered a strong erosion trend with average retreating rates of respectively 5.9 and 5.0 m/yr (Table 1 and Figure 3(D)).

Ongoing trends to shoreline retreat promoted the progressive construction of defence structures that led to achieve a maximum coverage of 64.2% by the year 2029. In Map 2, the distribution in time and space of coastal defence structures is illustrated,

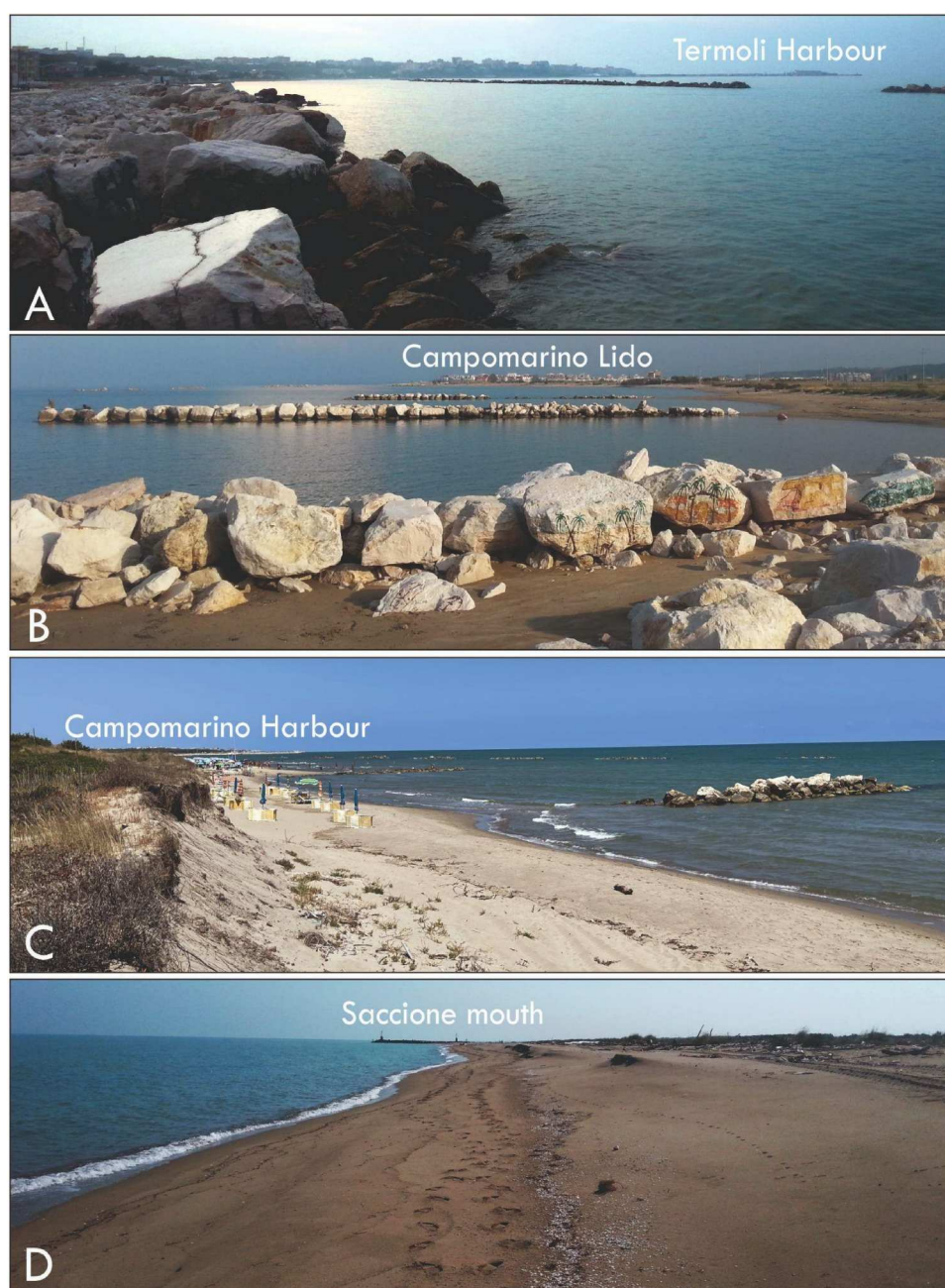


Figure 4. Some views of the southern Molise coast: (A) emerged and adherent breakwaters placed between Termoli Harbour and Biferno mouth; (B) groynes and adherent breakwaters present between Biferno mouth and Campomarino Lido; (C) partially detached groynes located south of Campomarino Harbour; (D) progradational shoreline north to Saccione mouth.

Table 2. Coverage (in %) of the southern Molise coast with defence structures by the years 1957, 1985, 1992, 2002, 2012 and 2019.

Defence structure	1957	1985	1992	2002	2012	2019
Adherent breakwater (AB)	–	–	2.1	4.7	5.1	–
Emerged breakwater (EB)	–	6.7	16.7	–	–	1.5
Submerged breakwater (SB)	–	18.3	18.7	40.8	34.0	37.5
Groyne (G)	–	–	–	–	1.1	1.6
Mixed defence structure						
EB + SB	–	–	5.4	–	–	–
AB + SB	–	–	–	2.0	2.0	9.7
G + SB	–	–	–	–	11.4	4.3
Harbour	7.0	7.0	7.0	9.6	9.6	9.6
Total (%)	7.0	32.0	49.9	57.1	63.2	64.2

showing first of all that the study coast was devoid of them in 1957. The first defences, mainly constituted by alternating emerged and submerged breakwaters, were placed in the coastal sector extending from Termoli harbour to Marinelle locality (Figure 4(A)) and covered 25.0% of the study area by the year 1985 (Table 2). In 1992, mainly due to the addition of emerged breakwaters and mixed defences of emerged and submerged breakwaters (EB + SB in Table 2) the total coverage including the Termoli harbour reached 49.9% (Table 2). The breakwaters were further modified and extended southwards, and the construction of the Campomarino harbour occurred, leading to a total coverage of 57.1% in 2002. First groynes were placed only after 2002 (Figure 4(B,C)). Furthermore, between 2012 and 2019, first breakwaters were constructed in the northern part of Bonifica Ramitelli sector. Nowadays, the only sector free from hard defence structures is the southernmost one, extending from the central area of Bonifica Ramitelli up to the Saccione mouth (Figure 4(D)).

4.3. Near-future coastal hazard and risk aspects of the southern Molise coast

The areas prone to flooding were identified for the year 2050 using the sea-level projection SSP5-8.5 (an average rise of 0.22 m – NASA, 2022), together with the Digital Elevation Model of the investigated area. Table 3 and Map 3 show the four hazard classes (H4, H3, H2, H1) for the selected scenario, aiming to identify the different levels of hazard characterising the study area. The current sandy beaches and the lowlands located behind the dune systems as well as near the mouth of the Biferno River, represent the areas that could be affected by permanent flooding in the near future. Nevertheless, results obtained highlight that the study coast will be only modestly affected by

coastal flooding, with the areas characterised by hazard classes H3 and H4 (Table 3) covering only about 5.0% (1.32 km²). In detail, the areas affected by frequent and permanent inundation are mostly concentrated between P.ta Pizzo and Campomarino Lido. Moreover, the remaining areas are unlikely to be inundated by 2050, as they are referred to classes H1 and H2, but particular attention should be given to the expanding areas of Campomarino Lido that are very close to the mouth of the Biferno River.

Another factor taken into consideration was the expected erosion, which was assessed for 2040 by projecting the shoreline employing the DSAS Kalman filter methodology, as explained in paragraph 3, by using all available shorelines shown in Maps 1 and 2. The model allowed for generating with the available data a linear regression, resulting in a probable shoreline for 2040. Unfortunately, the model used does not allow for projections further into the future because the error increases significantly, giving excessively high values. Therefore, Map 3 shows the shoreline projection up to 2040 which, although rigorous, represents a possible interpretation with uncertainties in its extrapolation (estimated error of approximately ± 50 m). Anyway, the future shoreline shows that about 6 km of the 15 km long coastline, could be characterised by erosion, with peaks of retreat of about 250 m (Marinelle), while the remaining coast could be dominated by progradation reaching up to about 200 m (Campomarino Lido).

These methods, despite the limitations, allow for a quick and effective assessment of areas that may experience significant consequences due to future climate change and subsequent sea-level variations. This is particularly evident when considering that some areas near the mouth of the Biferno River already experience temporary flooding during storms and periods of high tides. Therefore, the data emphasises that the areas near the mouth of the Biferno River are the most vulnerable zones of the analysed coastal system, as they will be significantly affected by both inundation and erosion resulting from sea level rise.

5. Discussion and conclusions

The present study has been developed starting from the basic thought that the comprehension of the

Table 3. Coastal inundation hazard assessment.

Hazard classes	Elevation range (m)	km ²	%
H4	≤0	0.36	1.4
H3	0–0.5	0.96	3.6
H2	0.5–1	3.65	13.4
H1	1–5	21.43	81.6

The surface of each hazard class is indicated in square kilometres and percentage with respect to the total surface investigated by considering sea-level rise scenarios for the years 2050 (SSP5-8.5).

history, the present dynamics and fragility, as well as possible near-future threats that may loom over a coastal zone represent an essential step for its sustainable management and development. This is valuable both for designing adaptations to the effects of climate change that local communities have to face in the near future and for promoting, in an effective and sustainable manner, the socio-economic development of vulnerable coastal zones, i.e. sensitive to modifications and coastal hazard events. The investigative approach used in this work consists in the reconstruction of conditions and modifications of a selected low coastal area, the southern Molise coast, considering two time intervals, i.e. Holocene-1950s and 1950s-Present, to which a near-future scenario, consisting in predictions about its possible future evolutive trends under the control of climate change, is added. The resulting map is composed of three panels. The first two panels (Maps 1 and 2) allow a comparative view of the geomorphological and anthropogenic features and related modifications that have characterised the southern Molise coast in the two above mentioned time intervals, while the third panel (Map 3) gives precious information about its possible near-future evolution in the period Present-2040/50 related to coastal erosion and inundation hazard and risk. Examining individually the single maps along with their comparison allows for several observations, including the following, among the most important ones: (i) the study area has shown a high mobility of the shoreline especially in the alluvial plain sector of the Biferno River that has been affected by conspicuous shoreline advance in approximately 300 years (1600-beginning 1900) and related Biferno River delta growth and, subsequently, by very rapid delta erosion and overall shoreline retreat, showing a very high mobility and sensibility to erosion; (ii) the construction of hard defence structures to protect the investigated coast under erosion has not solved the problem and erosion is still ongoing, especially in the Biferno mouth sector; (iii) near-future developed scenarios regarding coastal vulnerability highlight that, without specific interventions, this coastal stretch will most probably undergo significant erosion and local permanent inundation in the near-future.

Software

The map has been produced using Esri Arcgis 10.7© for the vector and raster datasets, and Corel Draw 2019© for the editing.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author, [E.V.], upon reasonable request.

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References

- Abd-Elhamid, H. F., Zelenáková, M., Barańczuk, J., Gergelova, M. B., & Mahdy, M. (2023). Historical trend analysis and forecasting of shoreline change at the Nile Delta using RS Data and GIS with the DSAS Tool. *Remote Sensing*, 15(7), 1737. <https://doi.org/10.3390/rs15071737>
- Amorosi, A., Bracone, V., Campo, B., D'Amico, C., Rossi, V., & Roskopf, C. M. (2016). A late Quaternary multiple paleovalley system from the Adriatic coastal plain (Biferno River, Southern Italy). *Geomorphology*, 254, 146–159. <https://doi.org/10.1016/j.geomorph.2015.11.023>
- Anfuso, G., Postacchini, M., Di Luccio, D., & Benassai, G. (2021). Coastal sensitivity/vulnerability characterization and adaptation strategies: a review. *Journal of Marine Science and Engineering*, 9(1), 72. <https://doi.org/10.3390/jmse9010072>
- Aucelli, P. P. C., Di Paola, G., Rizzo, A., & Roskopf, C. M. (2018). Present day and future scenarios of coastal erosion and flooding processes along the Italian Adriatic coast: The case of Molise region. *Environmental Earth Sciences*, 77(10), 371. <https://doi.org/10.1007/s12665-018-7535-y>
- Benassai, G., Di Paola, G., & Aucelli, P. P. C. (2015). Coastal risk assessment of a micro-tidal littoral plain in response to sea level rise. *Ocean & Coastal Management*, 104, 22–35. <https://doi.org/10.1016/j.ocecoaman.2014.11.015>
- Bracone, V., Amorosi, A., Aucelli, P. P. C., Roskopf, C. M., Scarciglia, F., Di Donato, V., & Esposito, P. (2012). The Pleistocene tectono-sedimentary evolution of the Apenninic foreland basin between Trigno and Fortore rivers (Southern Italy) through a sequence stratigraphic perspective. *Basin Research*, 24(2), 213–233. <https://doi.org/10.1111/j.1365-2117.2011.00523.x>
- Bracone, V., Cozzolino, M., De Benedittis, G., Mauriello, P., Roskopf, C. M., & Valente, E. (2016). Un approccio geo-archeologico integrato per lo studio dell'evoluzione geomorfologica ed antropica recente della piana costiera del fiume Biferno. *Atti del Convegno "Realtà medioadriatiche a confronto. Contatti e scambi tra le due sponde", a cura di De Benedittis G.*, 22–23. luglio 2016.

- Buccino, M., Di Paola, G., Ciccaglione, M. C., Giudice, G. D., & Roskopf, C. M. (2020). A medium-term study of Molise coast evolution based on the one-line equation and "Equivalent Wave Concept". *Water*, 12(10), 2831. <https://doi.org/10.3390/w12102831>
- Budillon, F., Amodio, S., Alberico, I., Contestabile, P., Vacchi, M., Innangi, S., & Molisso, F. (2022). Present-day infralittoral prograding wedges (IPWs) in Central-Eastern Tyrrhenian Sea: Critical issues and challenges to their use as geomorphological indicators of sea level. *Marine Geology*, 450, 106821. <https://doi.org/10.1016/j.margeo.2022.106821>
- Budillon, F., Amodio, S., Contestabile, P., Alberico, I., Innangi, S., & Molisso, F. (2020). *The present-day near-shore submarine depositional terraces off the Campania coast (South-eastern Tyrrhenian Sea): An analysis of their morpho-bathymetric variability*. MetroSea 2020 IMEKO TC-19 International Workshop on Metrology for the Sea. Naples, Italy, October 5–7, 2020. Proceedings (pp. 132–138).
- Chrisben, S. S., & Gurugnanam, B. (2022). Coastal transgression and regression from 1980 to 2020 and shoreline forecasting for 2030 and 2040, using DSAS along the southern coastal tip of Peninsular India. *Geodesy and Geodynamics*, 13(6), 585–594. <https://doi.org/10.1016/j.geog.2022.04.004>
- Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., & Unnikrishnan, A. S. (2013). Sea level change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 1137–1216). Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9781107415324.026>
- Ciritci, D., & Türk, T. (2020). Assessment of the Kalman filter-based future shoreline prediction method. *International Journal of Environmental Science and Technology*, 17(8), 3801–3816. <https://doi.org/10.1007/s13762-020-02733-w>
- Creach, A., Chevillot-miot, E., Mercier, D., & Pourinet, L. (2015). Vulnerability to coastal flood hazard of residential buildings on Noirmoutier Island (France). *Journal of Maps*, 12(2), 1–11. <https://doi.org/10.1080/17445647.2015.1027041>
- D'Amico, C., Aiello, G., Barra, D., Bracone, V., Bella, D., Esu, L., Roskopf, D., & M, C. (2013). Late Quaternary foraminiferal, molluscan and ostracod assemblages from a core succession in the Trigno River mouth area (Central Adriatic Sea, Italy). *Bollettino Della Società Paleontologica Italiana*, 52(3), 198–205. <https://doi.org/10.4435/BSPI.2013.23>
- De Benedittis, G. (Ed.). (2008). *Il porto romano sul Biferno tra Storia e Archeologia*. Campobasso.
- De Benedittis, G. (Ed.). (2013). Campomarino. La Necropoli Di Marinelle Vecchie. Campagne di scavo 2009–2010. *Considerazioni di Storia e Archeologia. I Quaderni III*.
- Didier, D., Baudry, J., Bernatchez, P., Dumont, D., Sadegh, M., Bismuth, E., Bandet, M., Dugas, S., & Sévigny, C. (2018). Multihazard simulation for coastal flood mapping: Bathtub versus numerical modelling in an open estuary, Eastern Canada. *Journal of Flood Risk Management*, 12(S1), <https://doi.org/10.1111/jfr3.12505>
- Di Paola, G., Rizzo, A., Benassai, G., Corrado, G., Matano, F., & Aucelli, P. P. C. (2021). Sea-level rise impact and future scenarios of inundation risk along the coastal plains in Campania (Italy). *Environmental Earth Sciences*, 80(17), 608. <https://doi.org/10.1007/s12665-021-09884-0>
- Dolan, A. H., & Walker, I. J. (2006). Understanding vulnerability of coastal communities to cli related risks. *Journal of Coastal Research, Special Issue 39*, 1316–1323. <https://www.jstor.org/stable/25742967>
- EUROSION. (2004). Living with coastal erosion in Europe: sediment and space for sustainability. Reports on-line. Retrieved 23 November 2022. <http://www.euroSION.org>
- Filangieri, R. (1970). Registri della cancelleria angioina, vol. VI, 1270–1271, Napoli p. 237, nr. 1266.
- Gornitz, V. (1991). Global coastal hazards from future sea level rise. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 89(4), 379–398. [https://doi.org/10.1016/0031-0182\(91\)90173-O](https://doi.org/10.1016/0031-0182(91)90173-O)
- Griggs, G., & Reguero, B. G. (2021). Coastal adaptation to climate change and Sea-level rise. *Water*, 13(16), 2151. <https://doi.org/10.3390/w13162151>
- Helama, S., Stoffel, M., Hall, R. J., Jones, P. D., Arppe, L., Matkovsky, V. V., Timonen, M., Nöjd, P., Mielikäinen, K., & Oinonen, M. (2021). Recurrent transitions to Little Ice Age-like climatic regimes over the Holocene. *Climate Dynamics*, 56(11–12), 3817–3833. <https://doi.org/10.1007/s00382-021-05669-0>
- Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G., & Farris, A. S. (2021). *Digital Shoreline Analysis System (DSAS) version 5.1 user guide: U.S. Geological Survey Open-File Report 2021–1091*, 104 p. <https://doi.org/10.3133/ofr20211091>
- Hossen, F., & Sultana, N. (2023). Shoreline change detection using DSAS technique: Case of Saint Martin Island, Bangladesh. *Remote Sensing Applications: Society and Environment*, 30, 100943. <https://doi.org/10.1016/j.rsase.2023.100943>
- IPCC. (2021). *Sixth assessment report – Climate change. Impacts, adaptation and vulnerability: Regional aspects*. Cambridge University Press.
- Kalman, R. (1960). A new approach to linear filtering and prediction problems. *Journal of Basic Engineering*, 82(1), 35–45. <https://doi.org/10.1115/1.3662552>
- Karle, M., Bungenstock, F., & Wehrmann, A. (2021). Holocene coastal landscape development in response to rising sea level in the Central Wadden Sea coastal region, Netherlands. *Journal of Geosciences*, 100(E12), e12. <https://doi.org/10.1017/njg.2021.10>
- Kopp, R., Kemp, A., Bittermann, K., Horton, B., Donnelly, J., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D., & Rahmstorf, S. (2016). Temperature-driven global sea-level variability in the common era. *Proceedings of the National Academy of Sciences*, 113(11), 1434–1441. <https://doi.org/10.1073/pnas.1517056113>
- Long, J. W., & Plant, N. G. (2012). Extended Kalman Filter framework for forecasting shoreline evolution. *Geophysical Research Letters*, 39(13), 1–6. <https://doi.org/10.1029/2012GL052180>
- Magini, G. A. (1620). Mappa di Contado di Molise e Principato Ultra.
- Marino, L. (1977). *La difesa costiera contro i saraceni e la visita del marchese di Celenza alle torri di Capitanata*. Nocera Editore.
- Martin, J. M., Cuozzo, E., Gasparri, M., & Villani, M. (2002). Regesti dei Documenti dell'Italia Meridionale 570–899, *École française de Rome*, p. 316, nr. 618.

- MATTM. (2012). *Ministry of the environment and protection of land and sea*. <http://www.pcn.minambiente.it/mattm/progetto-coste> Accessed on 23 November 2022.
- McLaughlin, S., & Cooper, J. A. G. (2010). A multi-scale coastal vulnerability index: A tool for coastal managers? *Environmental Hazards*, 9(3), 233–248. <https://doi.org/10.3763/ehaz.2010.0052>
- NASA. (2022). *IPCC 6th assessment report sea level projections*. Retrieved 23 November 2022. <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool>.
- Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding – A global assessment. *PLoS One*, 10(6), e0131375. <https://doi.org/10.1371/journal.pone.0123867>
- Paola, D., Ciccaglione, G., Buccino, M. C., Roskopf, M., & M, C. (2020). Influence of hard defence structures on shoreline erosion along Molise coast (southern Italy): A preliminary investigation. *Rendiconti Online Società Geologica Italiana*, 52, 2–11. <https://doi.org/10.3301/ROL.2020.10>
- Poulter, B., & Halpin, P. N. (2007). Raster modelling of coastal flooding from sea-level rise. *International Journal of Geographical Information Science*, 22(2), 167–182. <https://doi.org/10.1080/13658810701371858>
- Roskopf, C. M., Di Paola, G., Atkinson, D. E., Rodríguez, G., & Walker, I. J. (2018). Recent shoreline evolution and beach erosion along the central Adriatic coast of Italy: The case of Molise region. *Journal of Coastal Conservation*, 22(5), 879–895. <https://doi.org/10.1007/s11852-017-0550-4>
- Rowley, R. J., Kostelnick, J. C., Braaten, D., Li, X., & Meisel, J. (2007). Risk of rising sea level to population and land area. *EOS Transactions American Geophysical Union*, 88(9), 105–107. <https://doi.org/10.1029/2007EO090001>
- Scorpio, V., Aucelli, P. P. C., Giano, S. I., Pisano, L., Robustelli, G., Roskopf, C. M., & Schiattarella, M. (2015). River channel adjustments in Southern Italy over the past 150 years and implications for channel recovery. *Geomorphology*, 251, 77–90. <https://doi.org/10.1016/j.geomorph.2015.07.008>.
- Valente, E., & Cozzolino, M. (2019). GIS mapping of the archaeological sites in the Molise region (Italy). *Archeologia e Calcolatori*, 30, 367–385. <https://doi.org/10.19282/ac.30.2019.21>
- Xu, H., Hou, X., Li, D., Zheng, X., & Fan, C. (2022). Projections of coastal flooding under different RCP scenarios over the 21st century: A case study of China's coastal zone. *Estuarine, Coastal and Shelf Science*, 279, 108155. <https://doi.org/10.1016/j.ecss.2022.108155>
- Zannoni, R. (1792). *L'Atlante marittimo delle Due Sicilie*. Stamperia Reale.
- Zannoni, R. (1808). *L'Atlante del Regno di Napoli*. Stamperia Reale.