


Historical maps and satellite images as tools for shoreline variations and territorial changes assessment: the case study of Volturno Coastal Plain (Southern Italy)

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Abstract Anthropogenic pressure has caused severe variations of Mediterranean coastal areas currently hosting about 480 million people. The replacement of natural land covers with crops and urban environment coupled with the reduction of sediment supply to the coast, subsidence, Relative Sea Level Rise and the high frequency of storm events, have caused severe shoreline erosion. In this paper, we stress the key role of historical maps, topographic maps and free satellite images to forecast the rates of coastline changes and to recognize the main features of past landscapes as tools for risk reduction. This data was recorded into a Geographical Information System dedicated to coastal management that allows to compare different coastal zones and elaborate maps. The analysis was applied to the case study of Volturno Coastal Plain (VCP), extending from the town of *Mondragone* to *Patria Lake* (*Campania* Region, Southern Italy). Indeed, the intense territorial modification that occurred between the seventies and eighties, coupled with the exposure to coastal erosion, make the VCP a good test area. The spatial analysis algorithms allowed to outline the main features of past landscapes and how they changed from roman times to present while the coastal evolution (erosion, accretion) and possible future coastal trend was assessed with the Digital Shoreline Analysis System (DSAS) software. Starting from the Bourbon domain, the reclamation caused the first great territorial change (e.g. wetlands were transformed into agricultural lands, regimentation of superficial water) but the negative effects of anthropic pressure, as the intense urbanization of

the coastal belt, emerged in the seventies of the last century. The shoreline position was defined for 9 time intervals (from 1817 to 2012) as the ratio of the distance between two shorelines and the relative elapsed time. Moreover, for the 1957–1998 and 1998–2012 time windows, the shoreline trends were calculated with the weighted linear regression method. The first trend pointed out an intensive erosional phase (mean value: 5 m/yr) for a wide sector close to the Volturno River mouth, the eroded sediment nourished the beaches of other coastal sectors. This phase was related to the reduction of River sediment supply mainly due to the construction of the *Ponte Annibale* dam on the *Volturno* River. The second (1998–2012) showed an alternation of erosion and accretion sectors due to a sediment starved condition to deltaic zone and to a sequence of 52 sea protection works in the Gaeta Gulf. Furthermore, the regression values of more recent time interval, was assumed as a scenario to draw the probable shoreline position in 2022. The overlay of this shoreline on the Technical Maps of *Campania* Region at 1:5000 scale highlighted the urban area that could be exposed to damages.

Keywords Historical analysis · Coastal trend · Natural landscape · Natural hazards · Coastal management

Introduction

The presence of fresh water, easily cultivable lands and natural resources offered by the sea exposed the coastal zones to an uncontrolled urbanization.

Currently, the world coastal population density (99.6 people per km²) is more than double of inland areas (37.9 people per km²), (Millenium Ecosystem Assessment 2005). In European coastal regions (Nomenclature Des Unités Territoriales Statistiques – NUTS3; EUROSTAT 1988), this

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value is on average 10% higher than inland, only in some countries it is more than 50% higher (EEA Report 2006). However, the population density map for European coastal zone (NUTS3) shows a value varying from 100 to 500 inhabitants per square kilometer. Higher values generally characterize the Southern Europe.

The presence of one-third of the population (480 million people) in the Mediterranean coastal areas has caused strong territorial transformations in the last centuries (SOER 2015). The replacement of wetlands with crops, roads, and urban environment coupled with the changes in sediment supply to the coast (about 45% of the sediments are retained behind dams or extracted from rivers (UNEP/MAP 2009) are the main causes of shorelines realignment. Moreover, artificial structures, the destruction or degradation of sea grass beds and dune vegetation, the extraction of gas and water may also affect the cycling and redistribution of sediment in neighboring coastal areas (UNEP/MAP 2009). Approximately one-fourth of the European Mediterranean coastline is subject to erosion.

In the last centuries, the *Sele* and *Volturno-Garigliano* coastal plains, the two largest sandy coastal areas of the *Campania* Region, as many other Italian coastal plains (Cocco and Pippo 1988; Cocco and Magistris 1988; Cocco and Iuliano 1999; Bellotti 2000; Pranzini 2001; Aucelli et al. 2009; Alberico et al. 2011), have suffered erosion.

Starting from the analysis of historical documents and free satellite images, the main aim of the present work was to identify the main features of past landscapes, territorial changes, shoreline variations and shoreline trends (del Pozo and Anfuso 2008; Dickson et al. 2007; Dolan et al. 1980; Dolan et al. 1991; Gibeaut et al. 2003; Hapke et al. 2006; Jimenez et al. 1997; Leatherman 1983; Morton et al. 2004; Pajak and Leatherman 2002; Romagnoli et al. 2006; Alberico et al. 2011). This knowledge can be considered essential for natural risk reduction. In fact, past land-uses represent a guide for environmental restoration (Sutton-Grier et al. 2015 and reference therein) while the shoreline variations and shoreline trends point out the coastal changes and the possible future shoreline position.

The Volturno Coastal Plain (VCP) was chosen as a case study because it was exposed to erosional hazard and had been deeply modified by anthropic pressure. The urban environment currently occupies the greatest part of the coastal belt.

The coastal erosion at VCP followed two main events: the reclamation works, realized in the lower part of this plain during the *Bourbon* domain, and the construction of *Ponte Annibale* dam on the Volturno River in the fifties, both events caused a reduction of river sediment supply to the coast. After the seventies, the extensive urbanization of coastal zones and the construction of several coastal defense structures caused the

alternation of accretion and erosion. Moreover, the trend calculated for the 1998–2012 time window, was used to identify the possible position of shoreline in 2022. The overlay of this shoreline over Technical Maps of *Campania* Region offered the possibility to identify the urban areas possibly exposed to risk in the next future.

The data and the procedures implemented for this study were integrated into the VPC coastal management framework (Alberico et al. 2017). Taking into account that coastal erosion is not the only threat to coastal zones, this framework is flexible and can easily be upgraded and integrated with other environmental data related to natural hazards (marine inundation, salt water intrusion, storm events), often exacerbated by Global Warming (IPCC 2014) and land-uses.

Geological and geomorphological setting

The Volturno Coastal Plain is an integral part of Campanian Plain (~ 5700 km², therein CP), which stretches for several kilometers inland from the coast and is bounded toward the Tyrrhenian Sea by a narrow coastal strip (2–0,15 km) running from the eastern border of Massico Mountain to Patria Lake. The continental shelf is about 16 km wide in front of the Volturno River and narrows southward, the shelf break is located at about 125 m depth (Iorio et al. 2014). The convexity of the isobaths in front of Volturno River at 100–150 m depth, identify the ancient river mouth shifted seaward during the last glacial cycle (Pennetta et al. 1998) (Figs. 1a–c).

According to several geological reconstructions (Ippolito et al. 1973; Aprile and Ortolani 1978; Ortolani and Pagliuca 1986; Cinque et al. 1987; Cinque et al. 2000; Bruno et al. 2000), the CP represents a morphostructural basin that has been evolving since Late Pliocene along the palaeo-Tyrrhenian margin of the Apennines fold-thrust belt as a consequence of the post-orogenic phases and extensional processes (stretching and thinning of the continental crust) linked to the Tyrrhenian rift-basin (e.g., Doglioni 1991; Patacca and Scandone 2007; Ferranti and Oldow 1999; Milia and Torrente 2003) (Fig. 2).

The CP boundaries are defined at the surface by NW–SE, NE–SW and E–W trending faults with poly-phasic history, which define several half-grabens in subsurface (from northwest to southeast: Volturno, Patria Lake, Campi Flegrei-Acerra and the Naples Bay basins) and downthrow the Meso-Cenozoic Apennine units forming the basin flanks and basement by about 2000–5000 m (Mariani and Prato 1988; Milia and Torrente 2003; Milia et al. 2013).

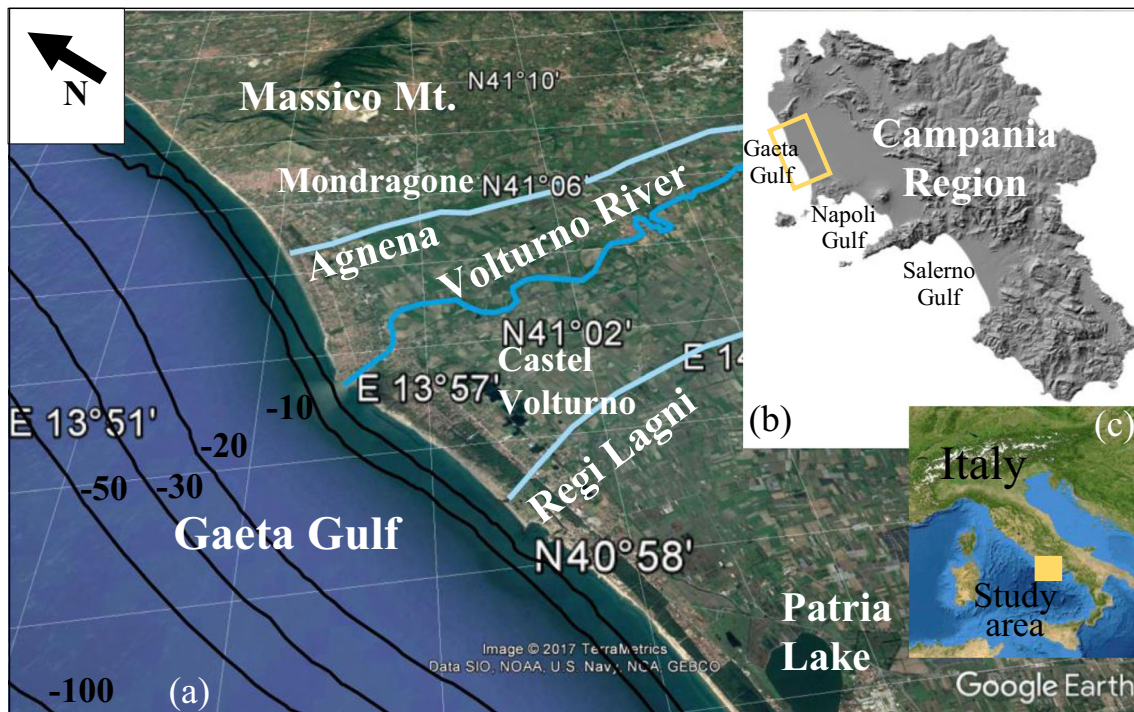


Fig. 1 The Volturno Coastal Plain is bounded by *Massico Mountain* to the northwest and by *Patria Lake* to the south (a). The location of the study area is illustrated at Regional (b) and National scale (c)

Starting from the early Pleistocene, the CP has recorded the onset of rapid tectonic subsidence and intense infilling of continental and marine deposits (mainly constituted by alluvial, fluvial, swampy, lagoonal, and paludal deposits) interfingering with the products of intense explosive eruptions related to the Somma-Vesuvio district and Campi Flegrei supposedly controlled by regional faults (De Vivo et al. 2001; Milia and Torrente 2003; Romano et al. 1994; Cinque et al. 1997).

The late Pleistocene-early Holocene sea-level rise (ca. 15 ky–6 ky BP) promoted the rapid flooding of lower VP followed by the maximum coastline retreat, which from 6 km reached to 10 km inland with respect to the present shore (Amorosi et al. 2012; Sacchi et al. 2014). Since ca. 6.5 ky BP, a progressive change from transgressive to regressive conditions marked the establishment of a coastal progradational trend (ca. 4 ky BP) causing the seaward migration of the adjacent plain and the growth of Volturno River delta (Amorosi et al. 2012; Barra et al. 1989; Cinque et al. 1997). At about 2 ky cal BP, the continuous progradation favored beach, marsh and lagoonal environments which still persist along the present coastal zone (Ruberti et al. 2014; Amorosi et al. 2012; Sacchi et al. 2014).

At present, the coastline is fairly straight, except for the prominent Volturno River mouth, where a large swamp area as the remnants of a series of beach ridges and swales elongated in NW/SE direction is preserved. This coast is classifiable as dissipative-type and wave-dominated (Bellotti 2000). The surface circulation in the Tyrrhenian Sea is characterized by

complex patterns, dominated by both (semi) permanent recirculation and transient features, often hindering the identification of a consistent mean flow even at the large (basin) scale, and specifically in its south-eastern sector (Rinaldi et al. 2010; Iacono et al. 2013). The situation is further complicated in the coastal areas, and particularly in the Gulf of Gaeta, where the local circulation is influenced mostly by wind direction and variability, as evidenced by recent studies by Iermano et al. (2012) based on both numerical modelling and satellite remote sensing. In particular, their analyses suggest that the recurrence of periods of wind reversal and fluctuating freshwater discharge rates may substantially modify the local circulation and cross-shelf exchange close to the river mouths.

Materials and methods

The orthophoto maps, satellite images, historical and topographic maps are the data sources used to evaluate the main features of past landscapes and the shoreline variation at VCP from 1817 to 2012 (Table 1).

The main natural elements (i.e. wetlands, pinewoods, dunes, beaches) characterizing the past landscapes were digitized and designed as part of coastal management framework published by Alberico et al. (2017) (Fig. 3).

The shoreline variations were assessed with the Digital Shoreline Analysis System (DSAS) software (Thieler et al. 2009; Kumar et al. 2010; Abuodha and Woodroffe 2010;

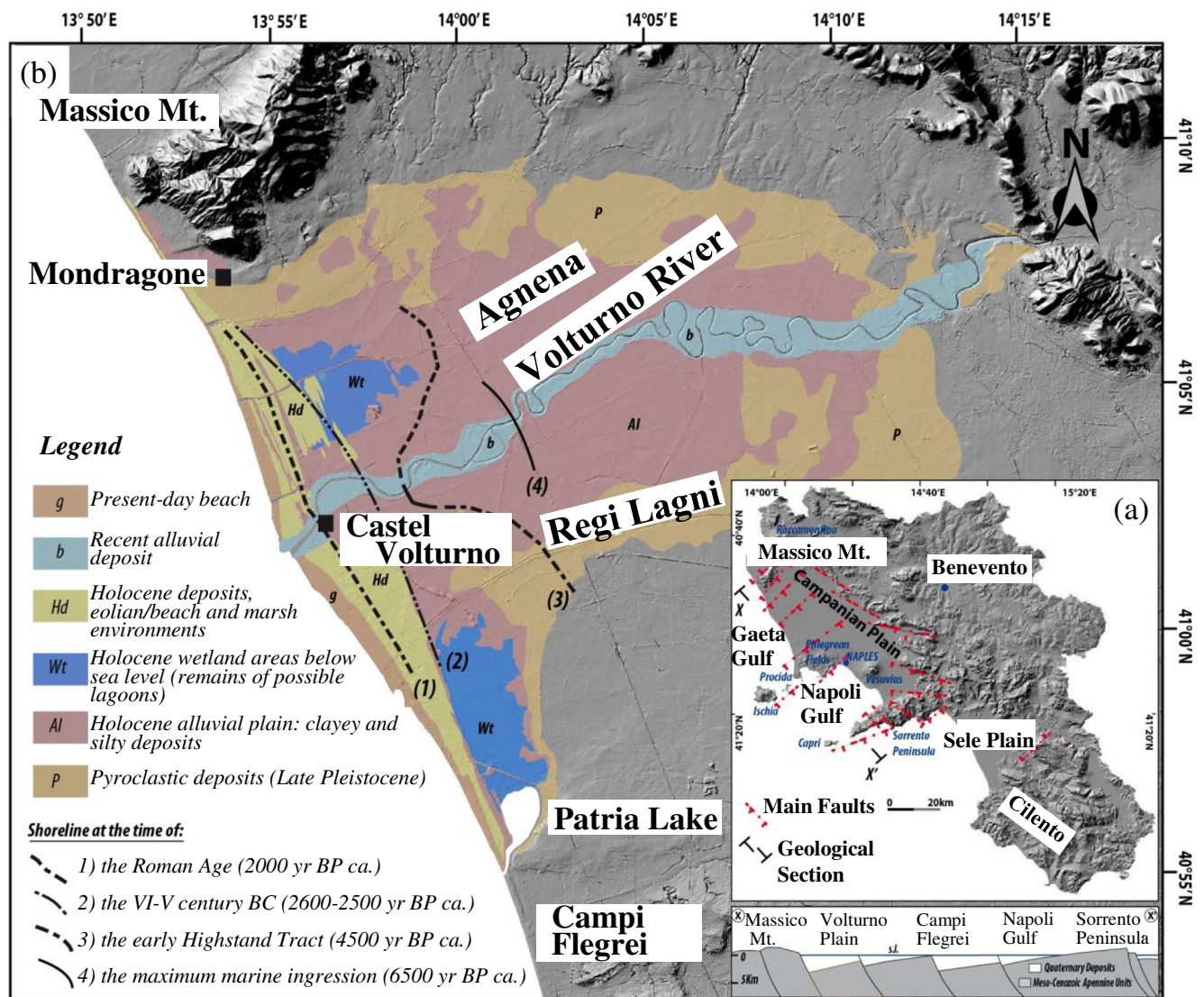


Fig. 2 (a) Schematic structural map of Campanian Plain and interpretative cross section of the Campanian margin redrawn from Milia and Torrente (1999). (b) Simplified geological-geomorphological map of the Voltumo Plain based on the reinterpretation of survey works of

1:100,000 scale Geological sheets n°171, 172, 184 (ISPRA – Servizio Geologico d'Italia 1966; 1967; 1968). Ancient shorelines are derived from Amorosi et al. (2012); Sacchi et al. (2014); Ortolani and Pagliuca (1999); Cocco et al. (1992)

Alberico et al. 2011; Kuleli et al. 2011; Aiello et al. 2013; Albuquerque et al. 2013; Kaliraj et al. 2015; Nguyen and Woodroffe 2016). The software ensures a repeatable procedure, favors a systematic update and allows a comparison between different coastal zones.

For this analysis, the geo-referencing procedure, seasonal shoreline variations and the accuracy in identifying and digitizing the land–water interface (Crowell et al. 1991; Moore 2000; Morton et al. 2004; Romagnoli et al. 2006; Thieler and Danforth 1994) are sources of potential errors affecting the shoreline variations assessment.

In accordance with del Pozo and Anfuso (2008) the shoreline position was defined as the water line at the time of the historical documents or satellite images because the study area is located in a microtidal environment (± 20 cm). Moreover,

for the same reason we considered the daily and seasonal water line position exposed to a very low uncertainty and thus the accuracy of shoreline detection is based on the accuracy of geo-referencing process.

The historical and topographic maps were georeferenced according to the technical map of Campania Region at 1:5000 scale that resides in the WGS84 coordinate system. The process involves the assignment of geographical coordinates, as read on the technical map of the Campania Region, to the various control points (road junctions, historic monuments, geodetic points) identified on non-geo-referenced maps. The accuracy associated to this procedure, expressed by RMSE (Route Mean Square Error) is shown in Table 1.

The positional accuracy of GoogleEarth® imageries required the comparison of georeferenced points, defined on

Table 1 Topographic maps, orthophoto maps and satellite images employed for the study of territorial changes and shoreline variation at Voltumo Coastal Plain. For each documents are reported: scale and Root Mean Square Errors (RMSE) of georeferencing process

Date	Input data	Data Source holder	Scale	Uncertainty (RMSE, m)
1817	Topographic and hydrographic map of areas close to Naples	Historical map of IGM	1:25,000	30
1860	The map of the kingdom of Naples	Historical map of IGM	1:20,000	20
1936	IGM topographic map	Topographic map	1:25,000	12
1957	IGM topographic map	Topographic map	1:25,000	4
1987	IGM topographic map	Topographic map	1:25,000	8
1989	Orthophoto map	Ministry for the Environment, Land and Sea	1:10,000	5.7
1997	Orthophoto map	Ministry for the Environment, Land and Sea	1:10,000	6.2
1998	Technical map	Campania Region	1:5000	2
2004	Google Earth image			6.81
2010	Google Earth image			2.67
2012	DAEDALUS satellite image	Consorzio TELAER STA	Pixel size:1.3 m	4.8

the technical Map of Campania Region, with corresponding points as displayed by the GoogleEarth® application (Potere 2008; Casella et al. 2010; Becek et al. 2011a, 2011b;

Kazimierz et al. 2011). To this aim, the coordinates of 16 control points, mainly corresponding to building corners, are compared to define the RMSE of the Google Earth imagery

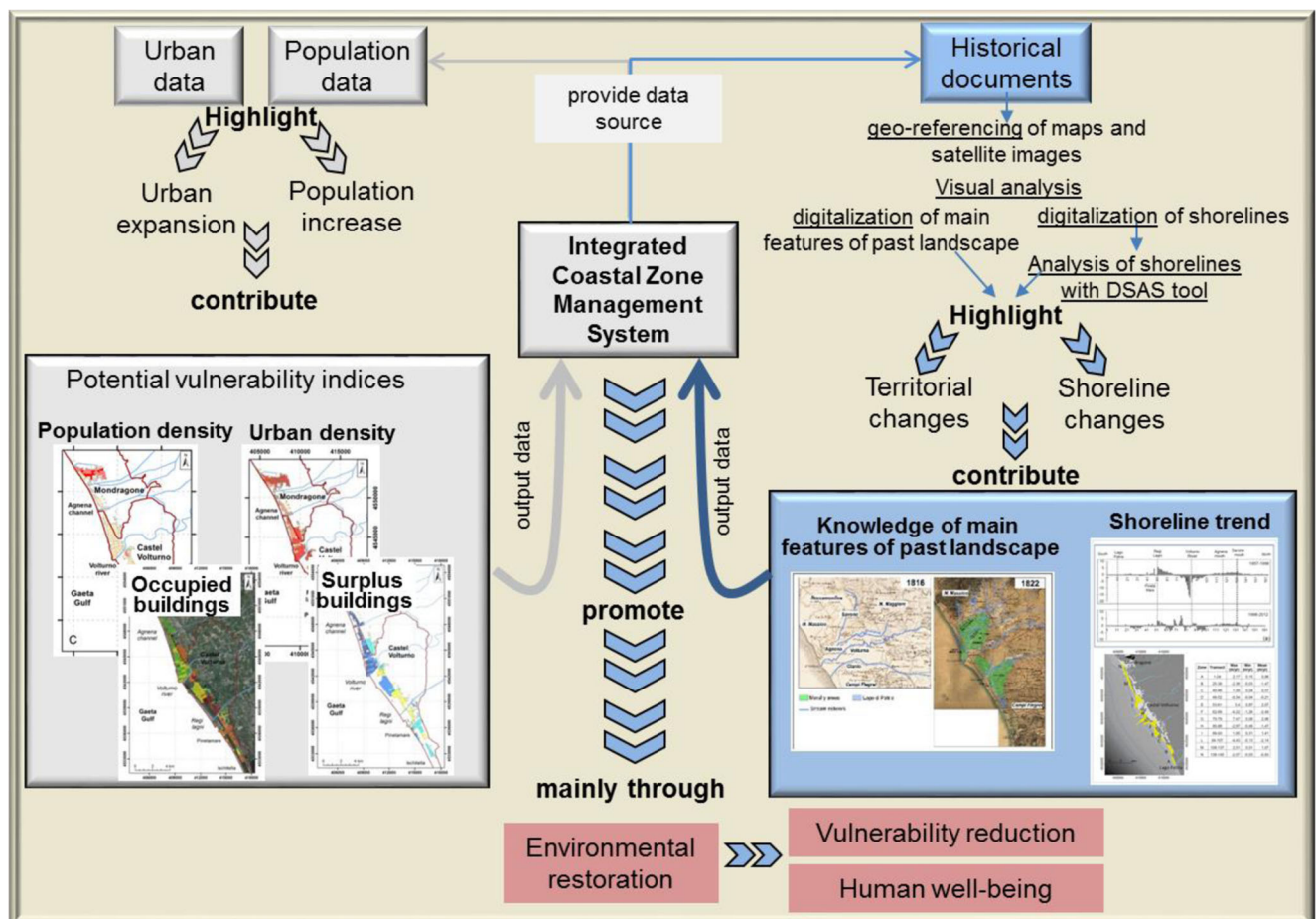


Fig. 3 Flow chart illustrating the main steps of procedures adopted in the present work for the territorial changes analysis and the shorelines variation assessment (right side of image). A simplified representation

of framework (left part of image) dedicated to the anthropic pressure assessment (Alberico et al. 2017) and the key role of data integration are illustrated

(Table 2). A similar procedure was applied to assess the accuracy of orthophoto maps of the Italian Environmental Ministry and Daedalus satellite image (Table 2).

For the shoreline analysis, 10 shorelines, 170 transects (lines along which the shoreline variations and trends are calculated), a baseline (the starting point for all transects), the spacing and length of transects and the shoreline parameters (e.g. shorelines date, uncertainty in position) were used as input data. The baseline was traced back to all shorelines; it matches with a more smoothed shape of the shoreline in 1998. The transects were spaced every 200 m; their intersection with the shorelines identify the coastal points used in DSAS to calculate, for the single transect, both the rate of shoreline changes and the shoreline trend (Figs. 4a–c).

The shoreline changes were calculated, for each pair of consecutive shorelines, as the ratio of the distance between two shorelines and the elapsed time (Fig. 4b) (Addo et al. 2008; Alberico et al. 2011; Houseret et al. 2008; Leyland and Darbya 2008; Thieler and Danforth 1994). These measurements allowed to reveal the shoreline behavior for nine time intervals.

The shoreline trend was evaluated by applying the weighted linear regression method. All the coastal points available along the single transect (Fig. 4c) contributed to the trend assessment with a weight related to the accuracy of shoreline position in detail, the lower the uncertainty (low geo-

referencing error) the higher the weight (Genz et al. 2007). The coastal trend was calculated for the 1950–1998 and 1998–2012 time windows. The latter was also used to identify the shoreline position for the year 2022. To this aim, assuming that the driving factors were unmodified, the rate of erosion calculated for each transect was multiplied by ten years. This shoreline was then superimposed on the Technical Map of Campania Region at 1:5000 scale to identify the urban zones possibly exposed to erosion in the next future.

The environmental change of coastal area from roman times to present

During the Roman Empire (27 B.C. - 476 A.D.), the plain close to the *Volturno* River, named *Campania Felix*, became the core of a rich agricultural resource. In this period several infrastructures were built; the *Domitiana* road and the bridge connecting the *Volturno* River sides (Canino 1981). After the fall of the Western Roman Empire (476 A.D.), the agricultural crisis and the barbarian invasions caused an abandonment of plain. This event was probably associated to the unset of Late Antique Little Ice Ages from 536 to ca. 660 AD. This cooling phase, spanning most of the northern hemisphere, was considered by Büntgen et al. (2016) and also recognized in Margaritelli et al.

Table 2 List of points used in the georeferencing process of Google Earth (2004, 2010), orthophoto maps (1989) and Daedalus image (2012). For each point, the differences in coordinates (DX and DY) between the Technical map, used as master map, and the other documents and the Root Mean Square are listed

Point	Difference in coordinates							
	1989		2004		2010		2012	
	DX(m)	DY(m)	DX(m)	DY(m)	DX(m)	DY(m)	DX(m)	DY(m)
1	0,00	0,00	4,42	-2,86	0,35	-2,05	-0,53	-1,59
2	-2,14	2,10	4,39	-4,24	0,39	-0,08	0,00	-3,44
3	0,00	4,42	4,11	-4,12	0,00	0,00	-1,59	-2,38
4	-1,46	2,19	2,74	-3,52	0,00	0,00	-8,14	1,48
5	0,00	3,32	2,38	-2,70	-0,10	-2,42	-3,64	0,99
6	0,00	2,65	3,39	-2,61	0,74	1,56		
7	-0,75	2,25	3,38	-2,39	3,05	-1,61		
8	0,33	0,23	2,50	-3,31	2,08	-3,72		
9	1,24	3,30	5,78	-5,57	1,47	-0,44	-2,87	0,52
10	1,56	2,26	4,38	-4,07	-0,04	-3,52		
11			5,18	-6,16	1,35	-2,36		
12			4,51	0,27	0,55	-3,74	4,30	0,33
13	-2,13	-0,42	7,39	-4,62	-2,27	-1,67	-6,83	3,10
14	-2,55	-0,87	7,45	-0,17	-0,63	-2,84		
15	-2,92	-0,05	7,42	-8,55	-0,83	-2,93		
16	-3,14	-0,99	7,83	-7,28	-0,67	-2,88		
RMSE	2,91	4,98	5,14	4,46	1,26	2,35	4,41	2,04
RMSE _{XY}	5,77		6,81		2,67		4,86	

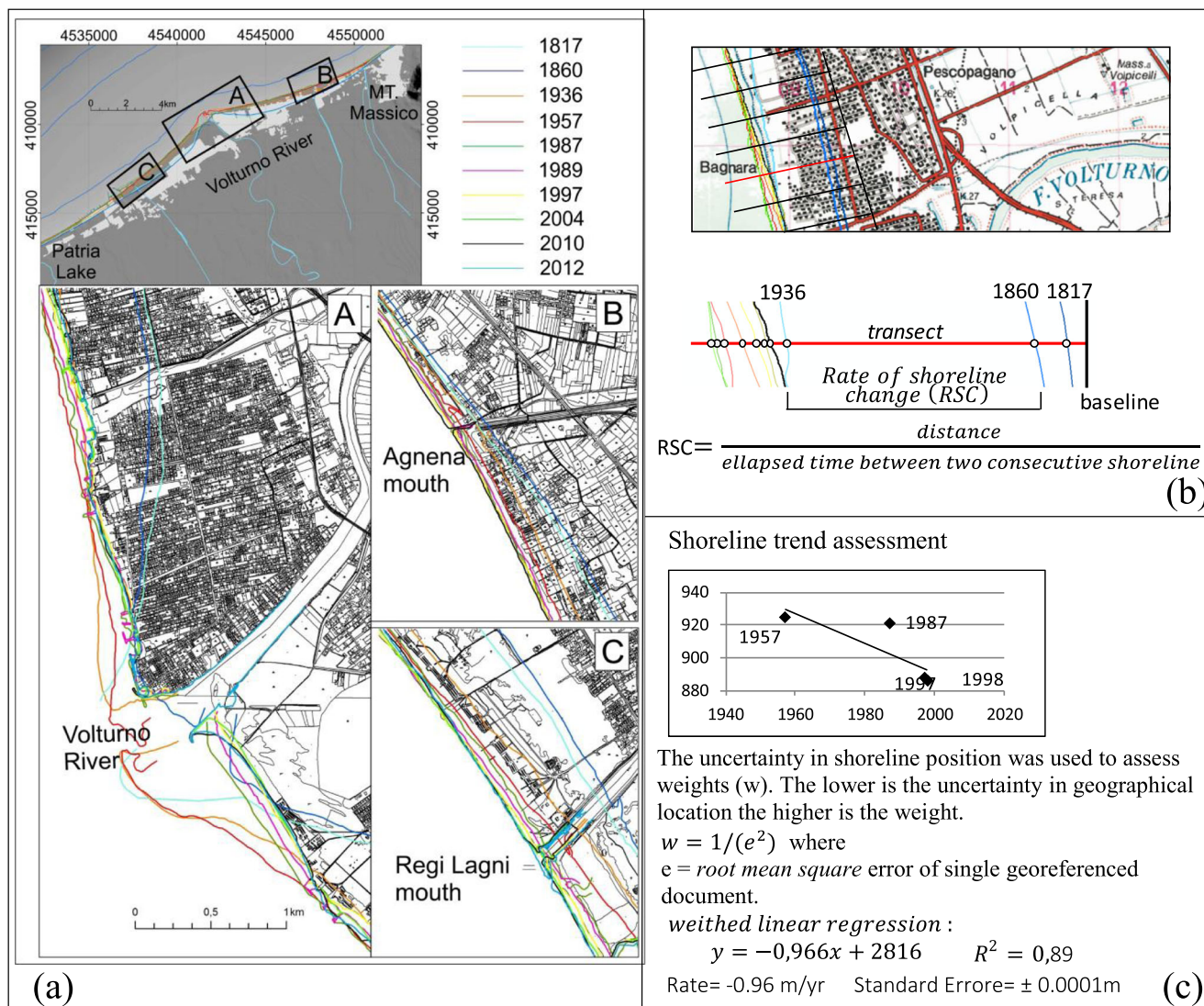


Fig. 4 The shorelines detected from the 1817 to 2012 were superimposed to Digital Elevation Model of *Volturno* Coastal Plain (upper left side of image “a”). Three detailed maps show the shoreline variation at *Volturno River* (A), *Agnena* (B) and *Regi Lagni* mouths (C). In figure “b”, the map illustrates a subset of 170 transects

realized along the *Volturno* Coastal Plain to assess the shoreline variation, the red transect illustrates the methodology followed to assess the rate of shoreline change between two shorelines consecutive in time. In figure “c”, the shoreline trend from 1957 to 1998 is pointed out

(2016), as an additional environmental factor contributing to change in social reorganization in Europe and Asia. During the Norman domain (1130–1189 A.D), the *Campania* was enclosed in the *Regno di Sicilia* and dominated by *Altavilla, Hohenstaufen, Angioini and Aragonesi*. During the Aragonese dynasty and under Alfonso V *Napoli* became a capitol of the Mediterranean area while a decline occurred as a consequence of high tax pressure applied by Carlo V during his domain. Only after the Austrian domain, the ascension to the throne of Bourbon dynasty (1735–1860) favoured the improvement of human well-being thanks to the promulgation of economic and legislative reforms.

In the topographic map of 1816, the VCP is a natural land and four main rivers are present in the area: a) the *Volturno River* in the central part of the plain, b) the *Savone* and *Regia Agnena*

rivers in the northern territories, they ending their path in swamp areas close to the coast and c) the *Clanio River* in southern territories, which ran into the *Patria Lake* through the *Vena* channel (Figs. 5a, b) (Savarese 1856). The reclamation of *Clanio River*, renamed as *Regia Agnena*, started in 1592 by will of Conte Di Miranda and continued under the *Conte Lemos*, from 1599 to 1603, ending in 1610 under the *Conte di Benavente*. The morphology of territories to the left of *Volturno River* was described as a plain with very low slope while a variable morphology characterized the right side. The large amount of sediment discarded by the *Volturno River* favoured a rapid accretion of beach at the *Bagnane* mouth causing the development of homonym canal parallel to the coast (Fig. 5b). In time the river reconstructed a new mouth to flow directly at the sea. This process repeated itself several times (Afan de Rivera 1847).

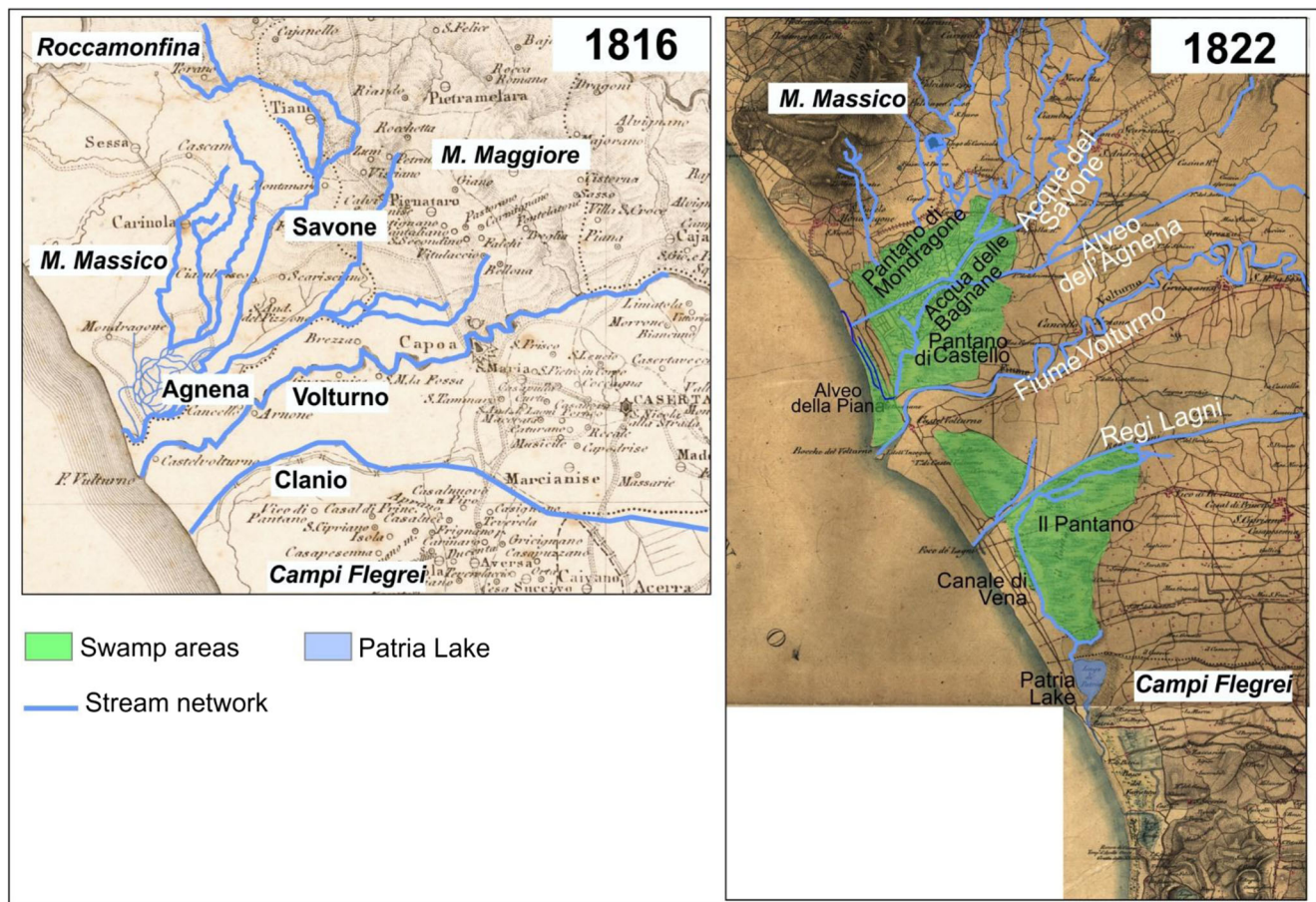


Fig. 5 The maps illustrate the main streams and swamp areas characterizing the Volturno Coastal Plain at the beginning of nineteenth century

In the cartography of 1817, *Mondragone*, *S. Nicola*, *S. Angelo* and *San Vito* urban centers characterized the northern area of VCP while a small group of houses, representing the source of modern *Castel Volturno* town, were located on the right side of the *Volturno* River (Fig. 6). A few farms were spread over the territory and the Domitiana road, joining *Castel Volturno* and *Capua*, is detectable. A pine forest characterized the area very close to the shoreline and dune systems, with elevation ranging from 3 to 5 m were present on the right side of the *Volturno* River. In the map of 1822, the swamp zones labelled *Pantano di Mondragone*, *Pantano di Castello* and *Il Pantano* and the *Regi Lagni* canals were well detectable (Fig. 5b). In 1831, Ferdinando II established the authority “*Amministrazione Generale di Bonificazione*” to reclaim these areas. In 1837, the hydraulic structures of *Regi Lagni* was improved. In 1841, the reclamation continued in the lower part of VCP and about 54.754 *moggia* (1 *moggio* in the study area = c.a. 3300m²) became agricultural lands. As first step, the *Regia Agnena*, used to drain the territory located between the *Volturno* and *Savone* rivers, was modified and its channel was extended to the sea. In 1842, a large pond located in the lowland area labelled “*le Bagnane*”, between the *Volturno* River and *Regia Agnena*, was infilled thanks to the construction of a diversion (*Bartolotti* canal)

from the *Voturno* River; this construction worked very well and thus in 1845 a new canal (*de’ Militari*) was built to infill this swamp area. In 1849, only the *Napoli* and *Caserta* Provinces supported the reclamation contributing to the construction of about 72 km of main canals, 254 km of secondary canals, 150 km of trenches and the new mouth of *Clanio* stream (today known as *Regi Lagni*).

Starting from 1850, the reclamation continued with the land-fill of lowland areas; *il Bosco*, *il Pantano di Mondragone*, *le Terre di Bartolotti* and *Pantano di Castello* well visible in fig. 5b. After 1855, the lack of preservation works favoured damages at the left bank of *Clanio* River and most of the territories close to the *Regi Lagni* canals were flooded (Ciasca 1928). In 1917, the Institution of “*Opera Nazionale Combattenti*” restarted with reclamation work; several water pumps were placed in the lower part of VCP, the *Regi Lagni* mouth was rebuilt and the left river bank of *Volturno* River was restored.

In 1860, two main elements structured the territory: a wide pine forest, namely “*Paneta di Mondragone*” and “*Paneta di Castel Volturno*”, located on both sides of the *Volturno* River mouth and the *Regi Lagni* channel in the southern area (Fig. 6).

In 1907, *Castel Volturno* preserved its extension while *Mondragone* grew towards the coast and the road network

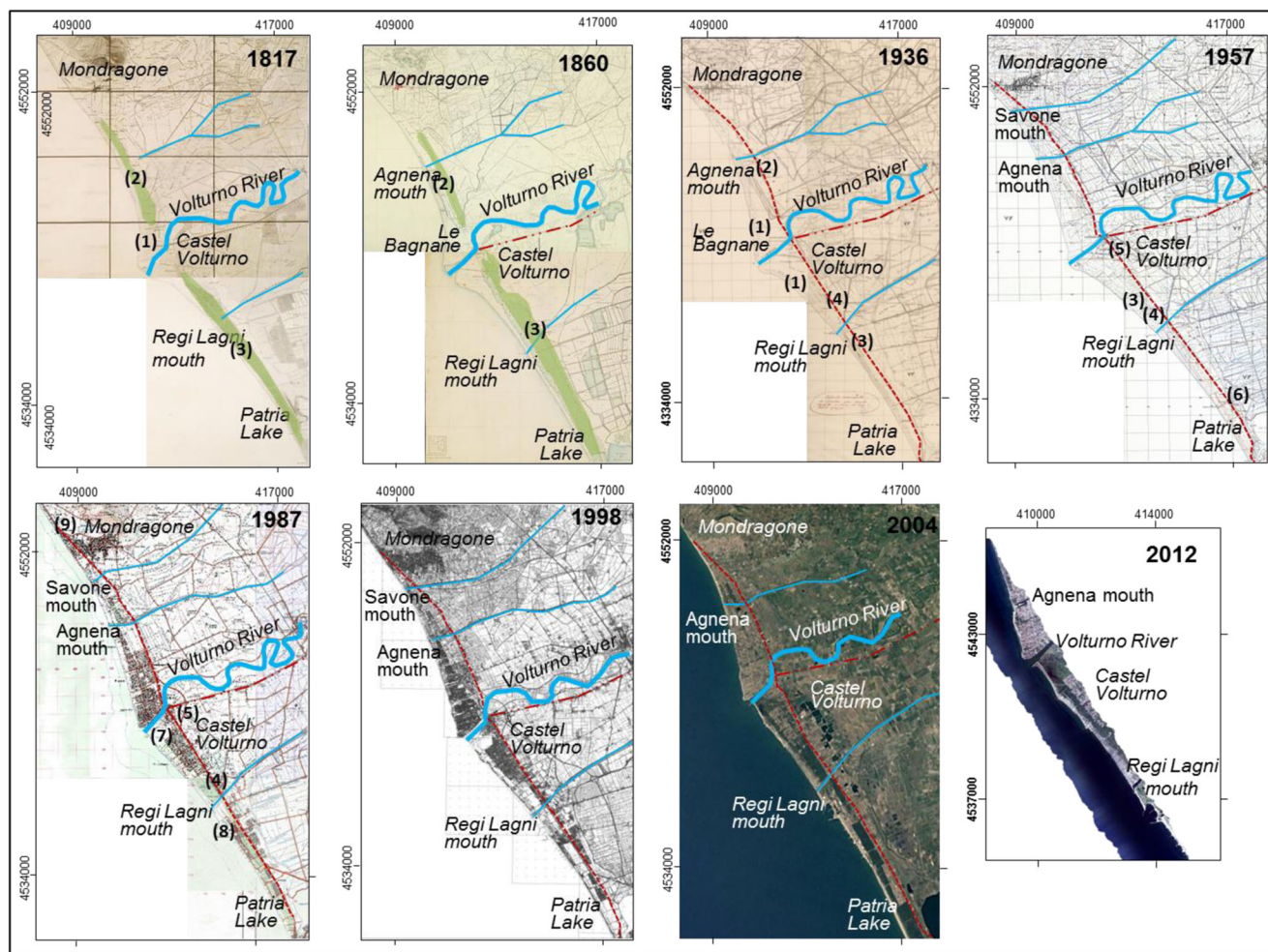


Fig. 6 The figures illustrates the main features characterizing the past landscape and its evolution through time. Only the principal elements were drawn, location of other elements or localities are indicated by a number. (1) dunes, (2) *Pineta di Mondragone*, (3) *Pineta di Castel*

Volturno, (4) *Scuderia* locality *Villaggio Agricolo* locality, (5) *Scatozza* locality, (6) *Masseria Pineta d'Ischitella*, (7) *I Variconi*, (8) *Pinetamare* locality, (9) *Punta dei Tamari* locality. The dotted red line is the *Domitiana* road

became denser than in the previous years (Fig. 6). After thirty years, *Mondragone* reached the coast and the *Cirio* factory was built at about 263 m from the shoreline. On the right side of the *Volturno* River, a cluster of buildings labelled *Villaggio Agricolo* was built at about 900 m from the shoreline and the road network become denser than in the past.

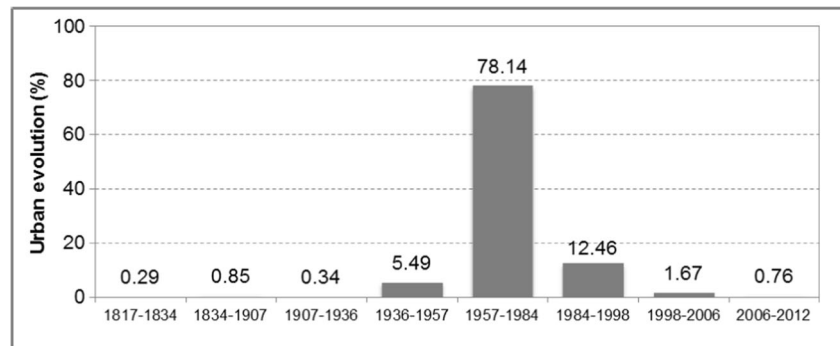
In 1936, the *Consorzio in Destra del Basso Volturno* deemed it fundamental to build the *Nuova Inalveazione del Torrente Savone channel*, realized from 1949 to 1954, to collect the waters of mountain rivers of the south-eastern sector of *Roccamonfina*, of the eastern slope of the *Monte Massico* and of north-eastern slope of *Monte Maggiore*. After World War II, the lower part of *Regi Lagni* and of *Regia Agnena* were improved and several depressed areas were infilled. The territorial reorganization of lower part of VCP ended in the fifties.

In the 1957, a group of houses were built north of *Cirio* factory at about 130 m from the coast (*Mondragone* municipalty); single buildings lined the *Domitiana* road and new

buildings rose in the *Scatozza* locality. In the locality “*Masseria Pineta d'Ischitella*” an increase of houses and of a single bathhouse very close to the coastline are evident (Fig. 6).

The quantitative analysis of urban growth for the last 200 years, pointed out that the VCP was affected by an urban expansion lower than 1% from 1817 to 1936. This value reached 5% at the end of 1957, although territorial transformation reached its peak between 1957 and 1984. In this period the urban expansion increased by about 80% and the seaside tourist centre of *Pinetamare* was also built (Alberico et al. 2017) (Fig. 7). This urban expansion occurred in areas very close to the shoreline between *Punta dei Tamari* and the *Savone* stream; southwards the urban environment was sparse, it became dense and closer to the coastline (about 400 m) at *Volturno* River. To the south of *Scatozza* locality, the urban environment was dense along the coastal belt with the only exception of *Variconi Oasis*. From *Scuderia* locality to *Regi Lagni* the urbanized zones were farther from the shoreline (850 m) than later areas. Southward, a wide

Fig. 7 Urban expansion from 1817 to 2012 for the whole investigated area (from Alberico et al. 2017; modified)



urbanized area overtook the *Domitiana* road while on the coast a big touristic village *Pinetamare* (also known as *Villaggio Coppola*) with a little harbor, was being built. In the *Masseria Pineta d'Ischitella* locality an increase of urban zones that reaches the *Patria* Lake was recorded (Fig. 8). In the following years, the percentage of new urbanized areas decreased by 12% because major urbanization had already saturated the area. After the nineties, urbanized areas increased by very low percentages (lower than 2%) similar to that characterizing the VCP before the sixties (Fig. 7) probably due to the publication of Campanian Regional Territorial Plan (2008), Caserta Provincial Territorial Plan (2012) and Hydro-geomorphological Setting Plan of Basin Authority of Liri-Garigliano-Volturno (2010).

Shoreline changes analysis

Starting from the cartography of the 1817, the first map useful for a quantitative evaluation, the shoreline variation was assessed for nine time intervals (Fig. 9). Prior to this data, thanks to the discovery of the ancient road “*Via Domitiana*”, of ruins of coastal villas (*villae maritimae*) and of the thermal settlements of “*Aquae Sinuessanae*”, the shoreline of Roman times (III – II century a.C.) was shaped by Cocco et al. (1992). The position of the coastline was very close to the present shoreline in the *Sinuessa* locality (north of *Mondragone*) while it was about 2 km behind the current shoreline at *Castel Volturno* locality. The progradation continued through time and in 1600 d.C. the shape of the shoreline mainly coincided with the alignment of coastal watchtowers. From this date to 1809 a coastal progradation, with a mean value of 1 m/year, characterized the study area (Cocco and Pippo 1988).

From 1817 to 1860, the VCP with the exception of the coastal sector between the *Volturno* River to *Agnena* channel was in erosion. This state was probably due to the infill of lowland area (reclamation) that caused a reduction in river sediment supply to the coast, mainly between 1840 and 1850, and to the long shore current that accumulates the sediment on the updrift side of *Volturno* mouth forming a progradational ridge and swale sequence of the strand plain (Fig. 9 and Table 3).

From 1860 to 1936 the whole shoreline was in accretion with the highest rates characterizing the zones close to the *Volturno* River mouth (Fig. 9 and Table 3). From 1936 to 1957 the shoreline was still in accretion and only the *Volturno* River mouth was in erosion with a mean rate of -1.52 m/yr. (Fig. 9 and Table 3). The erosion focused on the delta apex is likely to be the first signal of contraction of the sedimentary load due to the construction of the dam “*Ponte Annibale*” on the *Volturno* river in 1952, although the possibility that erosional hot spot is the result of focused effects of episodic wave attack during the later period of observation, cannot be ruled out.

In the beginning of the sixties, human pressure deeply modified the VCP. From 1957 to 1987, the areas close to the *Volturno* River mouth were in erosion with a mean rate of -3.6 m/yr., while northward the shoreline was in accretion with a mean rate of 1.7 m/yr. (Fig. 9 and Table 3). During this period, the erosion of the river mouth due to the reduction of sediment yields from the *Volturno* River is more evident than in the past while the other zones show low rate of accretion. Moreover, the coastline was stable to the north of *Patria* Lake while shoreline accretion characterized the *Regi Lagni* zone. This status was probably due to the breakwater built to protect the *Pinetamare* harbor in the beginning of the seventies. This structure influenced the local hydrodynamic regime; the sediment, transported southward by marine currents, stopped on its northern side favoring the accretion of beaches whereas the sediment reduction in the south caused erosion. To reduce erosion, several groins were built at the beginning of eighties, these structures reduced the erosion at *Villaggio Pinetamare* but shifted this process southwards.

In only two years, from 1987 to 1989, the coastal zone exposed to erosion was much wider than in previous years and extended from *Villaggio Agricolo* to *Panetelle* locality with erosion rates varying from -16 m/yr. to -8 m/yr. (Fig. 9 and Table 3). This intense erosional phase was probably the result of a sea storm reaching the areas between *Castel Volturno* and *Mondragone* in 1987 (Mimmi 1987). The coastal sector close to *Regi Lagni* mouth was in accretion with a mean rate of 16,59 m/yr.

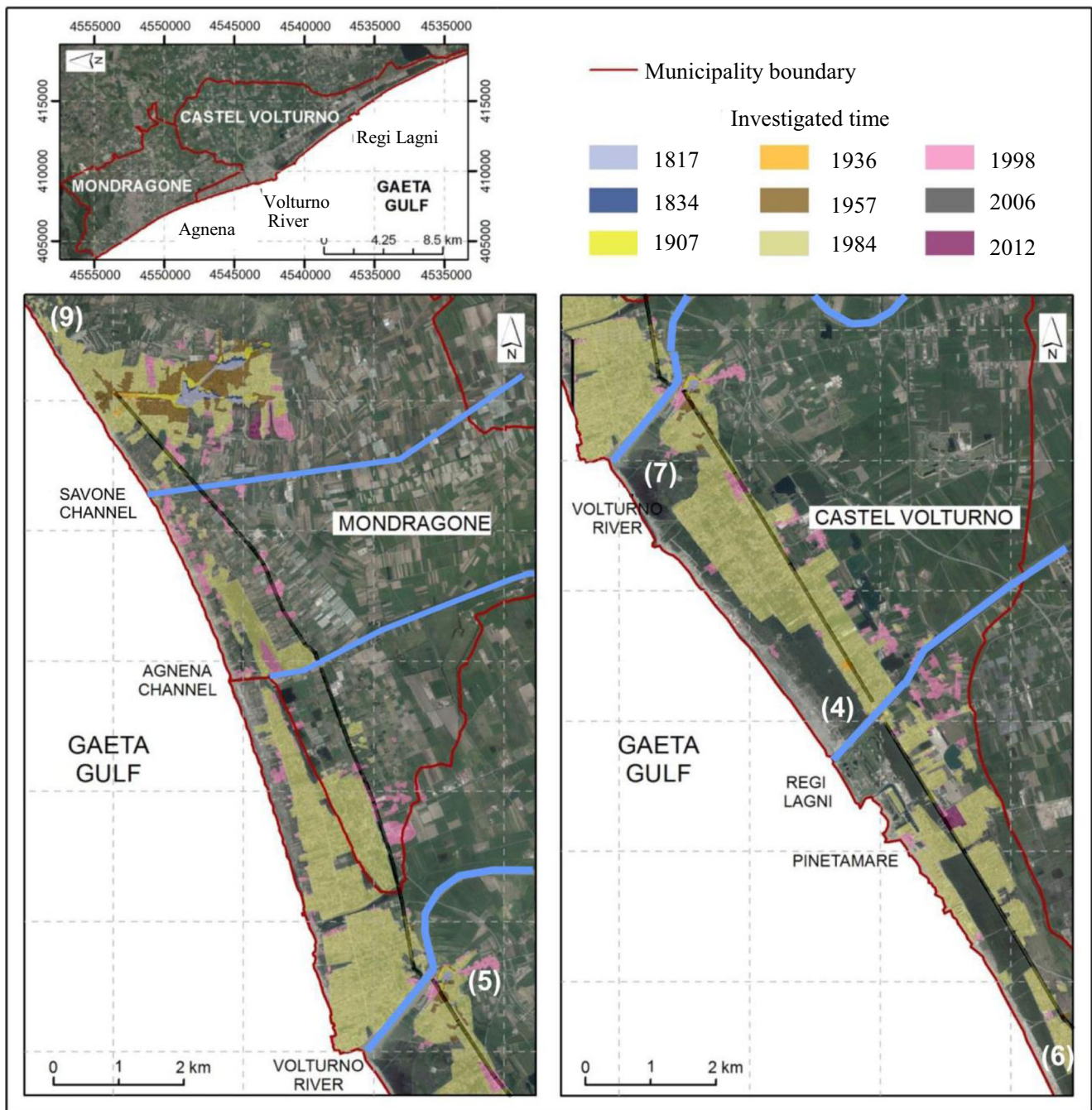


Fig. 8 Urban growth at *Volturno* Coastal Plain from 1817 to 2012. The municipality boundaries of *Castel Volturno* and *Mondragone* are illustrated in the image at the top of figure. The urban growth along the shoreline is shown in the two images at bottom of figure (from Alberico et al. 2017; modified)

From 1989 to 1998, the areas close to left and right banks of *Volturno* River were in erosion with a mean rate of -3.7 m/yr. and -6.1 m/yr., respectively; while to the north of *Volturno* River (mean rate 2 m/yr) and close to *Regi Lagni* mouth (mean rate of 4.8 m/yr) coastal accretion prevails (Fig. 9 and Table 3). The erosional status of apex and the accretion of the sides is a typical rotational behavior, easily visible along many deltas and barrier systems. The sediment yield is significantly reduced thus inducing a first phase of cannibalization, in the

form of erosion of the more vulnerable parts of the delta (fore-land apex). The waves erode the apex while sediments are distributed along the sides, thus the mass balance is maintained.

From 1998 to 2004 the left bank of *Volturno* River was still in erosion with a mean value of -3.1 m/yr. Southward for a sector of about 2 km long, the shoreline was in accretion with a mean rate of 4.4 m/yr.; lower values characterized the area of *Regi Lagni* mouth and *Pinetamare* locality. Southward, an

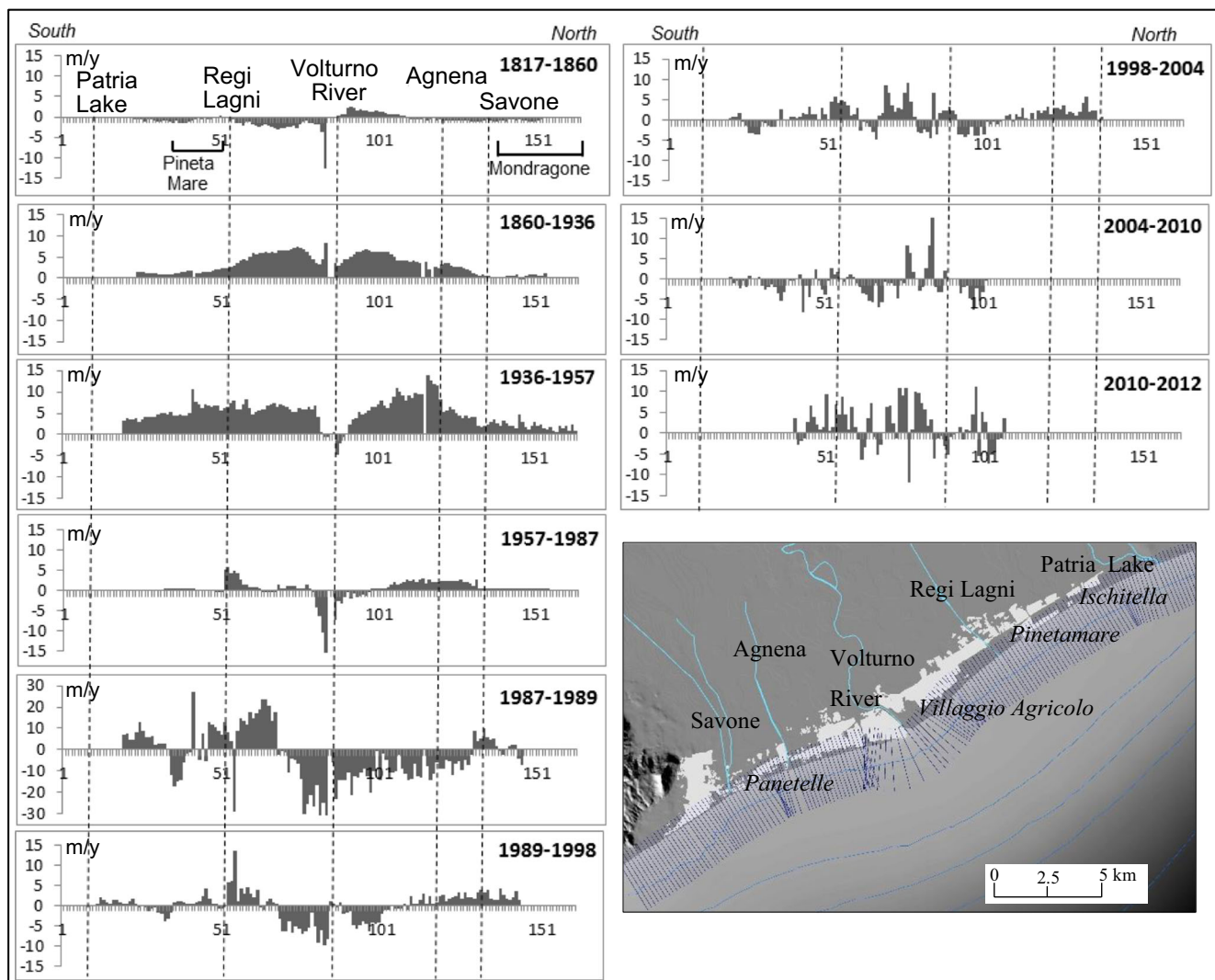


Fig. 9 The rate of shoreline changes between two shorelines successive in time is illustrated for nine time intervals. The location of transects is shown in the bottom right of the figure

erosional mean rate of -2 m/yr. was active at *Ischitella* locality. This condition was a consequence of groins built along the coast to the north of this locality. To the north of *Volturno* River, a 2.5 km long coastal sector was in erosion with a mean rate of -2.1 m/yr. followed by a wide zone, located beyond the *Agnena* channel, characterized by a mean accretion of 1.9 m/yr. (Fig. 9 and Table 3).

From 2004 to 2010 the left bank of *Volturno* River was in accretion while all the other sectors, with the exception of a few narrow zones, were in erosion. From 2010 to 2012 the VCP was characterized by coastal sectors in erosion alternated with those in accretion (Fig. 9 and Table 3).

We also analyzed the shoreline trends for two time intervals: 1957–1998, 1998–2012 (Figs. 10a, b). The first shoreline trend showed a more intensive erosional phase for a wide sector close to the *Volturno* River mouth, and accretion in the other coastal zones. The second shoreline trend showed sectors in erosion alternating with those in accretion (Figs. 10a, b). From south to

north, the first coastal sector in erosion (mean value: -1.47 m/yr) was located to the north of the *Patria* Lake, while moving towards the *Volturno* mouth, three sectors characterized by accretion (mean value: 2.07 m/yr), erosion (mean value: -2.49 m/yr) and accretion (mean value: 2.96 m/yr) were pointed out (Fig. 10a). As far as the *Volturno* River is concerned, the left bank was in erosion (mean value: -1.47 m/yr) while the right one was in accretion (mean value: 1.41 m/yr). Continuing towards the north, the area immediately after the right side of the *Volturno* River Mouth shows a mean rate of -2.14 (Fig. 10b) while the coast is stable from there to *Mondragone*.

Furthermore, the latter trend was used to identify the possible location of the shoreline in 2022, 10 years can be considered a long term to integrate this hazard into territorial management plans (Fig. 11). The erosion rate is similar for all sectors (about -2 m/yr). Only the sector “L” was characterized by higher values and an urban environment very close to the shoreline.

Table 3 Shoreline variations for the nine time intervals investigated. For each interval, several sectors (group of transects) with same shoreline variation (erosion or accretion) were recognized and for each one the mean, maximum and minimum value of erosion and accretion are reported

		Transect	Max (m/yr)	Min (m/yr)	Mean (m/yr)
Time window	1817–1860 (43 years)	25–51	–1,67	–0,12	–0,90
		51–85	–12,84	–0,09	–2,17
		86–108	2,42	0,22	1,26
		109–154	–1,38	–0,29	–0,87
	1860–1936 (76 years)	25–50	2	0,27	1,31
		50–80	7,36	2	5,17
		80–90	8,35	3,13	4,44
		91–117	6,79	3,72	5,26
		118–130	3,68	2,05	2,75
		130–145	2,05	0,12	0,74
		149–155	1,13	0,6	0,83
	1936–1957 (24 years)	21–83	10,58	2,96	5,70
		84–90	–4,88	–0,64	–1,52
		91–135	13,91	0,28	6,93
		136–165	4,6	0,44	2,23
	1957–1987 (30 years)	21–33	–0,12	–0,01	–0,05
		34–44	0,15	0,03	0,09
		45–53	–0,56	–0,04	–0,22
		54–64	5,74	0,56	2,54
		65–69	–0,48	–0,36	–0,41
		70–80	1,54	0,04	0,73
		81–99	–15,89	–0,38	–3,62
		100–134	2,93	0,13	1,75
		134–165	0,49	0,02	0,09
		1987–1989 (2 years)	21–34	12,99	2,05
	35–42		–1,5	–17,5	–9,78
	42–55		13,05	4,03	9,56
	56–69		23,46	8,92	16,59
70–85	–33,85		–0,14	–16,05	
86–100	–22,88		–6,19	–13,71	
101–131	–14,56		–0,16	–8,38	
132–139	9,99		1,71	5,68	
1989–1998 (8 years)	13–24		2,00	0,01	0,88
	25–36		–4,03	–0,11	–1,54
	37–50	4,15	0,01	1,04	
	51–62	13,43	1,13	4,80	
	63–84	–9,78	–1,81	–6,12	
	85–104	–6,46	–1,14	–3,74	
	105–146	4,19	0,06	2,06	
1998–2004 (7 years)	21–25	1,74	0,63	1,02	
	26–36	–3,55	–0,58	–1,99	
	37–62	5,74	–0,90	1,92	
	63–68	–4,85	–0,33	–2,18	
	69–80	9,09	0,72	4,49	
	81–85	–4,51	–2,32	–3,16	
	86–93	3,41	1,38	2,27	
	94–107	–4,22	–0,04	–2,33	
	108–139	5,77	–0,40	1,94	

Table 3 (continued)

	Transect	Max (m/yr)	Min (m/yr)	Mean (m/yr)
2004–2010 (6 years)	23–27	−2,40	−0,20	−1,23
	28–31	0,95	0,00	0,40
	32–43	−5,40	−0,01	−2,21
	45–47	−8,07	−1,55	−2,59
	48–53	−3,91	−0,16	−1,80
	53–61	1,71	−0,61	0,57
	62–77	−6,98	−0,17	−2,86
	78–81	8,44	1,74	5,58
	84–86	23,00	2,64	11,26
	86–89	−3,25	−3,21	−3,23
2010–2012 (2 years)	90–92	2,18	0,01	0,81
	93–103	−7,70	−0,54	−3,41
	43–45	−2,76	−1,16	−1,96
	46–61	9,17	0,45	3,84
	62–64	−6,47	−1,42	−3,79
	70–73	6,73	0,33	3,99
	75–77	10,82	9,1	10,21
	79–85	9,91	0,77	5,44
	86–92	−6	−0,02	−2,49
	96–99	11,23	0,52	4,29
	103–107	−7,23	−1,26	−3,91

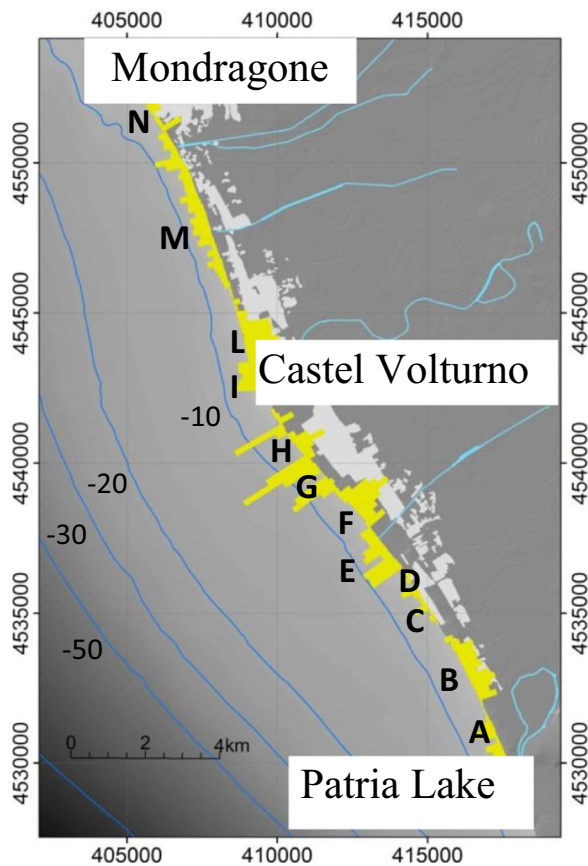
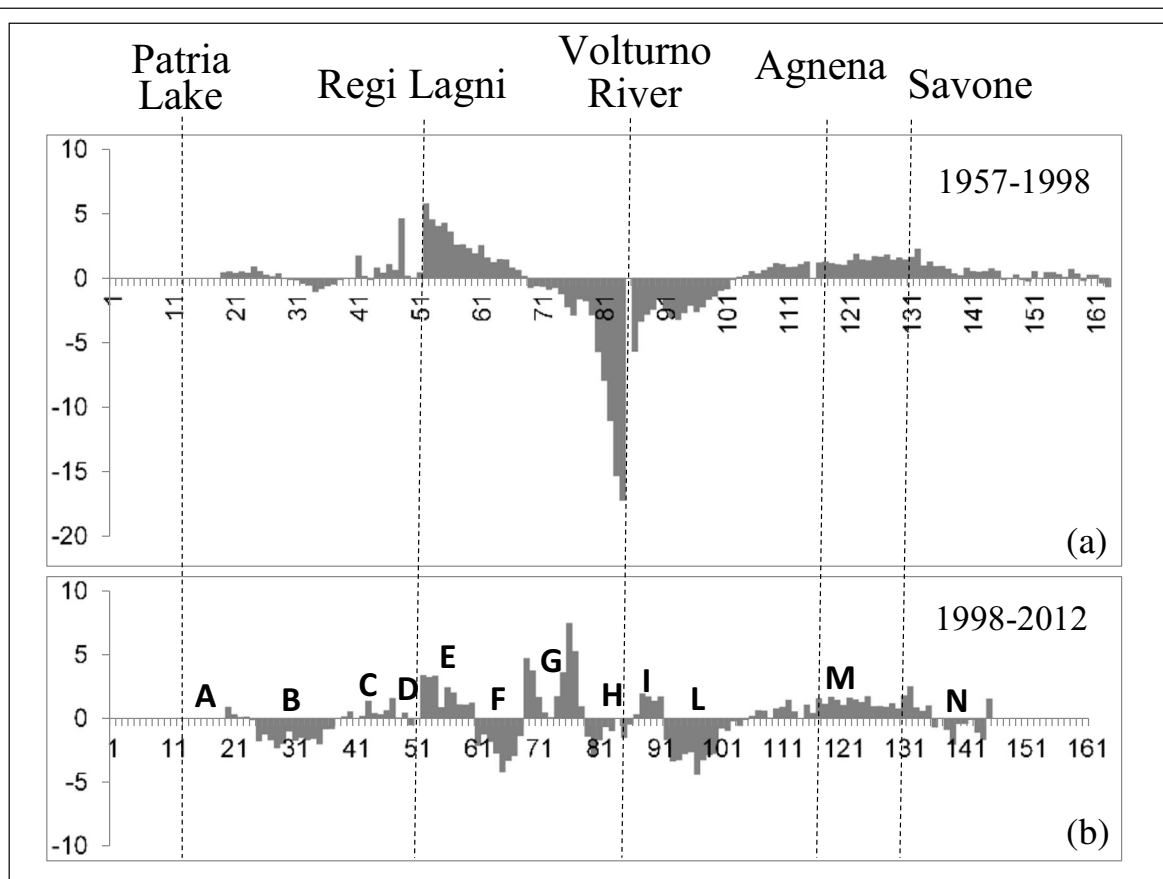
Discussion and conclusive remarks

In the frame of supporting the risk reduction, this work illustrates the key role of historical maps, ortophoto maps and free satellite images to collect data on the natural elements of past landscapes, territorial evolution and shoreline changes. The intense urbanization, that reaches the shoreline in several zones, and the exposure to many natural hazards (coastal erosion, marine inundation, fluvial flooding, salt water intrusion, subsidence) make the Volturno Coastal Plain (VCP) a good case study.

The shoreline variations for nine time intervals (1817–2012 time span) and the coastal trend for 1957–1998 and 1998–2012 time windows were assessed. The latter trend was also assumed as a scenario to identify the possible shoreline position for the year 2022. This data is integral part of the Coastal Management framework (Alberico et al. 2017) which already hosts data (e.g. urban areas, population, municipality boundary, censal district scale, historical documents) and contains procedures to identify the coastal zones where land use changes can be functional to risk reduction. The noticeable flexibility of this framework allows to register many other types of environmental data (e.g. climatic, land-use, soil erosion, human activities) as well as hazard data on both natural (e.g. floods, earthquakes, salt water intrusion) and anthropic (fires, explosion, diffusion of pollutants) events.

In the last centuries, the shoreline evolution at VCP was similar to other coastal areas along the Tyrrhenian and Adriatic coasts. The erosion prevailed at the river mouth while the areas close to the delta were generally in accretion or stable thanks to the redistribution of eroded sediment from the delta apex (Aucelli et al. 2009; Bellotti 2000; Pranzini 2001; Alberico et al. 2011). During the 1817–1860 time span the coast was in erosion; this condition was probably a consequence of reclamation works realized during the Bourbon domain that caused a reduction of river sediments supply to the coast. In the following years and until the sixties, the coastline of VCP was in progradation; only a narrow zone close to the Volturno River mouth was in erosion, likely due to the reduction of river sediments supply to the coast after the construction of the *Ponte Annibale* dam on Volturno River. Starting from these years, the construction of 3 new dams, 10 artificial barrages and the extraction of sediments from the Volturno Hydrographic Basin caused the reduction of sediment necessary for beach nourishment in the time interval 1962–1992. Moreover, the construction of 52 sea protection works, the

Fig. 10 The coastal trend for 1957–1998 (a) and 1998–2012 (b) time windows. For the latter time window, the map illustrates the shoreline trend of 12 zones superimposed to the shaded relief of Volturno Coastal Plain. The table reports the maximum, minimum and mean values for the single zone



Zone	Transect	Max (m/yr)	Min (m/yr)	Mean (m/yr)
A	12-24	2,17	0,15	0,86
B	25-39	-2,36	-0,03	-1,47
C	40-48	1,58	0,04	0,57
D	49-52	-0,54	-0,04	-0,21
E	53-61	3,4	0,87	2,07
F	62-69	-4,22	-1,26	-2,49
G	70-79	7,47	0,08	2,96
H	80-88	-2,97	-0,49	-1,47
I	89-93	1,95	0,31	1,41
L	94-107	-4,43	-0,13	-2,14
M	108-137	2,51	0,01	1,07
N	138-145	-2,07	-0,03	-0,93

Zone

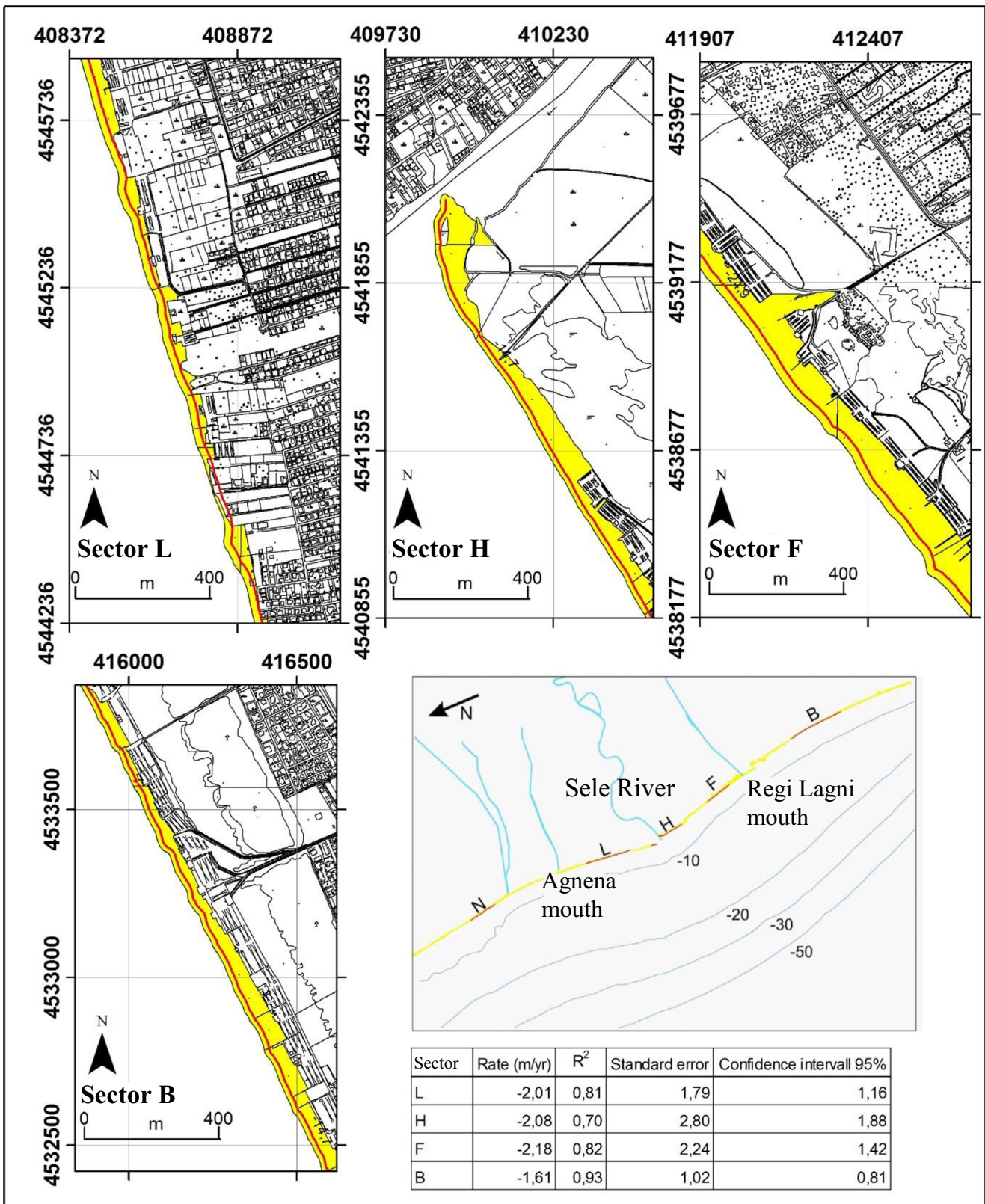


Fig. 11 The red line illustrates the possible position of coastline for the year 2022 in the four sectors (L, H, F, B) (for location see also Fig. 10). The map on the bottom right side of figure illustrates the location of these sectors along the *Volturno* Coastal Plain while the table shows the rate and

the statistic parameters showing the accuracy of the model. For the sector “N” also in erosion, the available data does not allow the identification of a trend value

urban environment growth and the destruction and degradation of dune vegetation favored the increase of instability conditions in the VCP.

The coastal dynamics changed along the investigated period; the delta recorded the decrease of sediment supply during the progressive changes from progradation, stabilization toward initial disequilibrium (rotational behavior) to the advanced disequilibrium (small-scale cannibalization). As reported in Fig. 9, there is a clear shift in sediment budget: all the pre-II World War conditions up to the post-II World War time (1957) indicated a clear accretionary behavior, linked to the large amount of sediment supplied by the river. From 1957 to 1998 interval, a classical rotational behavior of both sides of the delta, possibly due to intervention in the *Volturno* basin occurred (i.e. construction of dams and barrages and sediments quarrying from 1962 to 1992). The critical time of radical change of the erosional/depositional style is represented by the alternating erosional/depositional cells in the more recent time span 1998–2012. This could be considered an example of short-scale cannibalization, occurring when a deltaic coastline is sediment starved (Simeoni et al. 2007).

The erosional rate, assessed from 1998 to 2012, was assumed as a reference value to draw a reasonable location of the coastline for the year 2022. The overlay of this shoreline on the Technical Maps of Campania Region allowed the identification of urban areas possibly exposed to erosion in the future. In detail, the rate of -2 m/yr, typifying three (sectors: L, H, F) out of four sectors in erosion, could expose to damages several buildings close to the coast (Fig. 11).

The rapid growth of the urban environment without rules in the sixties (Frallicciardi and Cerisano 2013), lead to the present-day territorial status: a northern sector characterized by a wide urbanized environment (1,5 km depth from the coast) close to the shoreline, separated by Mondragone urban center by a narrow sector that still preserves natural features; a southern sector with a Natural Reserve (Variconi Oasis) and urbanized environment, except for Villaggio Coppola, far from the shoreline. For these areas, according to Alberico et al. (2017) a risk reduction through the natural environment restoration could be functional because the greatest part of urban environment close to the coast is inhabited all year long. In this frame, the past land-use (the Mediterranean maquis, pinewood, belts of psammophyte and halophyte vegetation, wetlands areas and ponds) was considered a good guide to identify the measures to make this environment resilient.

The flexibility of the system here proposed also ensures the possibility to archive shorelines from a monitoring activity making it possible to analyze the shoreline with a detailed spatial and temporal scale at a fixed time interval.

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