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Human influence over 150 years of coastal evolution in the Volturno delta system (southern Italy)

Daniela Ruberti[1] · Marco Vigliotti[1] · Anna Di Mauro[2] · Roberto Chieffi[2] · Michele Di Natale[1]

Abstract This paper focused on the past shoreline change rates along the coastal plain of the Volturno River, in southern Italy, western Mediterranean. A wide database comprising historical maps, aerial photographs, topographic sheets, bathymetric data was used to extract the spatial and temporal information of the coastlines at seven time points. Coastline displacement was calculated for two successive time points and relative surface variation (accretion and erosion) was estimated as well as minimum and maximum accretion/erosion linear values and rates. The surface variation analysis has revealed that the studied coast can be considered homogeneous since the 1970s, whereas it exhibits a variety of shoreline evolutionary trends after that time period. Timing and causes of trends and rates of variation were detected. Based on the estimated shoreline change rates, an appropriate morhodynamic one-line model was applied to predict evolutionary scenarios also in presence of port and defence works. The results obtained strongly emphasize that a successful coastal management requires a constant monitoring of the human-induced changes to account for the variability of rates over time.

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Introduction

Sandy coastal systems of the Mediterranean represent fast-responding and mobile geomorphic systems that are highly sensitive to environmental changes. On a long-term scale, coastal variability is mostly conditioned by relative sea level oscillations and river discharge, both driven by climatic changes. On a decade scale, changes in natural conditions and the influence of human actions will inevitably cause constant changes in coastlines which affect the coastal environment and, in particular, coastal wetlands and habitat distribution (Paskoff and Clus-Auby 2007; De Pippo et al. 2008; Pranzini 2008; Maiti and Bhattacharya 2009; Anthony 2014; Jabaloy-Sánchez et al. 2014; Zhu et al. 2016). The above activities and the related land use changes, for instance, have significantly altered, above all, the hydrographic system that supply sediments to the delta plains and the strandplains, contributing to accelerated coastal erosion with the consequent depletion of the coastal environment (Lotze et al. 2006; Airoldi and Beck 2007; Earle and Doyle 2008).

The problem of coastal erosion has been object of attentions and studies by the local governments and also at European level, so that in 2001 the General Environment Directorate of the European Commission launched the project EUrosion, a big initiative aimed at protect European coastal areas and quantify the impact and the conditions of coastal erosion in Europe (EUrosion 2007). The observations obtained from the EUrosion study, through study cases, have revealed that coastal erosion is often a consequence of a cumulative impact of various factors, both natural and human, and none of them individually may be considered as the main cause of erosion. This is the case of dams, industrial development, tourism (marinas, promenades), urbanization, sediment mining and defense works. The study EUrosion showed that, while the protection is possible, on the other hand extreme

events could exceed local coastal defenses with a negative impact on the resilience of a much larger sectors of coastline.

With this respect, studying temporal coastline changes and coastal land use are important issues in terms of Integrated Coastal Zone Management planning and for designing coastal defence (Sesli et al. 2009; Zhu et al. 2016, among others). Along sandy coasts, shoreline can change at different temporal scales. On a short-term scale (i.e. annual to seasonal), complex and interrelated factors contribute differently to the coastline migration; the response time of shoreline to each factor may be different. Long-term trends encompass periods from decades to centuries during which coastal variability is mostly conditioned by sea level changes and sediment supply (Eliot and Clarke 1989; Paskoff and Clus-Auby 2007; Bowman and Pranzini 2008; Walsh 2014). The assessment of such long-term changes usually minimises the quite rapid variation in time and space that occur at a seasonal-to-annual scale and this is true especially in the Mediterranean microtidal settings (Eliot and Clarke 1989). Long enough datasets of historical coastline changes are necessary to detect shoreline trends and identify causes of coastal erosion, in order to properly address mitigation actions (Crowell et al. 2005).

Coastal changes are surveyed using a variety of methods and datasets, according to the time period investigated. The most common techniques used for small spatial and temporal scales are beach topografical profiling, 3D surveys, high resolution satellite images, among others (cf. Anfuso et al. 2007; Bowman and Pranzini 2008; Maglione et al. 2015). The detection of shoreline position at long and medium temporal scales was usually carried out using ancient and recent maps, aerial photographs, satellite images (Basile Giannini et al. 2011). Although this method have inherent errors that depend upon accuracy in shoreline digitalization, numbers of data points (for georeferentiation) and scale of analysis, on a large scale (some tens of years up to a century) shoreline changes determined with the above technique can be considered reliable (Bowman and Pranzini 2008).

Monitoring the morphological evolution of a beach plays also a key role in the application of shoreline change models to predict future variations over long term, also associated with coastal structures or beach nourishment. These models are based on the single line or multiple line theories and allow accurate shoreline change prediction after suitable calibration (Willis 1978, Hanson and Kraus 1989, Kamphuis 1992, Dabees and Kamphuis 1998; Karambas and Tortora 2008).

This paper focused on the past shoreline change rates along the coastal plain of the Volturno River, in southern Italy, western Mediterranean. This coast is fed by one of the largest drainage systems along the southern Italy. The dynamics of the whole coastal system dramatically changed in the last century following reclamation interventions and human pressure. Sediment supply to the coast have reduced resulting in increase of erosional processes.

A wide database comprising historical maps, aerial photographs, topographic sheets, bathymetric data was used to reconstruct the morphological evolution of the study area. In detail, specific aims are: i) reconstruct the coastline at different time point; ii) highlight non-uniform shoreline behaviour due to anthropic interventions through time; iii) apply an appropriate morphodynamic one-line model to predict evolutionary scenarios also in presence of port and defence works, based on the hystorical shoreline change rates.

Study area

Similarly to other Italian alluvial coastal plains (e.g. Di Rita et al. 2010, 2011; Bellotti et al. 2011; Giraudi 2011; Amato et al. 2012; Milli et al. 2013), the Volturno delta system formed as a wave-dominated delta system, which started to grow in the form of bay-head delta, with flanking strandplains forming beach-dune ridges partially enclosing lagoonal-marshy areas. The progradation of the Volturno delta created favourable conditions for the development of continental environments, characterised by marshes and wetland, as an integral part of the alluvial floodplain within the lower Volturno delta system. The formation of a mature sand bar complex offshore caused a progressive isolation of the former coastal lagoonal area from the open Tyrrhenian Sea and incorporation of the present-day Lake Patria into a back-barrier depression of the Volturno delta plain. About 2 ky BP, beach and lagoonal environments still persisted along the present coastal zone. The recent evolution of the coastal plain was characterized by overall coastal progradation and alluvial aggradation, with subsequent infilling of swamp areas by crevasse and overbank fluvial processes and return to continental environments. The remnant of these areas nowadays lies at an elevation between 0 and −2 m with respect to the present sea-level and most of the marshy areas that characterized this area until the beginning of the nineteenth century was reclaimed and drained in the last almost 3 centuries (Fig. 1). Moreover, the whole coastal plain is subjected to vertical land movements (Sacchi et al. 2014; Matano et al. 2016; Aucelli et al. 2016).

The Domitia coastal zone is considered a dissipative-type shoreline with a microtidal regime (Wright 1977; Wright et al. 1979; Orton and Reading 1993). The continental shelf is about 200 km wide and gradually decreases from north (about 40 km wide) to south (about 12 km wide) off the Volturno river. Within 5 m depth two orders of submerged sand bars attenuate wave energy as a result of friction (Cocco et al. 1982; Cocco and De Pippo 1988; Verde et al. 2013). The outer bar is almost parallel to the coastline with ridges located at depths of 2 to 3 m; the troughs are at depth of 5 to 5.5 m, about 200 to 300 m
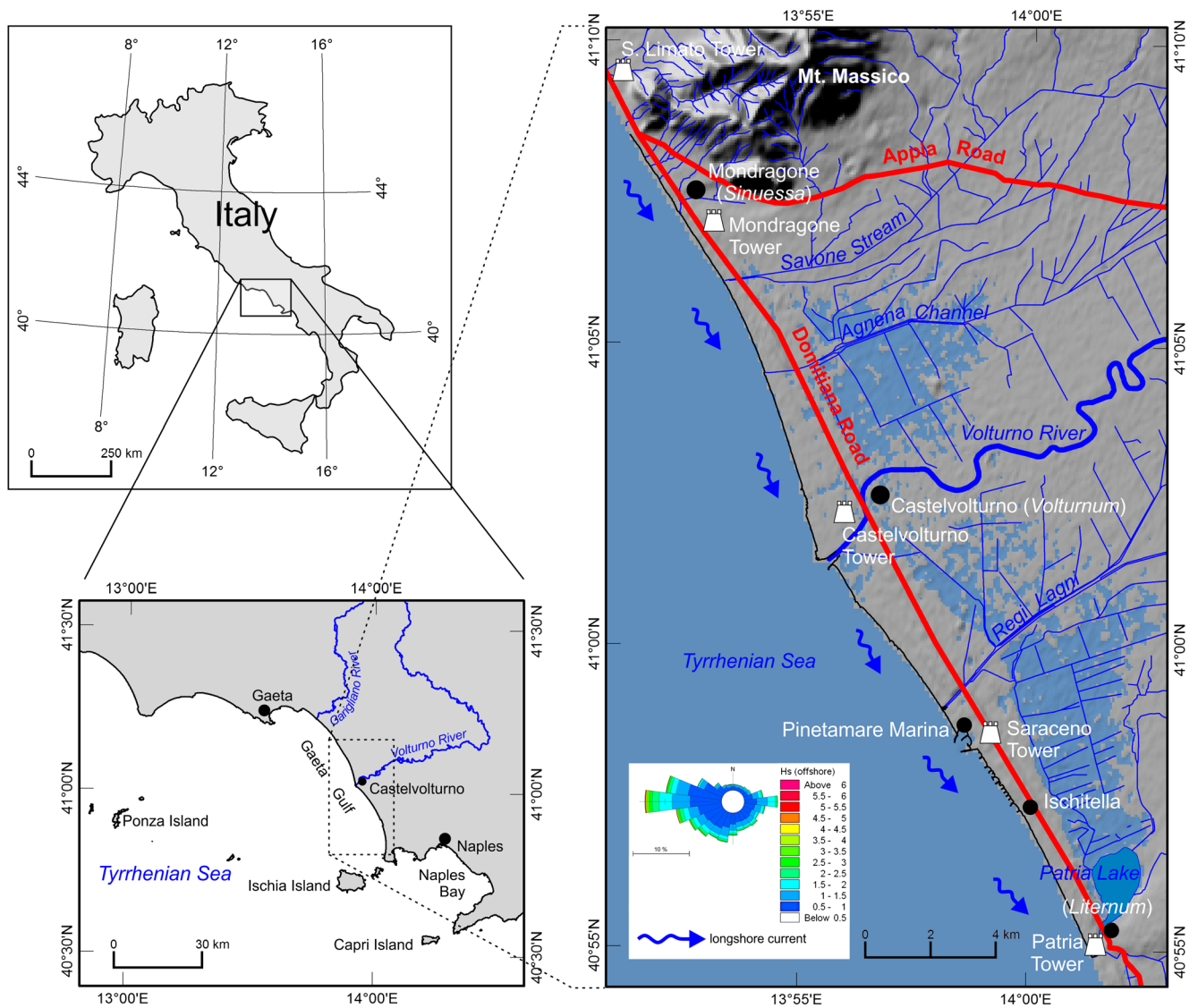
Fig. 1 Location map of the study area with the main landmarks mentioned in the text

from the shoreline. The inner bar is generally more irregular and articulated and is located at about 100 m from the coast; the ridge depth ranges between 0.5 and 1.5 m and the trough one between 2 and 2.5 m.

Table 1 Maps, aerial photographs and orthophotographs used in this study. *Incomplete coverage

Type of document	Author/Publisher	Date of detection/date of issue	Title	Scale	Pixel scale (m)
Map	Italian Military Geographic Institute	1876/unpublished	Carta dell'Italia meridionale Foglio 52 (parte occidentale) *Capua*	1:50,000	4.2 × 4.2
Map	Italian Military Geographic Institute	1954/1957	Carta topografica d'Italia	1:25,000	2.5 × 2.5
Aerial photographs		1974*		1:16,000	1.2 × 1.2
Map	Campania Region	1984/1987	Carta Tecnica programmatica Regionale	1:25,000	1.5 × 1.5
Orthophotos	Campania Region	1998	Orthophotos		1 × 1
Map	Campania Region	2004/2006	Carta Tecnica numerica Regionale	1:5000	0.4 × 0.4
Orthophotos	Spot Image	2011/2013	Orthophotos		0.5 × 0.5

Fig. 2 One-line cartesian plane showing the x (longshore coordinate) and y (shoreline position) axis. **a**) and **b**) boxes refer to location of Fig. 8 a and b respectively
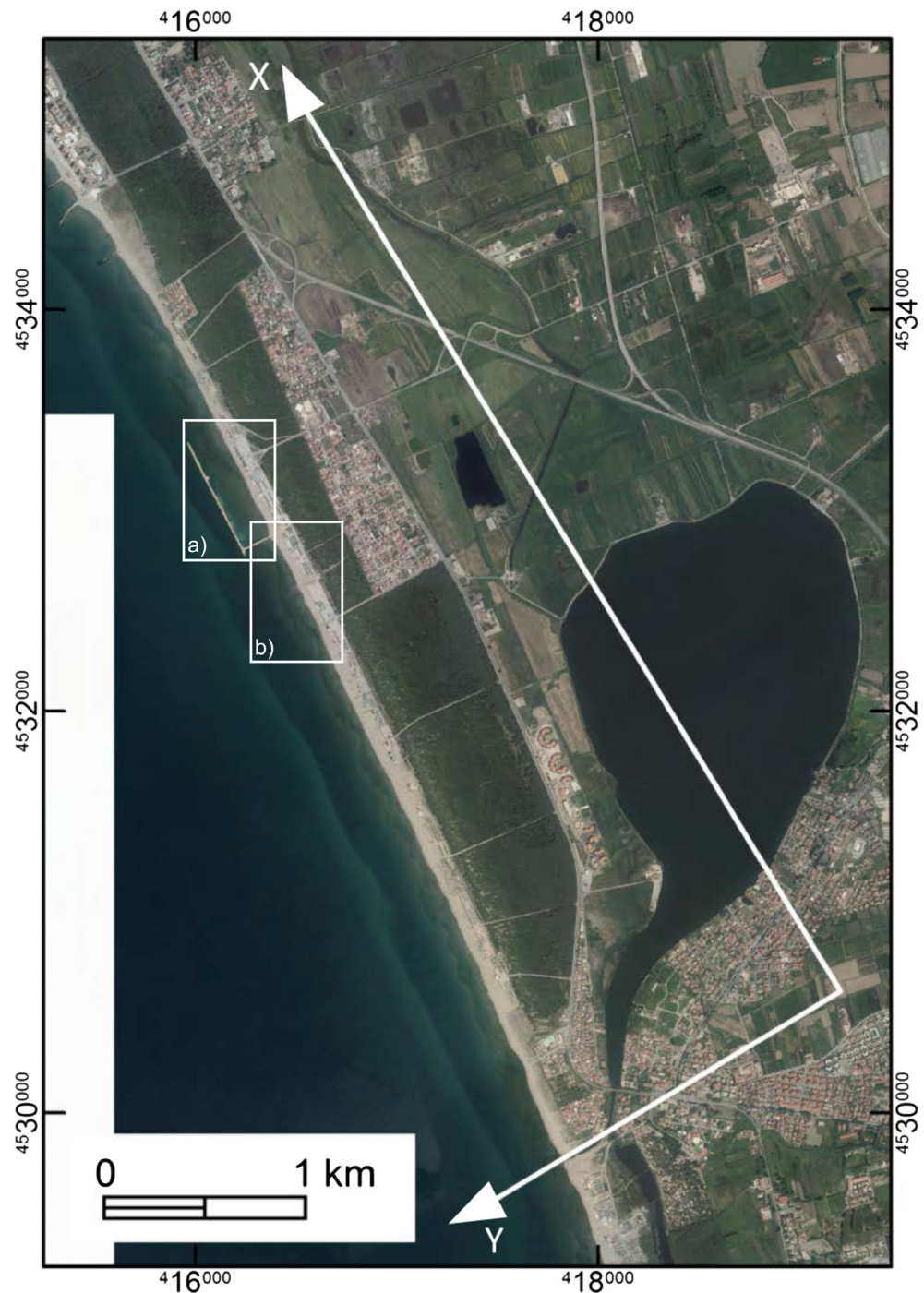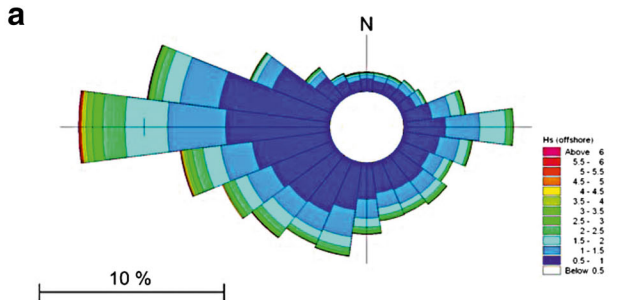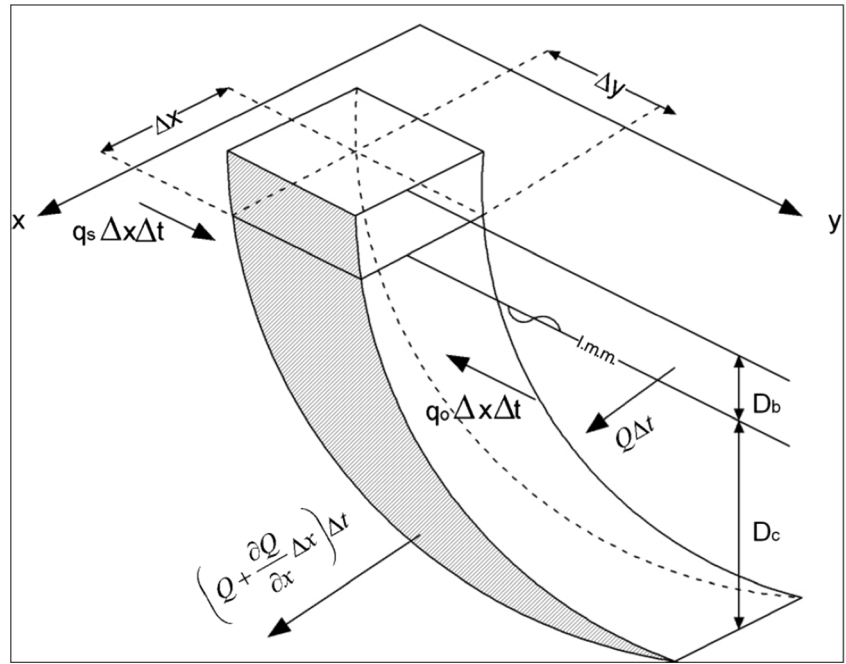

By a sedimentological point of view, the Domitia coast is characterized by medium-fine sands up to 5 m in depth and about 250 m from the shoreline (De Pippo et al. 2003, 2008).

Predominant wave directions are from W (N255°-285°) with average wave heights between 0.9 and 2.2 m (data for 2007, from Idromare-Apat, http://www.idromare.it/, Naples station); the maximum wave height is about 5 m for the 167.5° -172.5° direction (SE). with a longshore littoral drift toward SE.

We considered as morphological boundaries of the study area Mount Massico, to north, and Patria Lake outlet, to south. The longshore coherence of this 30 km long coastal segment inside the Gulf of Gaeta incorporates sediment source, homogeneous inner shelf characteristics, homogeneous littoral morphology. For this reason the studied setting can be considered as large-scale, homogeneous coastal behavioural segment.

Fig. 3 Reference sketch of the one-line model. For detail refer to text

Hs [m] Dir [°N]	< 0.5	0.5 1.0	1.0 1.5	1.5 2.0	2.0 2.5	2.5 3.0	3.0 3.5	3.5 4.0	4.0 4.5	4.5 5.0	5.0 5.5	5.5 6.0	6.0 6.5	6.5 7.0	>7.0	Tot
0 - 15	480	345	156	54	31	13	7	0	2	0	1	0	0	0	0	1089
15 - 30	419	337	157	65	39	16	12	7	0	0	0	0	0	0	0	1052
30 - 45	431	346	179	80	36	19	3	3	3	1	0	0	0	0	0	1101
45 - 60	496	376	204	67	34	11	6	1	1	0	0	0	0	1	0	1197
60 - 75	694	645	297	147	46	16	4	2	1	0	0	0	0	0	0	1852
75 - 90	936	1407	1160	615	149	44	15	3	2	0	0	0	0	0	0	4331
90 - 105	1011	1606	1047	433	102	42	13	3	6	0	0	0	0	0	0	4263
105 - 120	927	1167	480	195	72	34	7	4	2	0	0	0	0	0	0	2888
120 - 135	1008	997	492	233	82	37	13	2	1	0	0	0	0	0	0	2865
135 - 150	1131	1036	524	251	109	37	16	2	2	1	0	0	0	0	0	3109
150 - 165	1052	954	504	208	125	47	9	6	1	0	0	0	0	0	0	2906
165 - 180	1188	974	639	228	108	43	16	6	2	0	0	0	0	0	0	3204
180 - 195	1413	1396	808	306	175	56	26	9	4	0	0	0	0	0	0	4193
195 - 210	1954	1714	770	301	133	59	23	9	4	1	1	0	0	1	1	4971
210 - 225	2353	1474	645	322	154	68	41	8	7	9	5	1	0	0	0	5087
225 - 240	2498	1545	848	426	236	110	55	33	9	10	7	2	1	3	1	5784
240 - 255	2630	2049	884	510	254	101	62	28	24	10	2	1	2	1	3	6561
255 - 270	3257	2625	1410	938	466	312	165	103	43	41	7	9	2	4	1	9383
270 - 285	3863	3534	2166	1312	572	253	116	65	38	59	31	21	3	4	1	12038
285 - 300	3522	2041	560	152	88	36	21	10	9	4	2	2	3	0	2	6452
300 - 315	1865	888	337	109	67	29	14	7	3	1	1	1	0	1	0	3323
315 - 330	857	433	177	65	37	22	6	1	3	2	0	0	0	0	1	1604
330 - 345	527	359	154	50	26	17	12	7	4	1	0	0	0	0	0	1157
345 - 360	401	321	132	53	35	21	10	5	0	5	0	0	0	0	0	983
TOT	34913	28569	14730	7120	3176	1443	672	324	171	145	57	37	11	15	10	91393
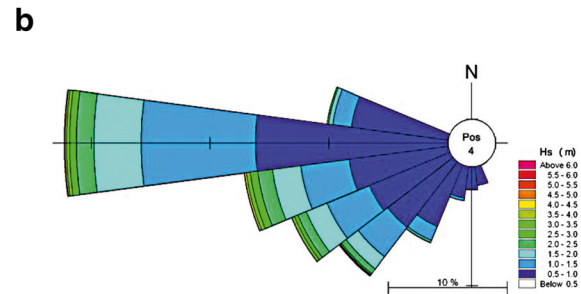
Hs [m] Dir [°N]	< 0.5	0.5 1.0	1.0 1.5	1.5 2.0	2.0 2.5	2.5 3.0	3.0 3.5	3.5 4.0	4.0 4.5	4.5 5.0	5.0 5.5	5.5 6.0	6.0 6.5	6.5 7.0	>7.0	Tot
0 - 15	7879	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7879
15 - 30	979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	979
30 - 45	811	0	0	0	0	0	0	0	0	0	0	0	0	0	0	811
45 - 60	420	0	0	0	0	0	0	0	0	0	0	0	0	0	0	420
60 - 75	315	0	0	0	0	0	0	0	0	0	0	0	0	0	0	315
75 - 90	242	0	0	0	0	0	0	0	0	0	0	0	0	0	0	242
90 - 105	214	0	0	0	0	0	0	0	0	0	0	0	0	0	0	214
105 - 120	254	0	0	0	0	0	0	0	0	0	0	0	0	0	0	254
120 - 135	254	1	0	0	0	0	0	0	0	0	0	0	0	0	0	255
135 - 150	387	2	0	0	0	0	0	0	0	0	0	0	0	0	0	389
150 - 165	2259	60	0	0	0	0	0	0	0	0	0	0	0	0	0	2319
165 - 180	2443	399	1	0	0	0	0	0	0	0	0	0	0	0	0	2843
180 - 195	1679	374	12	0	0	0	0	0	0	0	0	0	0	0	0	2065
195 - 210	2046	748	105	2	0	0	0	0	0	0	0	0	0	0	0	2901
210 - 225	3475	1326	378	110	21	3	0	0	0	0	0	0	0	0	0	5313
225 - 240	3132	1516	917	414	171	67	37	15	10	2	0	1	0	0	0	6282
240 - 255	2860	1750	745	416	168	82	42	16	3	4	0	0	0	0	0	6086
255 - 270	3683	2744	1807	820	444	211	108	72	21	3	0	0	0	0	0	9913
270 - 285	6855	3477	1258	443	102	29	11	1	0	0	0	0	0	0	0	12176
285 - 300	2982	304	40	1	0	0	0	0	0	0	0	0	0	0	0	3327
300 - 315	297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	297
315 - 330	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52
330 - 345	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
345 - 360	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOT	43522	12701	5263	2206	906	392	198	104	34	9	0	1	0	0	0	65336

Fig. 4 (**a**) Offshore and (**b**) nearshore wave rose. The tables below display the number of wave events classified according to wave height and direction (**a**) offshore and (**b**) nearshore

Table 2 Cumulative surface variation expressed as accretion and erosion

INTERVAL	Accretion (m²)	Accretion rate (m²/y)	Erosion (m²)	Erosion rate (m²/y)	Relative surface variation (m²)
1876–1954	7,825,274.90	99,054	242,615.80	3071	7,582,659.10
1954–1987	694,941.80	20,439	759,503.00	22,338	- 64,561.20
1987–1998	487,960.00	40,663	591,478.70	49,289	- 103,518.70
1998–2004	215,480.50	30,782	195,038.30	27,862	20,442.20
2004–2011	171,040.00	21,380	161,601.00	20,200	9439.00

The coastline in ancient time

Among the morphological changes of the landscape induced by land reclamation, the Volturno River delta plain and related strandplain variation is perhaps the most striking. Amorosi et al. (2012) and Sacchi et al. (2014) provided a datailed stratigraphic architecture and the evolution of the coastal plain during the Holocene and Recent, in line with the evolution of many Mediterranean delta (Bellotti et al. 1994, 1995; Aguzzi et al. 2007; Milli et al. 2008; Amorosi et al. 2009; Jabaloy-Sánchez et al. 2010, Jabaloy-Sánchez et al. 2014; Petropoulos et al. 2015; among others). The stratigraphic reconstruction, intergrated with the analysis of historical cartography and documents, suggests that from the Roman times to the XIX century, not only the delta system but the entire coastline has experienced progradational trends. Cocco et al. (1992) have reconstructed the Roman shoreline on the basis of numerous archaeological documents of the coastal area between *Sinuessa* and *Volturnum*, and the ancient route of the *Via Domitiana* (Fig. 1). In the northern part, the old shoreline can be located on the sea of the urban perimeter of the ancient ruins of *Sinuessa* (now partly below sea level); the landside of the village should have been uninhabitable owing to the widespread large swampy and marshy settings, as reported in the Strabo Chronicles. In the southern section, the coastline matches the remains of the ancient *Via Domitiana*, up to the city of *Volturnum* (Pennetta et al. 2016).

No data is available of the shoreline configuration for the period between the decline of *Sinuessa* (V-VI century A.D.)

and the Middle Ages. The shoreline from the mid XVI century can be positioned with the presence of towers and coastal defenses built between 1532 and 1563 during the Spanish viceroyalty (Fig. 1). By matching the shoreline with the line connecting the towers present in the area, it can be assumed that, from the Roman age, a progradation of the coast between a few tens of meters, in the *Sinuessa* area, and more than 600 m, in the Volturno river mouth area (maximum progradation rate of 0.5 m per year) took place.

The analysis of the historical cartography of the period between 1500 and 1700 and the comparison with recent maps up to the present, provide a sufficiently exhaustive picture of the evolutionary trend of the littoral. The shoreline was characterized by a continuous progradation with decreasing values from 100 m at 10 m per century, proceeding from southeast to northwest (Cocco et al. 1992).

Nevertheless, since the end of the XVI century gross land reclamation was performed under the Spanish viceroyalty resulting in relevant landscape and hydrographic changes. Most of the reclamation interventions were completed in the first decades of the 1900's and thus the coastal plain escaped direct human impacts. Since the second half of the XX century, built up land areas overgrew to the sea, wetland reduced dramatically and landscape fragmentation increased significantly (Ruberti et al. 2014; Ruberti and Vigliotti 2016). As a consequence of the negative sedimentary budget deriving from the reclaiming actions on the river courses, accelerated, severe coastal erosion was recorded since the beginning of the 1900's. The evolution of the shoreline since this time will be discussed in detail in the following paragraphs.

Table 3 Minimum and maximum linear shoreline displacements for each time interval. In gray the time interval used to evaluate the shoreline displacement in the delta area. *Incomplete coverage

| Interval	Num. years	Accretion zone				Erosion zone			
		max (m)	rate (m/yr)	average (m)	rate (m/yr)	max (m)	rate (m/yr)	average (m)	rate (m/yr)
1876–1954	79	654	8.3	291	3.7	348	4.4	123	1.5
1954–1974*	21	61.8	2.9	25	1.1	403.2	19.2	48.4	2.3
1974–1987*	14	123.1	8.8	44.5	3.1	344.2	24.6	48.4	3.4
1954–1987	34	178	5.3	49	1.5	532	16	47	1.4
1987–1998	12	97.2	8.1	30.1	2.5	147.2	12	42	3.5
1998–2004	7	50.4	7.2	13.2	1.8	50	7.1	13.2	1.8
2004–2011	8	123.3	15.4	13.8	1.7	47.4	5.9	10	1.2
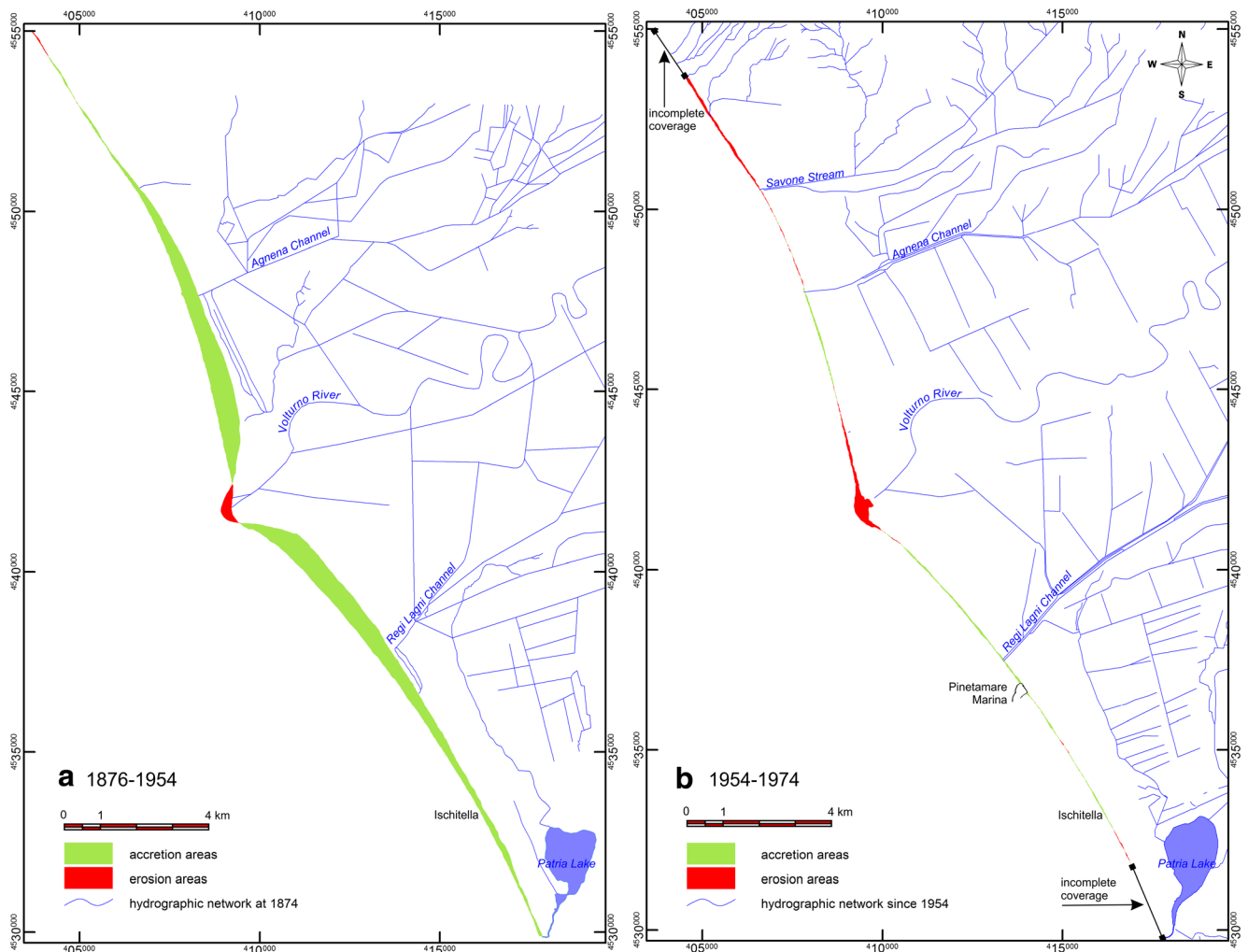
Fig. 5 Graphic representation of the surface analysis variation results for each time interval

Methods

Cartographic dataset

The shoreline changes occurred in the coastal area were assessed by means of aerial photographs, maps and orthophotographs spanning between 1876 and 2011, at scales from 1:5000 to 1:50,000 (Table 1). The above documents ensure a complete coverage of the whole area, 30 km long (Fig. 1). For the 1970s the photogrammetric flight was not complete; nevertheless it was used as representative of the beginning of the great anthropic impact and urban sprawl. Those points of the shoreline characterized by minimum-to-null variability during the observed period were selected as northern and southern end points of the analyzed coastline segment.

The above documents have been acquired in raster format and georeferenced in the reference system UTM 33 - WGS 84, through the GCP (Ground Control Points) technique, using as base map the georeferenced Technical Regional Map (CTR) of the Campania Region (1:25,000 scale). Around 100 GCPs

were identified on each document in order to achieve the most reliable accuracy. Data have been managed with GIS using the software Intergraph Geomedia Pro 6.1.

Shoreline evolution assessment

The spatial and temporal information of the coastlines was extracted at seven time points (1876, 1954, 1974, 1987, 1998, 2004, 2011). We used the water line at the time of the mapping as shoreline proxy. This was possible as the study area is characterized by a microtidal regime. We are aware of the uncertainties in mapping shoreline position owing to short-term fluctuations; nevertheless, the available cartographic record spans over 100 years and so it can be considered reliable (Bowman and Pranzini 2008). The estimates of long-term trends remove the "noise" of short term variability due to severe storms and seasonal changes (Douglas and Crowell 2000; Zhang et al. 2002). The large gap between 1876 and 1954 is mostly due to the lack of cartographic documents; nevertheless, the main landscape and land use modifications occurred since the second half of the XX
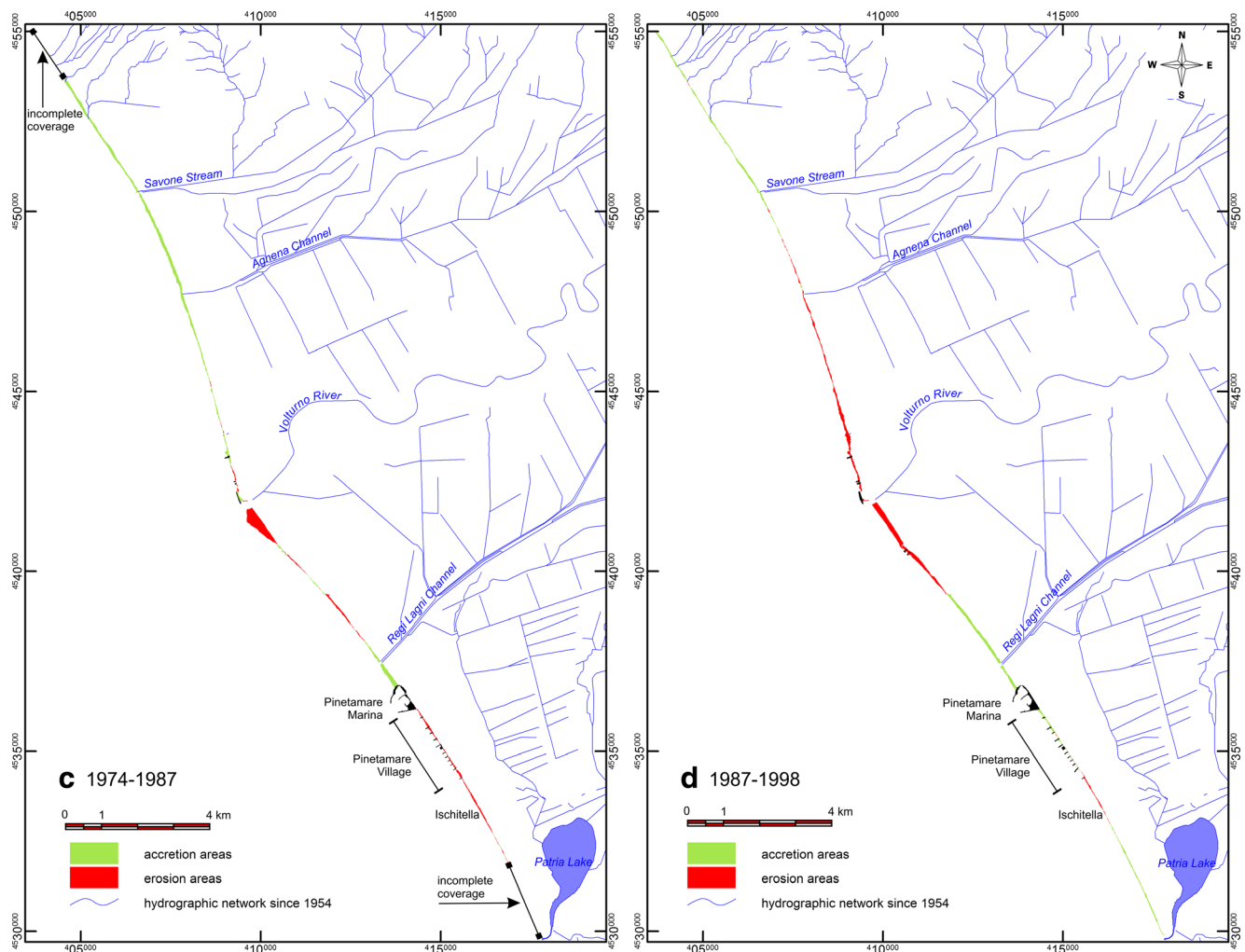
Fig. 5 (continued)

century, as a consequence of the land reclamation previously mentioned.

After identifying the position of the shoreline proxies for each document, they were digitized on GeoMedia Pro 6.1. Shoreline normal transects, 5 m spaced, were drawn and coastline displacement was calculated for each transect for two successive time points (for approximately 5600 transects). Relative surface variation (accretion and erosion) was estimated as well as minimum and maximum accretion/erosion linear values and rates. The transect spacing was chosen in order to better evaluate the response of shoreline stretches which underwent anthropic interventions (construction of coastal structures such as groins, breakwaters, marinas).

Assessment of trend evolution

Mathematical modeling of shoreline change has proven to be a useful engineering technique for understanding and predicting the evolution of the plan shape of sandy beaches

(e.g. Thomas and Frey 2013, ref. therein). In particular, mathematical models provide a concise, quantitative means of describing systematic trends in shoreline evolution commonly observed at groins, jetties and detached breakwaters and produced by coastal engineering activities such as beach nourishment and sand mining.

One-dimensional coastal morphology models (one-line models) are simplified models that have demonstrated practical capability in predicting long-term shoreline change (Willis 1978, Hanson and Kraus 1989, Kamphuis 1992, Dabees and Kamphuis 1998). The one-line concept rests on a common observation that the beach profile maintains an average shape that is characteristic of a given coast, apart from times of extreme change as produced by storms; the one-line model essentially solves two simple simultaneous equations: the equation of conservation of sand mass and the equation of sand motion.

According to the one-line assumption that the beach profile moves parallel to itself out to a limiting depth of closure (d_C), the equation of conservation of mass for an infinitely small
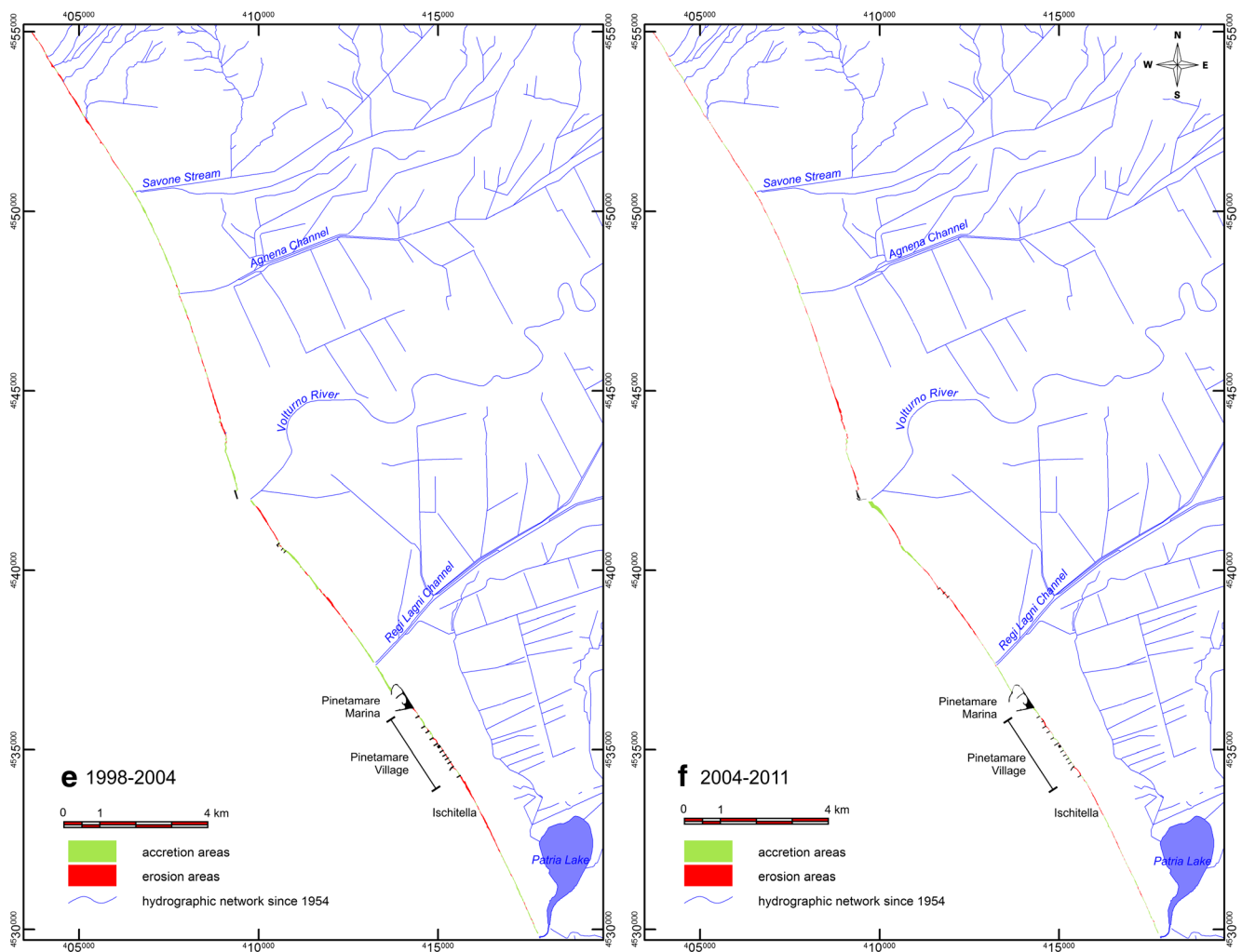
Fig. 5 (continued)

length of shoreline Δx can be expressed as follows (Kamphuis 1992):

$$\delta y/\delta t = -1/(D_c + D_b)\,(\delta Q/\delta x + q) \tag{1}$$

where y is the shoreline position, x is the longshore coordinate (Fig. 2), t is the time, Q is the longshore sediment transport, q represents the average on-offshore transport rate, D_c is the closure depth and D_b is the beach berm height (Fig. 3).

The longshore sediment transport rate expression is given by the CERC formula (Shore Protection Manual 1984):

$$Q = K_c H_{sb}^{5/2} \sin(2a_b) \tag{2}$$

where H_{sb} is the breaking significant wave height and α_b is the angle of breaking; the constant K_c is a function of breaking index H_{sb}/h_b (where h_b is the breaking depth), fluid and sand density and beach porosity. The value of K_c is estimated during the calibration phase of the model, by referring to two known shoreline positions at two different years and running the model from the initial to the final year, until the "modeled" line is approximately next to the "real" one.

One-line model predicts the evolution of a beach over a prolonged period of time. It uses the assumption that all changes to the beach are caused by changes to the rate of sediment transport due to waves (via longshore drift). In our case, the eqs. (1) and (2) have been solved numerically by using the finite difference technique proposed by Kamphuis (1992).

The model takes also into account the effects of hard coastal structures such as groins and breakwaters. These features allow more viability in solutions when considering beaches with different scenarios (including technical, economic and social feasibility). The model takes into account the effects of groins by introducing a by-pass coefficient C_i ($C_i < 1$) that reduces the Q-value in correspondence of each groin i-cell; the coefficient C_i is a function of the ratio between the length of the groin and the distance of the closure depth line from the shoreline.
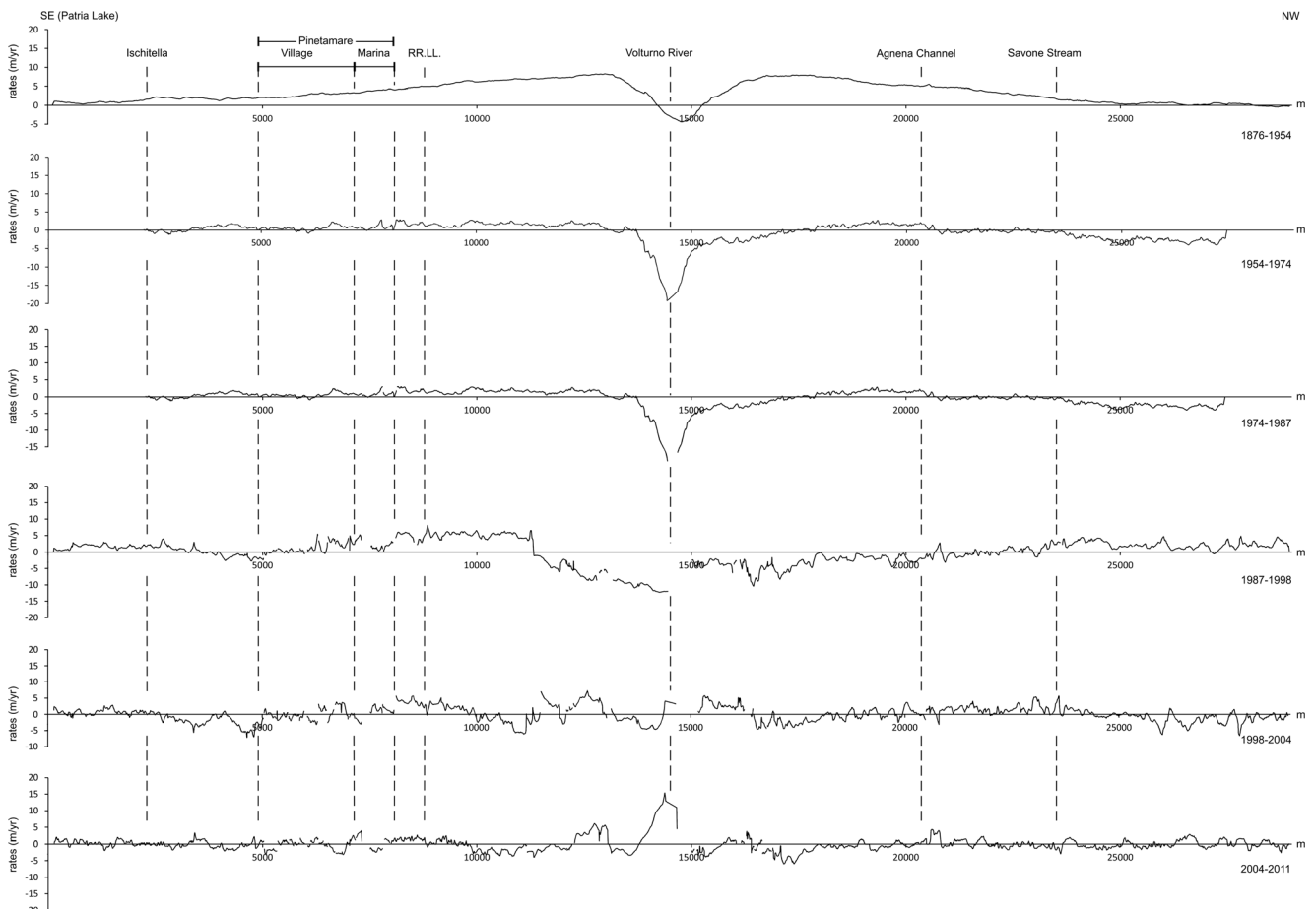
Fig. 6 Rates of shoreline changes recorded in the six time intervals. Labels indicate the main landmarks mentioned in the text

Vice versa, the effects of detached breakwaters are taken into account by applying an adequate transmission coefficient K_t (K_t < 1) to the wave incident height; typical values of K_t are 0.10–0.20 for emerged and 0.50–0.60 for submerged breakwaters.

For the studied coastline, the following data have been used (based on the Erosion Plan from Basin Authority of Liri-Garigliano and Volturno Rivers 2009):

i) the wave climate offshore obtained by using an hindcasting model calibrated on wave direct measurements made at the station of Ponza Island (Fig. 4a);

ii) near shore wave climate, assessed by means of appropriate numerical propagation model (Fig. 4b).

Based on the above results, the analysis of shoreline evolution was performed with the aim of the one-line prediction model.

The model calibration has been performed by referring to the analysis of historic evolutionary trend of the shoreline previously described. Particularly we referred to 2011 (shoreline derived by orthophoto as in Table 1) and 2016 (shoreline derived by topographic survey); the best value of K_c obtained in the calibration phase was about 5×10^4 m$^{1/2}$ year^{-1}.

The initial condition are given from the initial position of the shoreline at $t = 0$ (year 2016), while the boundary conditions have been assigned by fixing $\delta Q/\delta x = 0$ at the two ends of the model (Fig. 2).

The model has been used to forecast shoreline position for ten years (between 2016 and 2026) for the most impacted stretch of coast which corresponds to the sandy beach extended between the southern end of Pinetamare Marina on the outlet of Patria Lake to south (about 5 km).

Results

Long-term shoreline evolution

The surface variation analysis has revealed a variety of shoreline evolutionary trends since the 1970s. Table 2 and 3 display a synthesis of coastal change rates for each time interval; a graphic representation is given in Fig. 5.

On the whole, up to the 1970s the delta mouth was eroded at very high rates, whereas the coastline south and north was characterized by an apparent progradation (Fig. 5a, b). Since the end of 1970s the delta was completely eroded, the whole delta area underwent a general retreat and a slight accretion is detected only in the extreme sectors of the coast (Fig. 5 c,d).
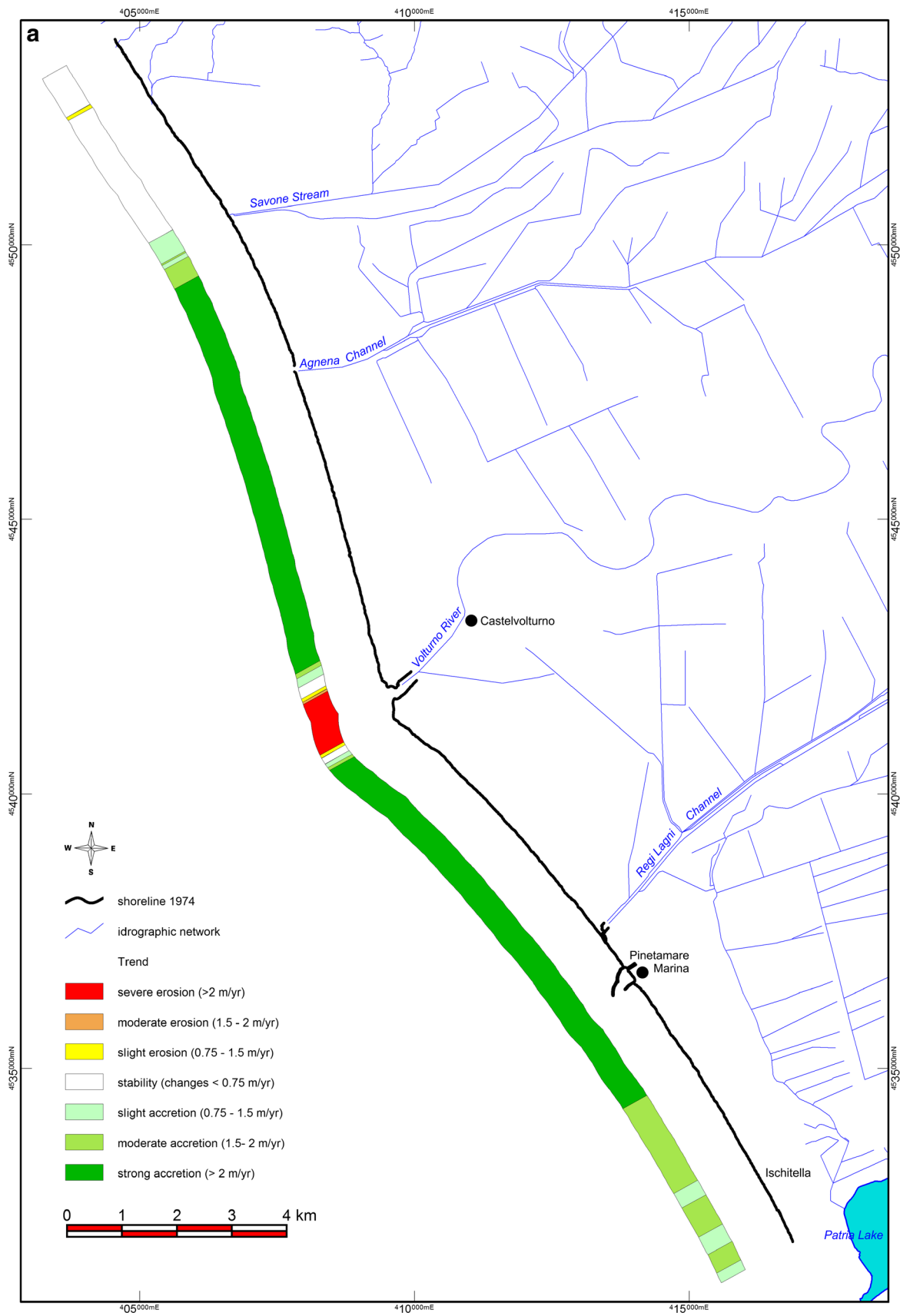
Fig. 7 Main trends in shoreline displacement between 1876 and 1974 (a) and 1974 and 2011 (b) in the study area
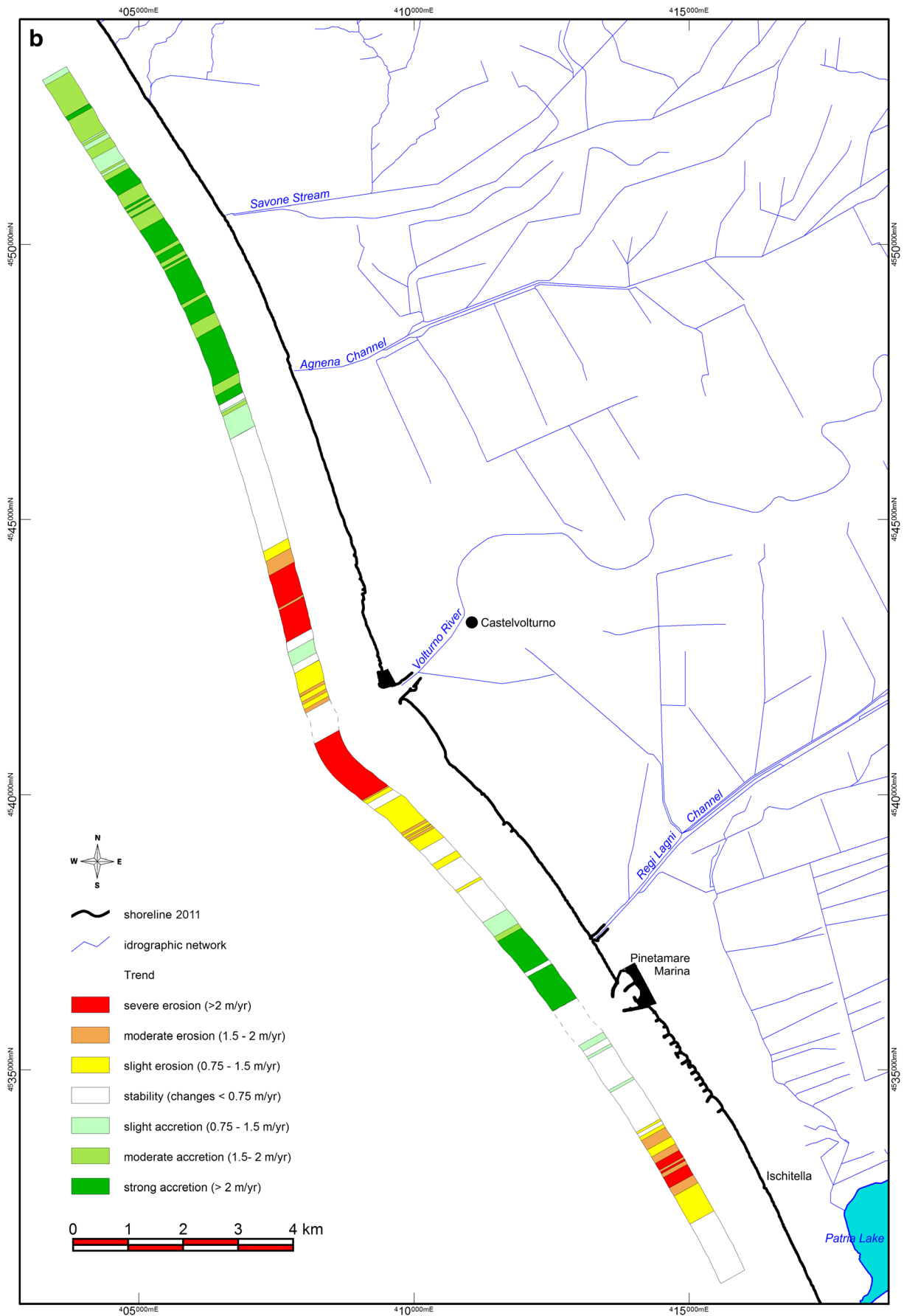
Fig. 7 (continued)

From now on, the displacement pattern became discontinuous (Fig. 5e, f), the surface variations being limited and mean accretion/erosion rates decreasing. An asymmetric retreat of the delta mouth is documented in a very short-term monitoring (i.e. 1974–1987), with retreating rate of 24 m/yr. of the left side. Apart of the delta mouth, the southern sector was the most severely affected by shoreline erosion and characterized by a great variety of trends. The coastline north of the Volturno delta showed a more regular erosional trend up to the end of the '900. Here, about 26 ha of beach and dune were lost in two decades, with mean retreat rate of 5 m/yr. in the stretch between the Volturno and the Agnena Channel. This extreme erosion trend was observed in about 30 years and reached slower regression rate since the 2000s.

A graphic representation of the rates of the above changes is given in Fig. 6. In Fig. 7 an overall pattern of prevailing erosion, stability or accretion along the considered coastline is shown, defined for two time interval, 1876–1974 and 1974–

2011, as the '70s appear the turning point of changes in rate and homogeneity of shoreline variations.

Simulation of shoreline evolution

The calibration of one-line model with the shoreline assessed through the GIS analysis demonstrated the good reliability of the application. The evaluation was performed with the 2011 and 2016 shorelines; a good correspondence with the measured shoreline and the estimated one was assessed (Fig. S1 – supplemental electronic material).

Fig. 8 shows the forecasting of shoreline position in 2026 along the stretch of Ischitella beach, taking into account the presence of the submerged breakwater offshore and also the groins downdrift the Pinetamare marina. The forecast encompasses a 10 year time interval. Data were calculated each 100 m along the x axis (Table 4). Main results are:
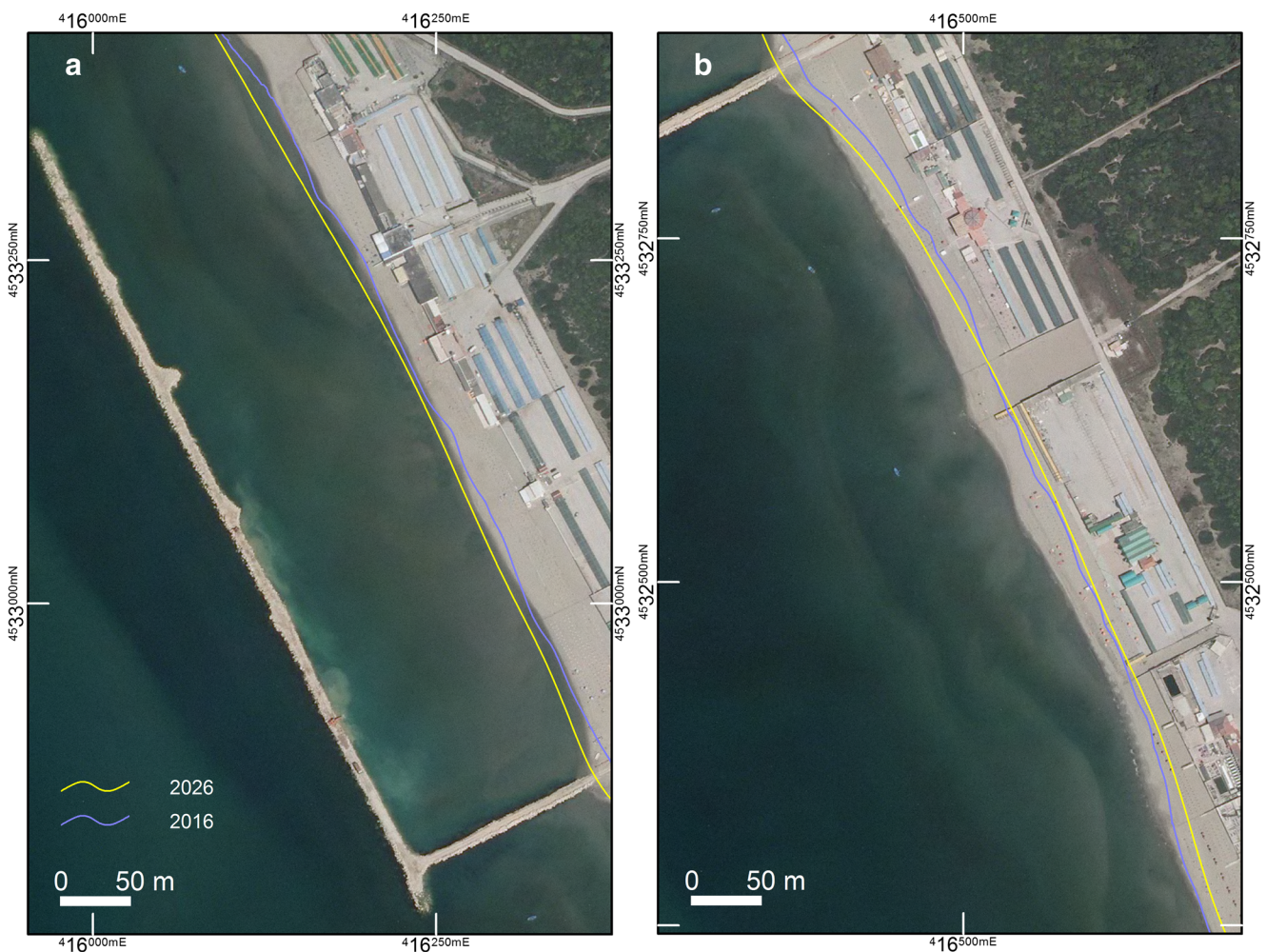

Fig. 8 Close-up of the shoreline position forecast for the 2026, based on the one-line model calculations. Note the retreat estimated downdrift the existing breakwater. See Fig. 2 for site location

Table 4 Linear shoreline displacements for each X-chainage value calculated for the time period 2011–2026 (+ accretion; − erosion). Reference axis as in Fig. 2

X [m]	Δ [m]
50	31.25
150	−25.27
250	−20.51
350	−18.70
450	−16.20
550	−13.14
650	−12.24
750	−15.10
850	−11.37
950	−5.50
1050	−1.27
1150	−16.04
1250	−25.70
1350	−24.08
1450	6.70
1550	0.95
1650	−5.40
1750	−10.53
1850	−9.60
1950	−10.84
2050	−12.06
2150	−12.08
2250	−18.01
2350	−23.54
2450	−22.06
2550	−16.75
2650	−0.79
2750	−9.81
2850	−8.54
2950	−3.59
3050	−2.67
3150	−1.98
3250	6.95
3350	18.55
3450	13.81
3550	9.00
3650	8.60
3750	4.93
3850	10.20
3950	12.15
4050	8.37
4150	8.40
4250	14.20
4350	14.13
4450	8.06
4550	11.73
4650	8.61
4750	15.49
4850	11.42
4950	8.33

i. Ischitella beach behind the existing breakwater (L = 810 m): 1 m/yr. accretion rate; the defence structure seems to have a positive effect in reducing erosion.

ii. Ischitella beach downdrift the breakwater up to Patria Lake (L = 3400 m): 1.5 m/yr. erosion rate. The presence of the breakwater seems to crush the coastal dynamics downstream the barrier, causing erosion at relatively high rates.

Discussion

The long-term erosion rates and trends assessed in this work allowed to highlight the trajectories of geomorphological change occurred along the Volturno coastal plain, focusing on the possible drivers for local variability. In the last almost two centuries, the human influence on the fluvial dynamics has prevailed over climate and volcano-tectonic controls, as documented for other deltas of the Peninsular Italy (e.g. Bellotti et al. 2007; Pranzini 2007; Simeoni and Corbau 2009; Amorosi et al. 2013). The draining of the wetlands, initiated in the XVI century, allowed anthropogenic changes in land use and land cover (Ruberti and Vigliotti 2016), especially in the coastal plain, and forced the delta system toward a "man-made river-dominated signature" (*sensu* Maselli and Trincardi 2013). The reclamation interventions were based on river water diversion and canalisation, with the aim of elevating the land surface by filling the marshy areas with alluvial sediments, eventually completely modifying the drainage network (Viparelli 1965). In the lower alluvial plain, more than 500 km of canals were built up to the first half of the 1900, most of which were removed or destroyed in the following years (Ruberti and Vigliotti 2016).

The reclamation, coupled with the first anthropic interventions along the coastal and catchment area, had the effect to reduce the volume of sediment available for the sedimentary balance; moreover, in 1953 and 1976 began the construction of two main barrages which went into operation in 1977 and 1986 respectively, resulting in the reduction of sand supply to river mouth. In addition, the demand for sand for increasing construction purpose led to widespread mining activity in the middle of the twentieth century. All this strongly influenced and altered river dynamics.

The impact of both river catchment and land use changes induced by human activities along the Mediterranean coasts has been considered the main cause of reduction in sediment supply to the coast (e.g. Surian and Rinaldi 2003; Hooke 2006; Wohl 2006; Boix-Fayos et al. 2007; Hoffmann et al. 2010; Aiello et al. 2013; Anthony 2014; Anthony et al. 2014) and had severe effects on many deltas and adjacent coasts (e.g. Anthony et al. 2014; Pranzini et al. 2015).

As a matter of fact, a continuous erosional trend was registered in the last century. Up to the 1970s, the erosion at the delta mouth triangle was the most impressive phenomenon (Fig. 5a, b), although an apparent progradation characterized the coastline to north and south. The apparent and ephemeral coastal advance can be explained by considering that the Volturno, like many other Mediterranean deltas, has evolved in symmetrical form, from cuspate to arcuate (*sensu* Wright and Coleman 1973), subjected to bi-directional drift that leads to sediment redistribution along the delta flanks (Pranzini 2001). The eroded sediments of the cuspate delta apex were gradually stored by longshore transport along the lee-side and

Fig. 9 Effects of the coastal erosion on the urbanized coastal area north of the Volturno delta (Ph. M. Vigliotti)

the coastline south and north of the delta mouth prograded due to the erosion of the delta mouth istelf and the nourishment of the wings (Fig. 5a). At the beginning of the 1970s the delta evolved in an estuary and the whole coastline continued to retreat, affecting also those segments which were growing in the previous decades (Ruberti et al. 2008; D'Ambra et al. 2009; Donadio et al. submitted).

Since the 1970s, following a demographic growth driven by socio-economic interests, unplanned human interventions altered the continuity of the coast resulting in differential coastline evolution (Fig. 6). The beach-dune system was altered by the growth of the cities and touristic villages along the entire coast. Hot spot interventions designed to mitigate the shoreline erosion were initiated, but without a precise prediction of the trend that would have triggered; most of them were carried out over short lenghts of coasts, very often with end points corresponding to administrative boundaries, as the considered shoreline falls in three municipalities and two different provinces. Pranzini et al. (2015) provided an exhaustive overview of the coastal protection in Europe, outlining the different national approaches and the main effects of the above unplanned, hot-spot

interventions, which "failed to consider the impact on adjacent coastline frequently resulting in downdrift erosion and flood problems". The differential coastline evolution herein evidenced can be referred to such a wrong management policy, as discussed below.

1) In less than a decade, a massive sprawl urbanization, mostly illegal, took place along the delta mouth. Along the right side, urban area overgrew to the sea; beach erosion had high rate until the end of 1900, afterwards it decreased when the sea began eroding the built area. At present, many houses are destroyed and partly submerged (Fig. 9). On the left mouth side, the establishment of the protected wetland area has left the coastaline exposed to the erosion process; the complete delta destruction resulted in the whole coastline retreat and the asymmetrical erosion of the coast in the left side that left the lighthouse below sea level (Fig. 10).

2) Since 2002, submerged breakwaters were built from the Volturno delta towards north, for 1.8 km, and to south, for 2.9 km, to mitigate the erosion phenomenon and protect the buildings from waves and storms. The retreat of right
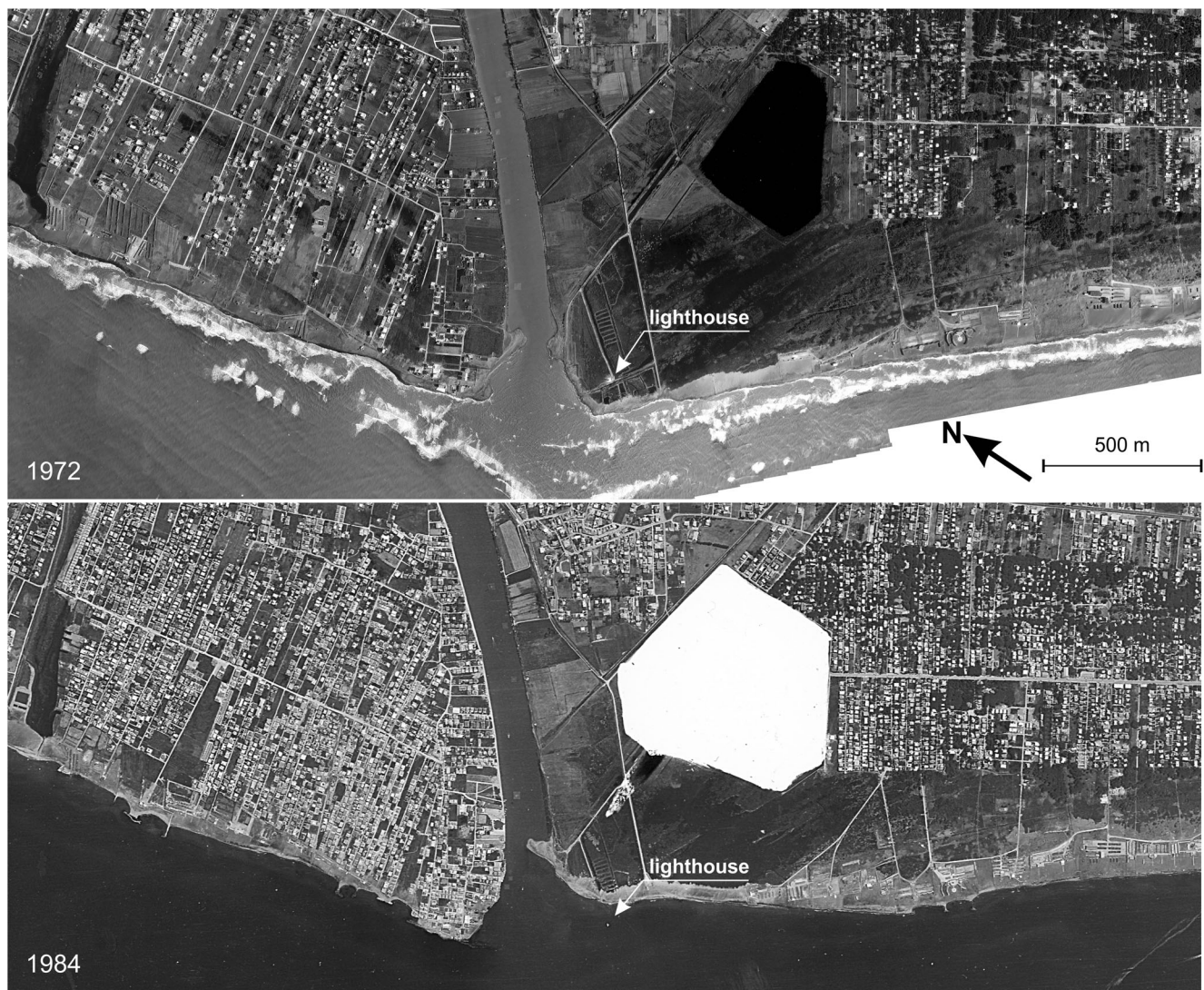
Fig. 10 Aerial photographs showing the strong urbanization of the right side of the river mouth and the asymmetric retreat of the coast in the left side occurred in less than a decade. In the latter side, about 200 m of shoreline retreat left the lighthouse below sea level

wing lasted while a slight progradation of left one occurred since 2004, behind the breakwater (Fig. 5e). Nevertheless, the small shoreline stretch immediately downdrift the breakwater was affected by increased coastal retreat (Fig. 5f).

3) The influence of protection structures (i.e. groins) and the construction of the Pinetamare marina were even more dramatic south of the Regi Lagni channel. Like most of the harbors (as outlined by Marriner and Morhange 2007 and Anthony et al. 2014), the above marina was created in a sheltered enclaves deriving from the lee of a spit at the Regi Lagni channel mouth (Fig. 11). This structure had to exert a strong influence on sedimentary dynamics alongshore. In the presence of longshore currents and of projecting structures (groins, ports, etc), the interruption of the sediment transport usually determines the disequilibrium of the coastline with accretions on one side of the

obstacle and erosions on the other. As a matter of fact, the southward littoral drift caused the frequent silting of the marina and the advance of the shoreline between the channel mouth and the marina breakwater; on the contrary, downdrift the port, accelerate erosion was recorded (Di Natale et al. 2017). For this reason, a dozen of groins were built along 2.2 km of coast to attenuate erosion during the 1980s (Fig. 12). Nevertheless, south of the above protection structures, the shoreline began suffering erosion, along with the touristic beach of Ischitella (Fig. 5 c, d, e). With the purpose to protect this latter, in 2011 a submerged attached breakwater began to be built for about 900 m over a 4500 m long beach stretch. Since the 2013 a slight shoreline advance was registered behind the breakwater, while erosion occurred downdrift. The forecasting of 10 year shoreline position performed with the one-line model confirms all the above considerations

Fig. 11 Evolution of the coastal stretch south of the Regi Lagni outlet. The Pinetamare Marina was built in the 1970s in the lee of a spit limiting the Regi Lagni outlet. Reference maps: 1817–1819 - Carta Topografica ed Idrografica dei Contorni di Napoli - Foglio 4; 1876 - Carta dell' Italia Meridionale - Foglio 52 parte occidentale - Capua; 1987- Carta Tecnica Programmatica Regionale Tavola 22

(Fig. 5): while the existing protection construction allows accretion rates of about 1 m/yr., downdrift it, instead, erosion will continue with high rates; for instances, in the next decade the Ischitella beach would suffer erosion rates of about 1.5 m/yr., with estimated loss of beach of about 3.4 ha in less than a decade, thus suggesting the importance of extending southwards the construction of protection structures.

Fig. 12 Shoreline evolution breakwater and downdrift the Pinetamare marina. It is noteworthy the shoreline accretion to north and the beach reduction to south, nowadays stabilized with a dozen of groins

The example of the Volturno coastal plain underlines the effects of anthropogenic pressures on coastal geomorphic changes in the absence of a sustainable management policy. The results obtained strongly emphasize that a successful coastal management requires a constant monitoring of the human-induced changes to account for the variability of rates over time, particularly in those areas where a strong anthropogenic impact has been highlighted. Therefore, given the socio-economic potential of the coast, the determination of long-term shoreline evolution and the forecasting of future shoreline position become fundamental source of information for

both scientists, decision maker and stakeholder in managing coastal environments and in designing erosion management master plans.

Conclusions

The aim of this study was to determine shoreline changes along the Volturno coastal plain over the last 150 years and analyse the detected spatial and temporal variability. Two main evolutionary trends in time were found. Until the

1970s, the erosion of shoreline was almost homogeneous, mainly caused by the alteration of the river catchment. The economic interests arised in the second half of the XX century forced tourism development and also engineering of the coast aimed at stabilising the shores. Indeed, the pervasive development often resulted in the destruction of aeolian dunes and the growth of urban fronts to the beach, thus increasing the erosion of the beach themselves. On the other hand, the "hot-spot" protections have caused localized beach accretion and severe erosion in other places; the predicted future shoreline position confirmed the disequilibrium observed through the long-term historical analysis.

Based on the present study, it can be concluded that long term time series of shoreline changes and the forecasts for coastline evolution provide important issues to understand the drivers for coastal changes and address management planning on short, medium and long term. Gaining knowledge on beach change processes increases our capability to manage risks, especially shoreline erosion, affecting the increasing population living in coastal areas.

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