ORIGINAL ARTICLE

Historical shoreline trend analysis and drivers of coastal change along the Ravenna coast, NE Adriatic

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Abstract

One of the most important aspects of coastal zone management is the analysis of shoreline dynamics. Over the last years, beaches of the Ravenna coast (NE Italy) experienced large modifications, in some places narrowing or even being completely lost, thus threatening tourism, coastal assets and nature. Coastal erosion has direct consequences for Ravenna tourist-based economy, which largely depends on the attraction provided by sandy beaches. In this study, long-term (> 50 years) coastal analysis was used to identify the sectors along the coast where the shoreline position has changed, either advancing or retreating. Shoreline changes were measured on GIS environment by means of Digital Shoreline Analysis System (DSAS) extension. Net Shoreline Movement (NSM) and Linear Regression Rate (LRR) strategies were employed to examine shoreline variability and reveal erosional/accretional trends. The results show that significant shoreline changes affected the entire coastal region, with most of the study area under retreat, mainly in the most valuable tourist assets of the littoral. The effects were found to be worsened by impacts of land subsidence, presence of harbor infrastructure and deficit in sediment budget. A simple shoreline classification was performed over the DSAS results and cross-checked with local knowledge of the area. The measurement of erosion or accretion rates in each studied segment is found to be useful for land use planning and coastal management plans, especially regarding the prediction of future shoreline positions. Especially important is the potential of the classification to identify areas of significant position change, with current and future implications for the design of sustainable shoreline management and mitigation measures.

Keywords Coastal erosion · Retreat · Accretion · Spatial analysis · DSAS

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Introduction

Coastal zones worldwide are facing many challenges, as changing shorelines and increasing human development pressures have caused serious threat to ecosystem integrity and acting processes (IPCC 2014). Whereas most of the assessments are assessed in a hazard-specific manner such as sea-level rise and storm surges (Perini et al. 2017; Muler and Bonetti 2014), multi-hazard approaches are gaining importance, acknowledging that coastal area is often exposed to more than one hazard and pointing to the diversity of coastal threats these regions may face (IPCC 2014). Likewise, many scientists adopt a multi-impact approach, meaning that a hazard can cause more than one impact such as erosion, flooding and salinization affecting the same coastal area (Addo et al. 2010; Bonetti et al. 2013).

Extreme weather events and associated coastal retreat are highlighted among the most serious threats affecting coastal environment and local communities (Global Risks Report

2016). The complex interplay of natural and anthropogenic processes is all capable of promoting beach erosion (Del Río et al. 2012). This has determined a growing attention towards studying shoreline changes (e.g., Dolan et al. 1991; Romine et al. 2012; Markose et al. 2016), potential impacts arising from coastal erosion (e.g., Ciavola et al. 2007; Katz and Mushkin 2013; Bonetti et al. 2018) and comprehensive analysis of accretion-erosion trends (e.g., Southgate et al. 2003; Esteves et al. 2009; Hapke et al. 2010). In an era when beach erosion is considered inevitable, understanding of shoreline behavior and contributing elements to coastal erosion are of major importance to coastal scientists, engineers and managers (Crowell and Leatherman 1999; Douglas and Crowell 2000). In this respect, gaining knowledge on factors driving coastal changes can increase the capability to deal with risks related to coastal retreat.

Shoreline management is increasingly concerned with adaptive responses to coastal changes (Nicholls et al. 2013). Shoreline change analysis is a well-developed field that has evolved rigorous data processing and analytical protocols (Dolan et al. 1991; Thieler et al. 2009). However, quantification of trends is only one aspect of the problem; understanding the drivers of change in a local context is crucial (Hapke et al. 2016). As progressive trends in shoreline and coastal system behavior tend to emerge over multi-decadal time-scales and at contemporary scale, it is fundamental to carry out integrated analysis of the available historical datasets (Rooney et al. 2003; Burningham and French 2017).

Quantitative information on shoreline position is vital to underpin varied aspects of coastal management, including flooding and coastal defense (Regnauld et al. 2004; Nicholls et al. 2013), climate change adaptation (Woodroffe et al. 2014; Sánchez-Arcilla et al. 2016) and coastal hazard and economic zoning (Ferreira et al. 2006; Gopalakrishnan et al. 2011). Knowledge of erosion rates can provide valuable information regarding effective beach width (Smith and Jackson 1992) and degree of beach loss (e.g., Genz et al. 2007; Del Río et al. 2013). Moreover, more studies on shoreline changes are getting conducted to determine suitable (or unsuitable) areas for land use development depending on their susceptibility to natural coastal hazards (Bathrellos et al. 2017). At the same time, quantitative assessment can help to solve management issues such as determination of appropriate coastal setbacks, wise land-use decisions and effective mitigation strategies (Bheeroo et al. 2016; Moore 2000).

Drivers of coastal change

Sandy shores are particularly dynamic systems where changes are associated with various factors and controlling processes influencing shoreline migration. Depending on the type of coastal setting shorelines exhibit distinct behavior. For example, coasts with different tidal ranges and wave energy incidences exhibit distinct coastal morphologies (Hayes 2013). A regional perspective and understanding is required, where shoreline changes in one beach should be viewed as a result of multiple influences and processes (Sexton and Hayes 1981). With respect to drivers of coastal change, these include natural physical forcing elements (e.g., storm events, changes in sea level, sediment supply) and human-induced factors (e.g., land reclamation, tourism development, coastal protection structures, land subsidence). Likewise, the analysis of geological and geomorphological setting is critical to contextualize shoreline changes (Komar 2000; Cooper and Navas 2004). Sea level rise is one of the main drivers of change in shoreline position, and it can accelerate coastal erosion (Umgiesser et al. 2010). Global sea level has risen 10–25 cm over the past 100 years, and it is predicted to rise another 50 cm (with some estimates as high as 98 cm) by 2100 (IPCC 2014). Shoreline migration has also been closely linked to the availability of sand to a coastal sediment transport system (Nicholls et al. 2007).

In fact, fluvial and alongshore sediment transport are of major importance for coastline shaping, so that any small change occurring in sediment supply usually is soon reflected on coastal morphology and morphodynamics (Elfrink et al. 1998). In this respect, dunes play a vital role in protecting sandy coastlines; they not only function as the first line of defense to the destructive forces of waves and storm surges, preventing or delaying flooding of inland areas, but they also operate as natural sand suppliers to eroded beaches during and after storms (Ciavola et al. 2007). When dunes can no longer undertake this protective function, coasts become vulnerable to erosion (Carboni et al. 2009). In addition to this, dunes are the recharge areas for coastal phreatic aquifers (Barbarella et al. 2015), where precipitation infiltrates and generates freshwater lenses. Worldwide freshwater lenses stored in dune areas are crucial to counteract saltwater intrusion (Mollema et al. 2013), as well as for human consumption (Okello et al. 2015). In this respect, increasing coastal retreat creates risks of groundwater salinization (Vandenbohede et al. 2014).

Human interventions on the coast, such as urban development, defense structures or infrastructure for recreational activities can also restrain shoreface sediment exchange and trigger or exacerbate shoreline displacement (Esteves et al. 2006; Matteucci et al. 2010). In fact, low-lying coasts with high levels of urbanization are often especially susceptible to storm impacts, including coastal erosion and flooding (Sekovski et al. 2015; Bonetti et al. 2018). Society's responses to threats imposed by shoreline retreat to infrastructure and development historically rely on armoring and other engineered forms of coastal defense (Nordstrom 2000; Dugan

et al. 2011). When combined, the aforementioned natural and anthropogenic forcing may have a synergic effect and increase the total displacement for a coastal area (Taramelli et al. 2014).

The Mediterranean basin has, in fact, been identified by the International Panel on Climate Change (IPCC) as a "hot spot" area "at risk of marine ingression, coastal erosion and land deterioration" (Coastance 2011). Within this context, the Ravenna province has one of the most threatened coastlines in the Mediterranean (Manca et al. 2013) and Europe (Eurosion 2004), highly vulnerable to widespread coastal erosion, seawater intrusion related to high sea level events known as 'acqua alta' phenomena, and ongoing land subsidence. About 4/5 of the Emilia Romagna coast is currently at a high risk of marine ingression (ARPA 2009). During next decades, the combined effects of land subsidence and of the sea-level rise in consequence of climate change are expected to increase shoreline instability, leading to a further retreat (Perini et al. 2017).

Despite many attempts to stabilize the coastline against erosional processes by establishing engineering frontage along the coast of Emilia-Romagna and several nourishment projects, the problem yet stands. In some cases, interventions may have solved erosion locally but have exacerbated it at other locations, or even have generated other environmental problems (ISPRA 2013). This has sparked our interest to develop a research on shoreline change analysis and determination of existing trends in Ravenna coast. Thus, the objective of this paper is to examine shoreline changes in the Ravenna coastal region over different spatial scales as a response to various coastal forcings and to delineate spatial segments based on the shoreline behavior.

Study area

Within the Adriatic coast, Ravenna province is a major tourist destination in Italy so-called the Riviera Romagnola, and holds one of the largest tourism industries in Europe. The wide sandy beaches are a major attraction for visitors (Semeoshenkova et al. 2016), but this unique coastal environment is fragile and affected by shoreline retreat to a great extent (Bertoni et al. 2005; Giambastiani et al. 2016). Among the many impacts, the coastline suffers from reduction of sedimentary resources, loss of coastal dunes and local land subsidence. In many places the combined effect of development pressures and natural processes has created 'coastal squeeze' issues.

Geographical setting

The study area is located in the Adriatic coast of northern Italy, and it belongs to the Ravenna province of the Emilia

Romagna region. It stretches for about 30 km alongshore, bordered by the mouths of river Reno (to the north) and river Savio (to the south). For practical purposes, the study area was subdivided into five sectors (Fig. 1) based on morphological features (e.g., river mouths) and differences in land use (e.g., urbanized/natural area), with the aim to better describe local dynamic patterns in different coastal settings.

Geomorphological and hydrodynamic setting

According to the shoreline classification based on tidal ranges proposed by Davies (1964) the Ravenna coast belongs to the microtidal type, with average tidal variations between 0.3 and 0.8 m for neap and spring tides, respectively. Prevailing winds in the study area are the so-called 'Bora' (ENE) and 'Scirocco' (SE) winds, which besides controlling general circulation in the North Adriatic Sea, are also responsible for generating northward longshore currents (ARPA 2009). However, at a smaller scale, there is a contrasting direction of local currents (north- and south-oriented) where the Ravenna harbor acts as a subdivision point.
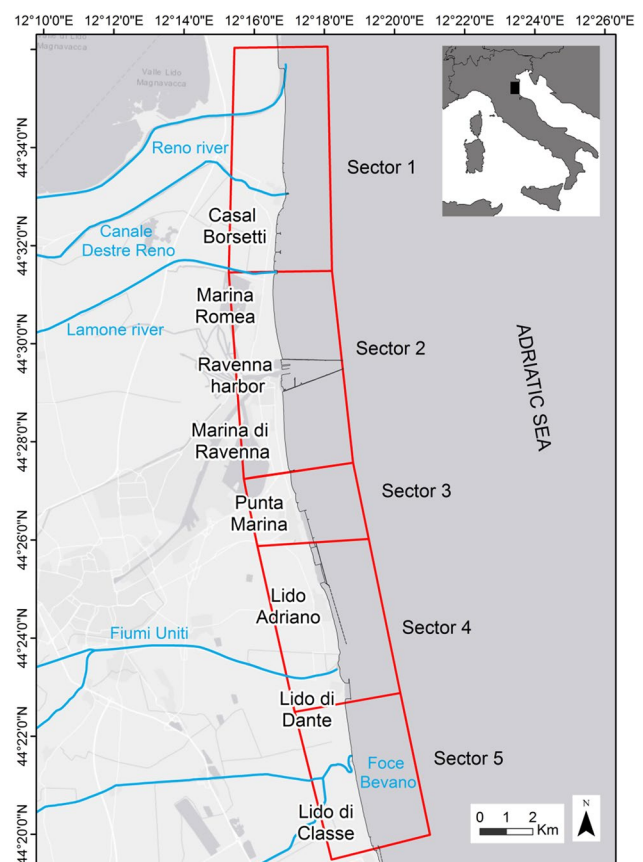

Fig. 1 Location map of the study area showing the main coastal features and locations referred to in the text. The area was divided into five sectors to allow further comparison among the study units. Basemap source: World Light Gray Base provided by ESRI©

Wave climate is characterized by a generally low wave energy, with 91% of significant wave heights below 1.25 m and maximum significant wave height of about 2.5 m (Perini et al. 2011). Prevailing wave approach direction is from the East with wave periods of 5–6 s (Ciavola et al. 2007). Most intense storms associated with highest water levels due to storm surge processes are mainly related to winter 'Bora' wind events.

From a geological point of view, Ravenna coast is characterized by very low elevations, not exceeding 2 m above mean sea level (Gambolati et al. 1999). As a part of the Po River plain it constitutes a sedimentary basin consisting of alternating sands, silts and muddy-clayey materials (Amorosi et al. 1999). The main source of fluvial sediment is the Po river (ARPA 2009). Several river mouths occur along the investigated area, namely Reno, Lamone, Fiumi Uniti, Bevano and Savio rivers (Fig. 1). The area is a mixture of urbanized, agricultural and natural coastal environments consisting of dissipative beaches with very gentle slopes (Perini et al. 2011), vegetated dunes and wetland areas around the river mouths.

Nowadays, about 60% of the Ravenna coast is engineered with the purpose to stabilize the coastline and prevent erosional processes (Nordstrom et al. 2015). Shore protection structures are widely distributed along the study area, mainly including detached breakwaters (semi- and submerged), groynes and revetments. The coast is greatly developed and exploited for tourism, and several urban areas are found along the study zone (Marina Romea, Porto Corsini, Marina di Ravenna, Punta Marina, Lido Adriano, Lido di Dante, Lido di Classe, Lido di Savio) (Fig. 1); they are nationwide known destinations for beach recreation. A total of 165 private beach establishments (locally known as *stabilimenti balneari* or *bagni*) are located within the coastal strip (Servizio Turismo e Attività Culturalì 2014), in many cases built very close to dunes and to the water's edge or directly replacing dunes, making them highly vulnerable to storms and generating serious problems of dune segmentation (Sytnik and Stecchi 2014).

Ravenna hosts valuable and protected coastal environments, as well as areas of historical and cultural heritage. The region falls within the Po Delta Regional Park, one of the largest protected areas in Italy included in the UNESCO World Heritage list. Besides, the region is in the scope of Natura2000 network, including Special Protection Areas (SPA's) and Sites of Community Importance (SCI). Coastal dunes of the Ravenna region have a special protection status and are included in the National Nature Reserve catalogue.

Materials and methods

Shoreline concept definition

When analyzing shoreline variability and its historical trends, a definition of 'shoreline' is required. Following Dolan et al. (1980) the shoreline in this study is interpreted as a dynamic boundary between water and beach surface which can be used as an indicator for analyzing erosion and accretion processes. Although vegetation line, dune toe or other morphological features could be better indicators of shoreline position according to several authors (Boak and Turner 2005; Esteves et al. 2009), the wet/dry line is the most commonly used proxy for detection of shoreline position and constitutes a reliable indicator of coastal change for many coastal areas (Smith and Zarillo 1990; Anders and Byrnes 1991; Sekovski et al. 2014; Serafim and Bonetti 2017), especially in microtidal environments and in low-declivity beaches such as the study area.

In this work shoreline extraction was performed in GIS environment by digitization of the wet/dry line identified on vertical aerial imagery (Fig. 2). The wet/dry line is defined as the line associated with a change in color/tone between the wet and dry sand (Boak and Turner 2005). Sampling of past shoreline trends was done by extracting shoreline from a set of available aerial photographs, which commonly constitute the primary data source for shoreline change studies (Crowell et al. 1991; Ryu et al. 2002) and generally yield satisfactory results (Leatherman 1983; Moore 2000).

Photo analysis and shoreline position change detection

A series of aerial photographs (1954, 1972, 1988, and 2000) and a satellite image from WorldView2 (2011) were used to assess temporal variations in shoreline position (Table 1). As the aerial photos were only available in hardcopy format, they were first scanned at high resolution. The WorldView2 image was a Standard Ortho-Ready product converted to the WGS84-UTM33N coordinate system. Aerial photos were georeferenced using ground control points (GCP) in ArcGIS 10.1 software and brought into a database with the satellite image. The five shorelines (using the wet/dry line as a shoreline proxy) were manually digitized on-screen, compiled as shapefiles and then imported into a geodatabase. Many studies of shoreline behavior suggest using a minimum time interval of 10 years between consecutive photos to obtain a more representative long-term shoreline trend (Elliot and Clark 1989; Dolan et al. 1991) by minimizing
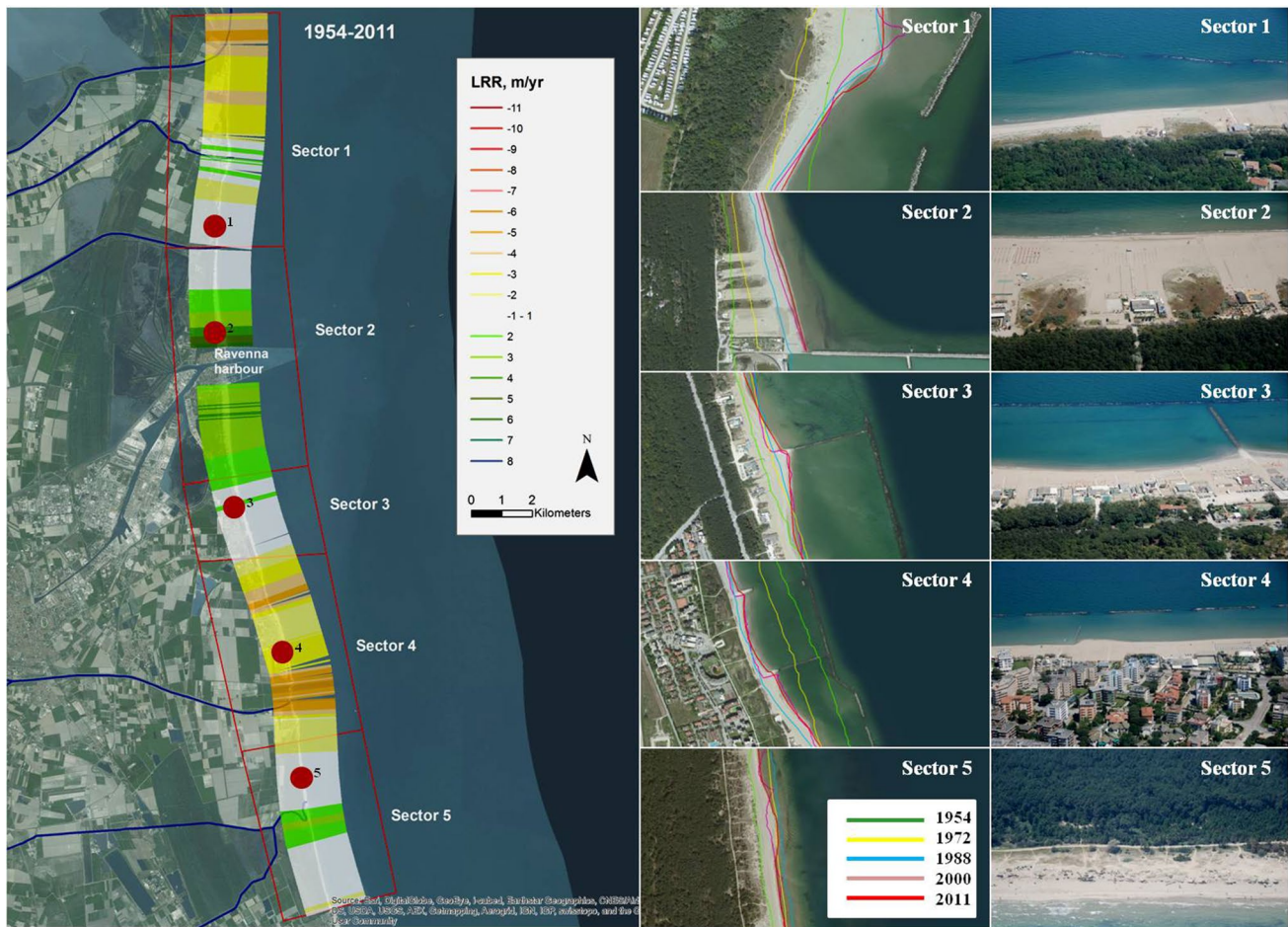
Fig. 2 Left: color marked transects representing long-term coastal displacement along the study area. Red dots indicate the positions of the examples shown to the right. Basemap source is provided by ESRI©. Center–right: examples of representative segments of each shoreline sector. Oblique images acquired during aerial survey on 8th August 2014

Table 1 Sources of historical data for shoreline extraction used in the study, where IGMI—Istituto Geografico Militare Italiano, CGR Spa—Compagnia Generale Riprese Aeree

Date	Data source	Contributor	Scale	Resolution (m/pixel)
24/06/1954	Aerial photography	IGMI	1:32,000	0.69
18/06/1972	Aerial photography	CGR Spa	1:23,000	0.55
03/06/1988	Aerial photography	IGMI	1:34,000	1.75
07/07/2000	Aerial photography	IGMI	1:29,000	0.65
11/05/2011	WorldView2 satellite	DigitalGlobe	–	PAN:0.46 / MUL:1.85

potential errors related to short-term variability. To exclude wintertime fluctuations and impacts of individual storms only photographs acquired in summer time were considered. Following this approach and based on the availability of aerial photographs, four time spans of 12–18 years were considered in this study (1954–1972, 1972–1988, 1988–2000, 2000–2011).

Uncertainties and potential errors

Several sources of error may affect accuracy of shoreline detection and digitizing of shoreline positions on aerial photographs, therefore affecting final rates of shoreline change (Moore 2000; Del Río and Gracia 2013). Common limitations are associated with positional uncertainties related to georeferencing (Genz et al. 2007) and identification of shoreline indicators (Crowell et al. 1991). The first one was minimized by properly georeferencing the aerial

photographs, with the use of a minimum of ten GCPs on each photograph, evenly distributed over the entire image.

Regarding the uncertainties related to the interpretation of shoreline position, excessive reflectance of sand on aerial images can hinder the proper identification of the wet/dry line on each examined photograph. However, the influence of shoreline position errors on long-term rates of change can be reduced because the period of analysis is long (> 50 years) (Romine et al. 2012). Images were acquired during late spring/summer time, so the seasonal component of shoreline dynamics (such as the influence of severe storms) was dismissed as major storms in the study area generally occur during late autumn–winter (ARPA 2009). Daily variations were neglected due to the time span of the analysis (> 50 years). Tidal influence was considered negligible (see 'geomorphological and hydrodynamic setting') and therefore was not accounted for as a source of uncertainty.

Digital shoreline analysis system (DSAS)

After all shorelines were digitized, rates of shoreline change were calculated in ArcGIS 10.1 using Digital Shoreline Analysis System (DSAS) version 4.3, an ArcMap extension developed by the USGS (Thieler et al. 2009). DSAS is a software tool adopted worldwide to compute rates of shoreline change in diverse coastal settings. It is reported to offer a high level of accuracy, allow error quantification and is more flexible than other techniques (Thieler et al. 2009; Addo et al. 2010; Romine et al. 2012). It employs the single-transect method to calculate rates of change on regularly spaced transects alongshore.

A total of 570 shore-normal transects were cast at 50 m intervals along the 30 km stretch of the investigated coast. An arbitrary landward baseline was established adjacent to the five shoreline positions to serve as a starting point for transects. The intersecting points between the transects and each shoreline were used to compute changes in shoreline position and calculate rate-of-change statistics for each transect. To keep transect numbering in sequence, sequential ID numbers were assigned along the baseline with the $ID = 1$ in the north of the study area (Reno river mouth). Shoreline changes were calculated, and three different parameters were obtained: Net Shoreline Movement (NSM), Linear Regression Rate (LRR) and R-Squared statistic (LR2), as defined in Thieler et al. (2009):

- The LRR statistics is derived from linear regression, by which the rate of shoreline change is calculated using a least squares regression line applied to all shoreline points at every transect. This method was selected because it has been shown to be the most statistically robust quantitative method for rate calculation (Crow-

ell et al. 1997; Manca et al. 2013; Perez-Alberti et al. 2013). It is also the most commonly applied technique for expressing shoreline movement and estimating rates of change (Deepika et al. 2013; Bheeroo et al. 2016).

- The NSM reports the total distance between the oldest and the most recent shoreline positions. This approach requires only two shorelines to enable the calculation. In this study, the available shorelines were examined in pairs in sequential order (i.e., 1954–1972, 1972–1988, 1988–2000, 2000–2011).

- In conjunction with linear regression rate, the R-squared of Linear Regression (LR2) was also reported. This dimensionless coefficient (coefficient of determination) reflects the linear relationship between shoreline points along a given transect, expressing the variance of the dependent variable (distance from baseline) as explained by the regression line. If all the values precisely matched the linear estimated trend, then R^2 would be equal to 1, while data without any relationship would have R^2 of 0.

Shoreline classification

A classification scheme was proposed for the study area to assess shoreline changes on the regional level using an objective method. The main purpose was to highlight general trends and to provide a relative measure of sensitivity to coastal retreat. The classification was developed using two variables: rate of change in shoreline position and percentage of eroding/accreting transects. Based on this, the classification assigns the coastal sectors (shown in Fig. 1) to a specific class representative of shoreline behavior. A number of classes was allocated to allow ranking from highest erosion to highest accretion. This way, for instance, a rate of − 1 m/year represents a relatively low level of erosion whereas − 3 m/year constitutes a high level of erosion. At the same time, a segment exhibiting 10% of eroding transects is considered as slightly erosional whereas a segment with 80% of eroding transects would be considered as highly erosional. However, a sector with a rate of − 1 m/year and 80% of erosional transects would be found as highly erosive, as almost the entire segment is experiencing erosion even at a relatively low rate. Likewise, a sector that recorded a higher rate of retreat but with less percentage of erosional transects would result in a lower erosive state.

In this way, a basic segmentation was proposed by combining shoreline change rates and percentage of eroding transects (Table 2). Each sector was assigned a certain class related to corresponding prevailing shoreline behavior. This allowed delineating general trends of the analyzed coastal system.

Table 2 The five classes shoreline classification scheme proposed in the study assigns different classes of erosion and accretion to the area, where shades of red and green are used to denote low, moderate, high and very high erosion and accretion, respectively

| Percentage of transects | Linear regression rates (m/year) | | | | | |
| | Erosion | | | Accretion | | |
	0/ −1	−1/−2	−2/−3	0/+ 1	+ 1/+2	+2/+ 3
0/10	Stable/no erosion	Low	Low	Stable/no accretion	Low	Low
10/20	Low	Moderate	Moderate	Low	Moderate	Moderate
20/50	Moderate	High	High	Moderate	High	High
50/70	High	Very high	Very high	High	Very high	Very high
70/100	Very high	Very high	Very high	Very high	Very high	Very high

Grey color indicates stability for both erosional and accretional classes

Results

Historical shoreline changes were measured on the 570 transects distributed at 50 m intervals along the study area over the 1954–2011 period. Long-term rates of shoreline change were determined at each transect by taking the slope of the regression line (LRR) applied to all five shoreline positions. Medium-term distances and rates were obtained using the two closest shorelines in consecutive order (1954–1972; 1972–1988; 1988–2000; 2000–2011). The results were color-coded with green colors indicating accretion and orange-red indicating erosion. Table 2 along with Figs. 2, 3 present the synthesis of the obtained results.

It should be noted that in this study, temporal coastal changes were considered as following the classification proposed by Crowell et al. (1991), i.e., long-term changes for a timeframe > 50 years, whereas medium- and short-term referred to a 10–50 and < 10 time period, respectively.

Long-term changes

This study revealed a general long-term erosive trend with little accretion at most portions of the Ravenna coast. Sectors 1 and 4 were the most erosive ones, with mean rates of shoreline change of − 1.75 to − 2.70 m/year, respectively (Table 3). Maximum recession rates were recorded at the north of Reno river mouth (sector 1) and in the vicinity of Fiumi Uniti (sector 4). Despite overall erosional trend in
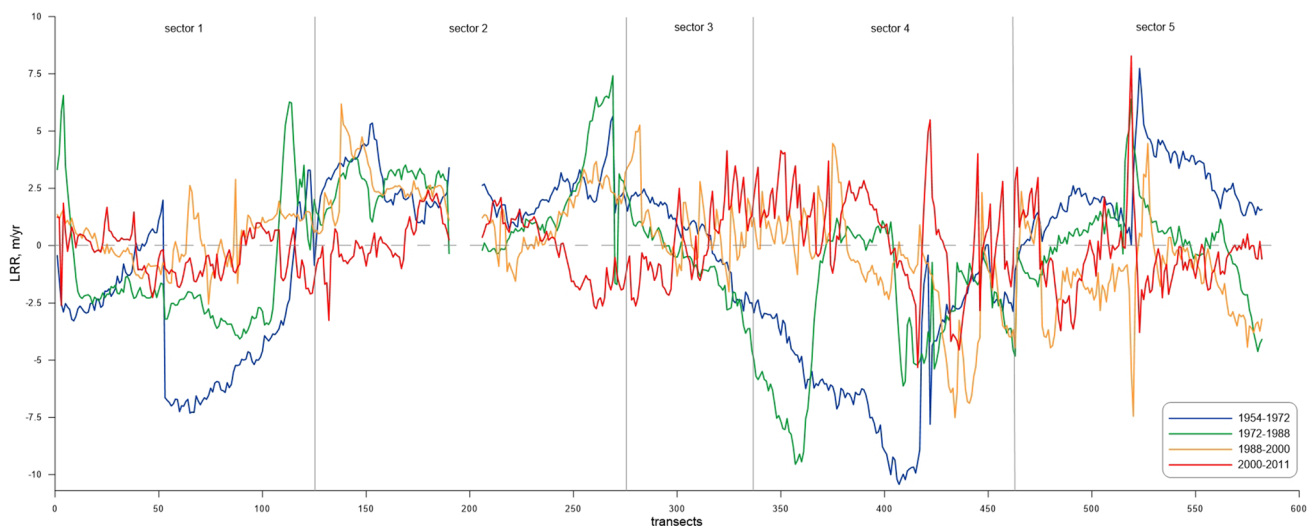
Fig. 3 Trends of medium-term shoreline change along the study area

Table 3 Long-term shoreline change trends derived from linear regression rates on each sector of the study area

LRR (m/ year)	Min	Max	Mean	Hverage NSM (m)	Average LR2
Sector 1	− 4.92	1.68	− 1.75 ± 1.58	− 20	0.83 ± 0.24
Sector 2	0.03	5.46	1.99 ± 1.13	27	0.97 ± 0.26
Sector 3	− 1.01	1.71	0.38 ± 0.65	6	0.45 ± 0.29
Sector 4	− 5.51	− 0.82	− 2.70 ± 1.20	− 38	0.74 ± 0.16
Sector 5	− 1.61	2.52	0.26 ± 0.95	5	0.40 ± 0.28

sector 1, there were a few accretional transects observed in the vicinity of Casal Borsetti coastal village (Fig. 2). Sector 4 was found to be the most erosional segment with extreme levels of erosion rates reaching over − 5.51 m/year. In this sector, retreat rates were generally lower in the central part with LRR value of − 2.52 m/year, and in the southern area with a LRR value of − 2.31 m/year, where a coastal protection work exists along Lido Adriano and Lido di Dante coastal settlements.

On the contrary, sector 2 presented clearly accretionary patterns with average positive LRR value of 1.99 m/year in long-term (Fig. 2). Maximum accretion was recorded around the port of Marina di Ravenna, with highest accumulation rates of 5.46 m/year at the north of the harbor. However, accretion rates decrease with increasing distance from the port, with a mean LRR of 0.23 m/year recorded in the northern part of the sector. Sector 3 showed prevailing stability or even moderate accretion with an average LRR value of 0.38 m/year (Table 3). Sector 5 exhibited slight shoreline advance at a mean rate of 0.26 m/year. However, several important exceptions to this general trend should be highlighted in this sector. Both the northern and the southern parts of the sector were affected by recession with rates ranging from − 0.28 m/year to − 1.61 m/year, whereas the central part in the surroundings of Foce Bevano river mouth experienced a significant shoreline progradation reaching 2.52 m/year at some transects (Fig. 2).

Medium-term trend reconstruction

To give an insight about the dynamics of shoreline changes within the research period, medium-term trends were analyzed. For this purpose, rates-of-change were derived from linear regression rates (Table 3) and plotted by transect (distance alongshore) for the four considered time intervals (Fig. 3). Figure 5 shows spatial and temporal distribution of medium-term shoreline changes computed by DSAS.

The medium-term analysis (Table 4) revealed a tendency of accretion over some portions of the coast towards the south of the study area. Nevertheless, a higher magnitude of shoreline change was observed in the north of the area with an evident slow-down trend towards the south. As a result, the shoreline is noticed to be somewhat stable. However, as average values may be a subject of contrasting trends along the site, it is necessary to account for short-term movements to get a full picture of it (Fig. 4).

Figure 3 demonstrates a great variability of shoreline change rates calculated over the analyzed periods with both rate and extent of erosion/accretion differing significantly in time. Thus, extreme recession rates of − 7.31 and − 10.43 m/year were recorded in the first time window (1954–1972) in sector 1 at the north of Reno river mouth and sector 4 at the south of Lido Adriano coastal settlement, where 100% of transects experienced retreat (Fig. 4). On the opposite, maximum accretion rates of 5.65 m/year and 7.74 m/year were observed in the same period around the harbor of Marina di Ravenna (sector 2) and in the surrounding area of the Bevano river mouth (sector 5), respectively.

Over the next two time intervals (1972–1988 and 1988–2000) the rate of shoreline retreat was observed to slow down in sectors 1 and 4 exhibiting a slight accretion by the end of the second time period. On the contrary, sector 2 showed a slight shift to erosional trend which continued towards the end of the study time.

The last period (2000–2011) recorded a certain reversal of trends (Fig. 3). Interestingly, the erosional trend earlier dominating in sectors 1 and 4 reverted and these sectors demonstrated more significant accretion and less pronounced

Table 4 Medium-term shoreline change trends derived from linear regression rates for the four investigated periods

| Coastal segment	Linear regression rates (m/year)											
	1954–1972			1972–1988			1988–2000			2000–2011		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Sector 1	− 3.2 ± 0.39	3.29	− 7.31	− 1.4 ± 0.39	6.56	− 4.07	0.3 ± 0.39	2.89	− 2.55	− 0.4 ± 0.39	1.85	− 3.26
Sector 2	2.5 ± 0.39	5.65	0.28	2.4 ± 0.39	7.42	− 1.69	2.1 ± 0.39	6.18	− 1.55	0.0 ± 0.39	2.42	− 2.75
Sector 3	1.0 ± 0.39	2.47	− 2.85	− 0.2 ± 0.39	3.13	− 4.56	0.4 ± 0.39	2.79	− 2.01	0.5 ± 0.39	4.14	− 2.63
Sector 4	− 5.8 ± 0.39	0.03	− 10.43	− 3.3 ± 0.39	1.19	− 9.55	− 0.6 ± 0.39	4.46	− 7.51	0.9 ± 0.39	5.49	− 5.32
Sector 5	2.4 ± 0.39	7.74	− 1.09	0.1 ± 0.39	6.41	− 4.62	− 1.6 ± 0.39	4.46	− 7.45	− 0.5 ± 0.39	8.28	− 3.79
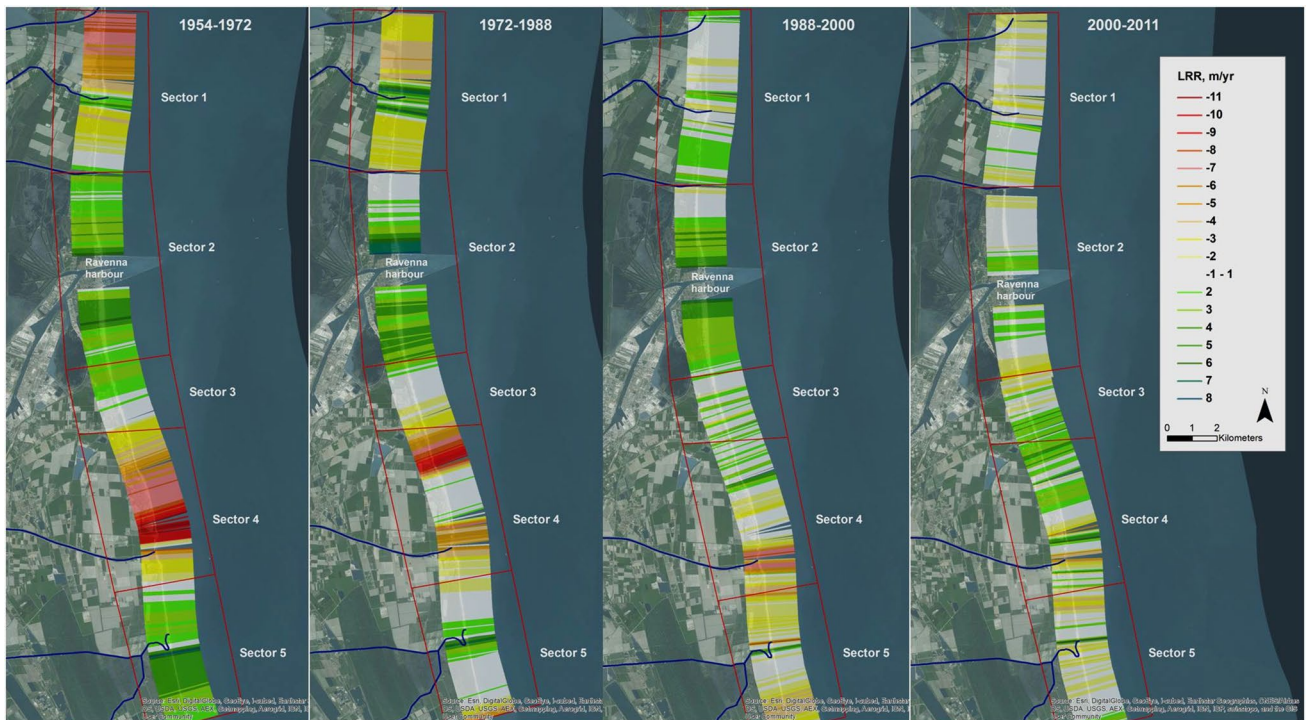
Fig. 4 Medium-term shoreline changes represented for the four investigated time intervals. Basemap provided by ESRI©
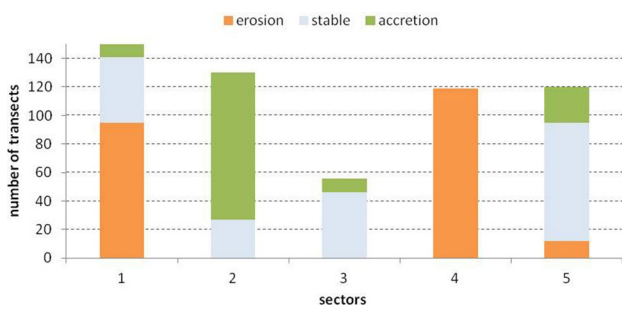

Fig. 5 Number of transects recording erosion/accretion in each sector

erosion overall compared to the previous decade. In case of sector 4, it became rather accretional with a positive mean rate of shoreline change of 0.9 m/year by 2011. Sector 5 showed a slight decrease in the erosional trend with an average value of − 0.5 m/year towards the end of the study. Sector 3 experienced stable conditions over the last two time intervals with LRR of 0.4 m/year (1988–2000) and 0.5 m/year (2000–2011).

Results for the LR2 statistics varied among sectors with a total range of 0.40–0.97 (Table 2). This contrasting behavior can be attributed to spatial and temporal variability of the shoreline points along a given DSAS transect. In the case of sectors 3 and 5, R^2 coefficient showed very low values, indicating a clear deviation of shoreline changes from the linear

trend. On the contrary, a relatively high R^2 value of 0.74 was detected in sector 4, related to a quite continuous trend in shoreline change (erosion in this case). High correlation was noticed for sectors 1 and 2, with $R^2 = 0.83$ and $R^2 = 0.97$, respectively, meaning that shoreline changes in both sectors showed a clearly linear behavior (with continuous erosion in sector 1 and continuous accretion in sector 2).

Figures 5 and 6 show the number and percentage of eroding/accreting transects in each sector for the whole study period. As previously observed, sectors 1 and 4 were found to be the most retreating ones, with higher number and percentage of erosion-dominated transects. In fact, sector 4 showed 100% of its transects under erosion. In sector 1 a total of 72% of its transects experienced erosion above − 1 m/year, with 22% retreating at a rate higher than − 3 m/year. On the contrary, sector 2 exhibited no erosional transects, with the most accretion (39%) occurring in the range of between 2 and 3 m/year. A total of 82% of the transects in sector 3 was found within a 'stability' domain in the range of ± 1 m/year. Likewise, sector 5 recorded 74% of 'stable' transects with only 8% experiencing erosion in the range of between − 1 and − 2 m/year; the remaining 14% and 4% of the transects showed accretion in the range of − 1 to − 2 and − 2 to − 3 m/year, respectively.

Fig. 6 Percentage of erosional/
accretional transects calculated
for each sector
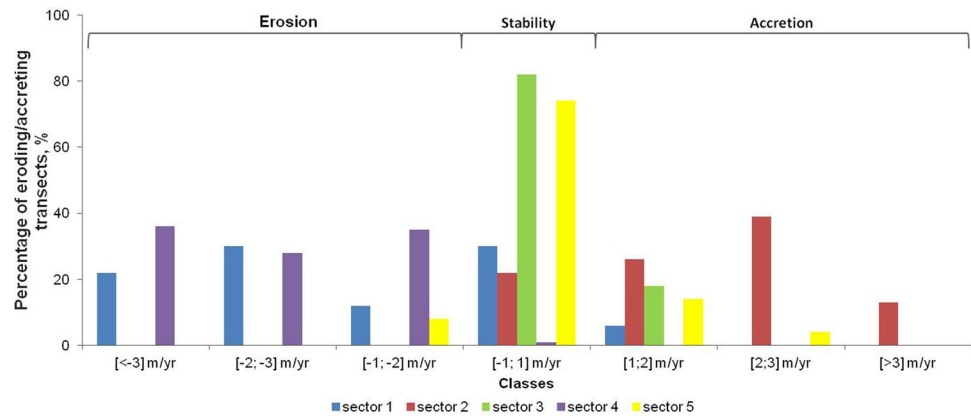
Net shoreline Movement

The average of net shoreline movement was an efficient strong indicator of the total shoreline displacement for each sector. Figure 7 shows total shoreline movement along with the characteristics of present coastal occupation. Maximum shoreline recession was recorded in sectors 1 and 4, with a net average retreat of 20 m and 38 m, respectively, over the long-time scale (1954–2011). In contrast, sector 2 showed shoreline advance up to 27 m seaward. Sectors 3 and 5 exhibited a total net shoreline progradation of 6 and 5 m, respectively, along the investigated period, which considering the uncertainty of manual shoreline digitization and the period of the analysis (> 50 years) can be deemed as negligible.

Table 5 summarizes the classification results by coastal sector. The classification allowed incorporating all the gathered data including rate-of-change statistics and percentage of erosional/accretional transects. This evaluation was conducted by assuming qualitative attributes for each variable, ranging from stable to very unstable/erosive classes.

As explained above, the Ravenna coast showed a great variability of trends in the long-term, exhibiting both erosional and accretional patterns. Most coastal segments present uniform alongshore characteristics for several hundred meters. Erosion was found to be the dominant trend for a large portion of the littoral with sectors 4 and 1 identified as the most erosional segments. Results were less conclusive for sectors 3 and 5, where the area showed mixed trends, with both moderate erosion and accretion and therefore, considered as relatively 'stable' beaches. On the contrary, sector 2 was characterized by a clear shoreline advance and therefore assigned to 'accretionary' class.

Discussion

A few considerations regarding shoreline trends should be taken into account prior to discussion to avoid misunderstanding of the classification proposed in Table 4. The transects with locally high rates of erosion can imply severe damage to coastal infrastructure in the given segment, regardless of the possible overall 'accretionary' state of the coastal sector in which they are located. Likewise, sectors identified as 'erosive' do not always represent continuous erosion along the entire area. In this case, it becomes important to examine shoreline behavior over the medium term to reveal most representative trends and the dynamics of the particular area. The primary aim of the proposed classification is to present findings related to the assessment of coastal changes and to use a relatively simple, objective method to identify those sections of the coast most affected by erosion.

Ravenna coastal area is a clear example of heterogeneous shoreline behavior, where the shoreline fluctuates between erosion and accretion, and includes a wide range of physical and human factors influencing coastal changes. Response of the shoreline to these factors varies from sector to sector largely depending on the prevailing processes acting in the area.

In this study, the assessment of shoreline trends was determined from a review of historic shoreline records and a shoreline classification was adopted for the examination of trends in coastal position over different timescales. According to Burningham and French (2017) any shoreline classification system is location-dependent, meaning that the intended purpose of any classification system should be based on an interpretation of the local natural and human-induced processes. Such, shorelines for different regions cannot be classified unless based on similar classification criteria.

Although the classification proposed in this study presented difficulties in comparing with others, it nevertheless showed some regional consistency and facilitated comparison with other study areas within the Adriatic region. In this

Fig. 7 An illustrative example of total shoreline movement for each sector and main uses of these coastal segments. 1954 year serves as a baseline
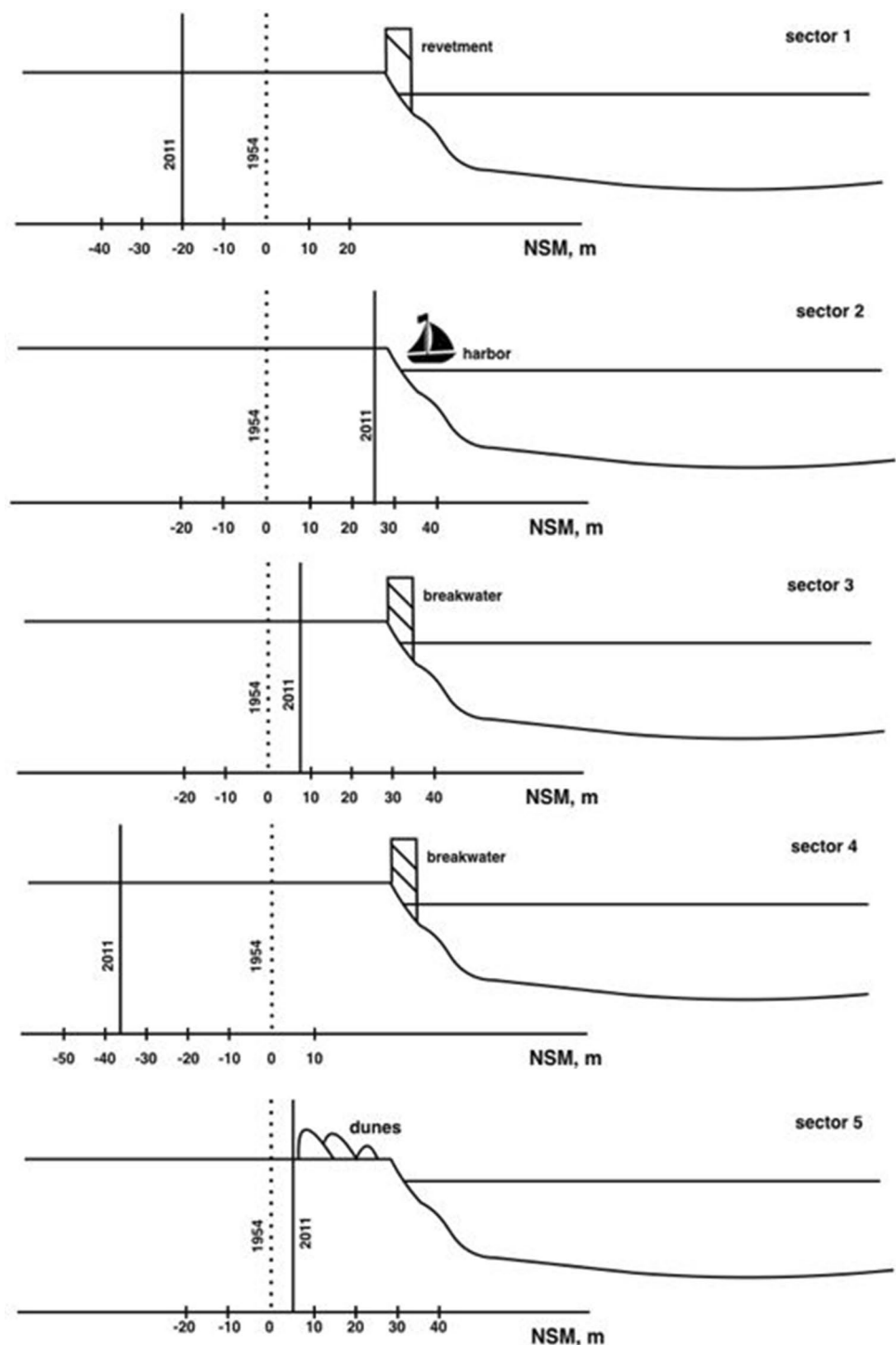
respect, different aspects of human-induced coastal drivers and associated impacts (land subsidence, deficit of sediment transport etc.) were found to be common for a large part of the Adriatic littoral and discussed in light of recorded shoreline changes and the proposed classification.

Within the Adriatic and Ravenna coastal region in particular, erosional processes have been extensively studied (Gonella et al. 1998; Simeoni and Corbau 2009; Aucelli et al. 2009; Perini et al. 2011; Armaroli et al. 2012, 2013; Manca et al. 2013), yet there are very few dealing with assessment of historical shoreline changes. A study by (Delle Rose 2015) used a classification system based on long-term shoreline displacement rates (erosion and accretion) for a 70 km-long southern Adriatic coast of Apulia. The results confirm with the ones of the present study,

Table 5 Results of the allocation of coastal sectors to classes of shoreline behavior

	Erosion	Accretion	Dominant trend
Sector 1	Very high	Low	Erosive
Sector 2	Stable/no erosion	High	Accretionary
Sector 3	Moderate	Moderate	Stable
Sector 4	Very high	Stable/no accretion	Erosive
Sector 5	Moderate	Moderate	Stable

showing a dominant erosional trend and significant retreats up to 50 (± 10) m over the coast.

Another example is the Sardinian shoreline (Manca et al. 2013) which demonstrated similar shoreline behavior when compared with Ravenna coast. For instance, a considerable advancement of the shoreline was observed at the breakwaters of Alghero harbor which serves as a shelter for the southern part of Lido San Giovanni beach from storm surges, at the same time areas close to the seawalls were found retreating. Also, the absence of natural coastal dunes (removed, highly occupied or largely modified) at Maria Pia beach, which no longer act as a source of sand to the littoral has led to narrow beaches. In regard to local subsidence effects, Taramelli et al. (2014), studying a sector of the northern Adriatic, allude to a direct link between the rate of recession and the subsidence, suggesting that this association is regionally consistent and significant.

Similar timescale (period 1954–2014) was adopted for an assessment of shoreline changes at the Molise coast (central Adriatic Sea). Analysis of short-to-long-term shoreline changes revealed that erosion has become more widespread involving a great part of the coast, especially in the vicinity of the mouths of major rivers Trigno an Biferno (Rosskopf et al. 2017). This is in good agreement with the results of the present study and those of Ciavola and Armaroli (2010) and Corbau et al. (2015), pointing out at the area around river Bevano mouth (sector 4 in this study), found to be one of the most erosive segments over Ravenna coast.

Several studies have also highlighted the important roles of fluvial sediment input and presence of harbor and coastal protection, as they can be retained as some of the primary control factors of observed negative shoreline changes in the region due to their interference with sediment transport along the coast. Shoreline progradation was evident both south to the Termoli harbor and in the segment around the Marina di Santa Cristina harbor, as well as close to their extended breakwaters where the sediment got trapped (Rosskopf et al. 2017), showing similar shoreline behavior in the area surrounding Ravenna harbor.

Thus, these studies suggest a considerable regional coherence in the shoreline behavior across the Adriatic shoreline, where several external factors, primarily induced by human activities (tourism and urbanization, water and gas extraction, construction of ports and ineffective coastal defense works) are triggering erosive processes and may have influenced in a similar way different coastal sectors, independently from their relative location (yet within the Adriatic region). Some of these factors are portrayed in the Fig. 8 and discussed in detail bellow.

Groundwater pumping and gas extraction activities

This study confirms previous findings and contributes to additional evidence with respect to landward migration associated with land sinking processes (Carbognin et al. 1984; Gambolati et al. 1999). The results appear to support the view by Morelli (1998) and Teatini et al. (2005, 2006) which claimed that the most drastic shoreline movements and associated erosion occurred mainly due to groundwater pumping from the regional multi-aquifer systems in the 40 s—late 70 s as a response to growing demand for domestic, agricultural and industrial uses. Sector 1 recorded strong erosion during the periods 1954–1972 and 1972–1988 (Fig. 4), which could be primarily linked to the extensive groundwater pumping in the north of the sector. The impacts of groundwater withdrawal were more pronounced in the sector 1 owing to the dense concentration of water extraction points in the area. In the adjacent segments, dominance of other processes such as construction of the Ravenna harbor and reduction of fluvial input may have masked the effects of the pumping.

Another factor contributing to land sinking is associated with gas exploitation offshore Lido Adriano coastal village which mostly affected sector 4 (Fig. 8). In fact, as the study revealed, sector 4 was the most erosive segment along the coast showing prevailing erosion-dominated transects throughout the whole study period. This way, the results also support the findings by Bertoni et al. (1995) and Gambolati et al. (1998), claiming that the subsidence effects caused by the gas extraction from the Angela-Angelina platform were manifested in a range of 4–5 km from the extraction field with subsidence rates reaching up to 18 mm/year.

Since the nearshore area along Ravenna coast is characterized by low gradients (Simeoni and Corbau 2009), the subsidence not only determines a certain degree of shoreline retreat, but also an increase of the seafloor gradient and therefore a reduction of the coastal sand body. Thus, it in turn leads to significant decrease in sediment supply that creates a serious obstacle for sediment accumulation and causes an adverse effect on coastline stability (Teatini and Gambolati 1999; Armaroli et al. 2012). Nevertheless, the results suggested that the erosion rates gradually decreased over time, especially when it comes to sectors 1 and 4 when the trend turned to more accretional, perhaps due to the
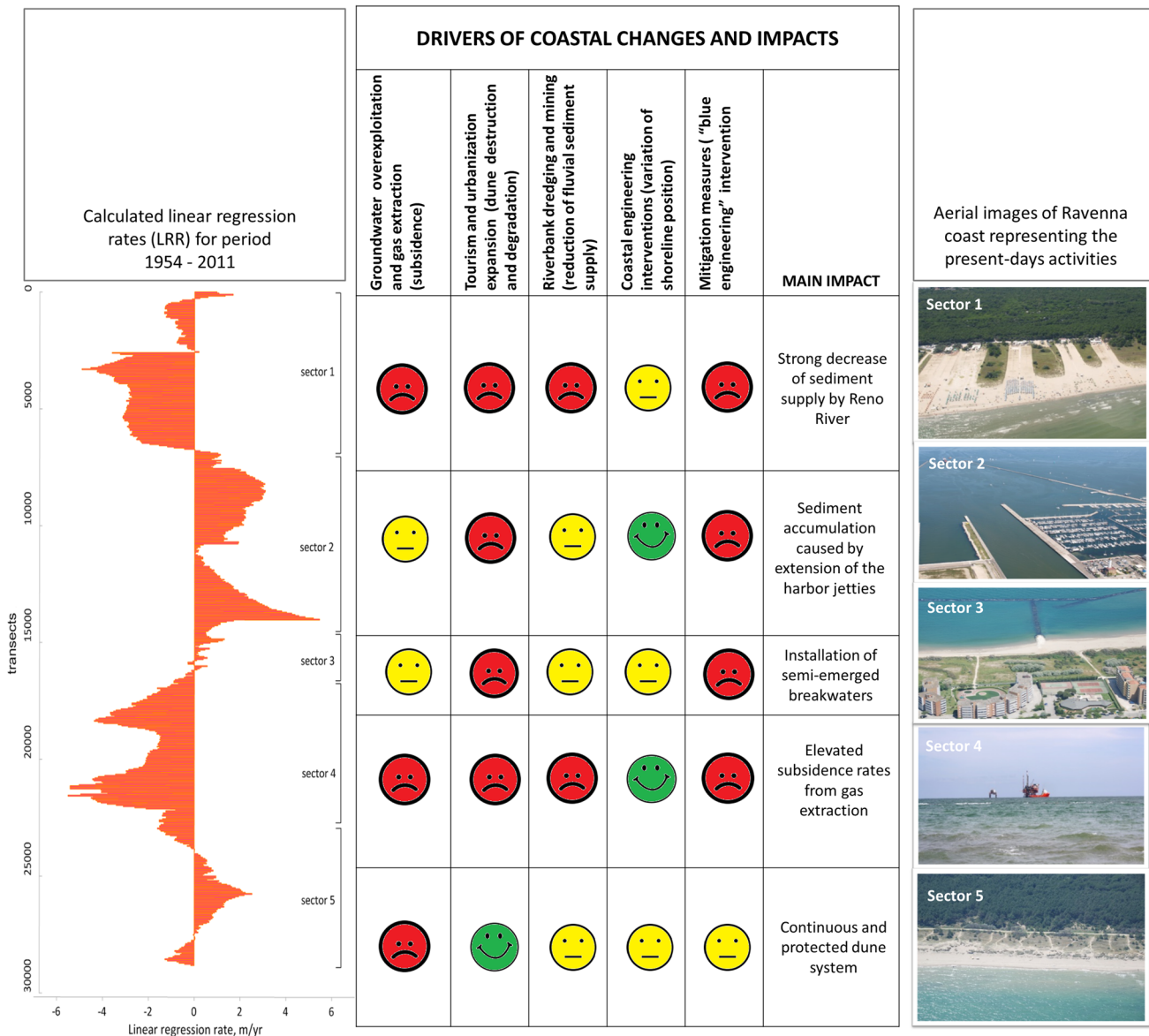
Fig. 8 Various drivers of coastal changes and their associated impacts (positive, neutral and negative) for each sector of Ravenna coast

restriction of groundwater pumping from the regional multi-aquifer systems in the end of 1980s.

Tourism and urbanization expansion

Dunes and beaches are intricately linked as integrated morphodynamic systems. A significant part of the general erosional trend of Ravenna coast can be associated with dune removal along the entire littoral over the last 60 years (Sytnik and Stecchi 2014). Before the tourism boom, which occurred in the second half of the last century, dunes in the North-West Adriatic coast were a widespread feature of the littoral (Caruso et al. 2006). Over time, intensification of human activities such as residential and tourism development contributed to landscape changes, mainly of the waterfront where dunes were graded or even completely removed to accommodate beach facilities and other tourist services. Land reclamation for agricultural purposes and construction of new beach establishments or expansion of the existing ones exacerbated erosion problems, thus inhibiting natural recovery processes of the coast. In many places beach

infrastructure replaced natural environment and became commonplace (Sytnik and Stecchi 2014). Today the remaining dunes are scarce, fragmented and undergo consistent pressures of tourism development. An exception is found in sector 5 where a large, continuous dune belt is present along the entire segment (Fig. 8), and in fact its overall trend was observed rather accretionary in the long term. However, some parts of this sector recorded a predominance of erosion, namely the northern area of Bevano river due to the high riverine activity thus facilitating erosion of the dunes adjacent to the river mouth.

River dredging and bedstream works

Presence of rivers and corresponding processes related to sediment supply and river mouth dynamics may also influence the coastline configuration. Sediment transport has been always the most undefined parameter with no quantitative evidence about river supply in the region (Elfrink et al. 1998). Recession of the shoreline in river-adjacent area might be largely due to complex morphological processes around the mouths of Reno, Lamone, Fiumi Uniti and Bevano rivers (Ciavola and Armaroli 2010). Unfortunately, no direct measurements of littoral transport and the sediment input from the rivers in the whole study area is available although some rough estimates were presented by APRA report (ARPA 2009) indicating drastic decrease of fluvial sediment input decreased by half over the last 70 years by 2007. The lack of reliable data makes it difficult to calculate the annual sediment budget and assess the impact of the sediment input on the migration of the coastline. Some authors (Elfrink et al. 1998; Billi et al. 2017) reveal that a diminution in the amount of sediment delivered to the coast via the rivers may have occurred as a consequence of upstream water management practices, streambed excavation and especially erosion control works on the river slopes.

Coastal engineering interventions

Coastal defense structures have a great potential to influence sediment transport and hence beach evolution (Angnuureng et al. 2013). In Ravenna coast, over the last decades numerous human interventions attempted to protect the coast from retreat by both passive and active methods, which eventually led to deep alterations in natural processes of shoreline evolution (Colantoni et al. 1997). Presently, coastal defense systems are widespread with different types of coastal works extending along the study area (Table 6). Except in sectors 2 and 5, Ravenna beaches are armored with hard engineering structures such as revetments, semi-submerged detached breakwaters and series of groynes.

Recorded shoreline changes did not follow a uniform pattern along the entire stretch of coastline affected by coastal protection. However, the medium-term analysis confirms that after building defense structures in the last two decades (1988–2000 and 2000–2011) erosion rates gradually decreased over time, demonstrating a shift from erosional to accretional trend in most of the study area. In fact, construction of detached breakwaters and groynes in sector 4 by 2005 facilitated shoreline advance and contributed to general widening of the beach over the last studied period (2000–2011). This supports the observation by Jackson et al. (2015) that presence of detached breakwaters in the area is likely to lead to development of salients in the lee of breakwaters and eventually positively influenced shoreline position. In sector 3, variation of erosion and accretion-dominated transects over the last two time intervals can be attributed to the interruption of littoral transport as a response to the placement of protection structures (Fig. 8), followed by erosion of unarmored portions of the sector.

Coastal erosion was also addressed by beach replenishments carried out between 1983 and 2007 along a total of 9 km in Punta Marina, Lido Adriano and Lido di Dante

Table 6 Characteristics of coastal defense systems in Ravenna coast (see locations in Fig. 1)

Name of settlement	Type of defense	Length (m)	Year of construction
North Casal Borsetti	Revetment	1750	2004–2006
	Semi-submerged breakwaters	100	1989
Casal Borsetti	Transversal groynes		1998
	Emerged detached longitudinal breakwaters	1300	1998–2002
Punta Marina	Semi-submerged breakwaters	3800	2000–2006
	Transversal groynes		2005
Lido Adriano	Emerged detached breakwaters	2700	2005
	Emerged longitudinal breakwater		2005
	Revetment		
Lido di Dante	Semi-submerged breakwater	800	1995
	Transversal groynes		2005
Foce Bevano	Protection with fixed wooden piles	300	2006
Lido di Classe	Emerged longitudinal breakwater	1200	2000–2006
	Emerged detached breakwaters		

beaches (sectors 3 and 4). The artificial supply of sand can be responsible for temporary accretion along the coast as shown in the results of the medium-term analysis shifting from negative (− 0.6 m/year) to positive rates (0.9 m/year) over the last two decades. Yet, regardless of the numerous nourishment works and extensive set of protection structures, erosion problems have only been locally mitigated (ARPA 2009) and shoreline retreat is still present at certain parts of the coast.

Harbor construction and its enlargement

Another factor responsible for the spatial variability in shoreline trends is the construction of Marina di Ravenna harbor (Fig. 8) in the late 1960s (Airoldi et al. 2015). The impact of harbor jetties on coastal dynamics is clearly visible at both of the adjacent areas in the beginning of the study period (1954–1972), where rapid shoreline progradation and expansion of nearby beaches occurred due to gradual accumulation of sand against the jetties. This enlargement can be attributed to the presence of opposite directions of local currents (north- and south-oriented) (ARPA 2009), where the port serves as a subdivision point. This way, the harbor intercepts both the north- and southward longshore sediment transport, trapping sediment in its northern and southern sides and eventually leading to sand deposition in the nearby beaches. However, the effects concerned only the adjacent beaches, and the accumulation rates rapidly decrease with distance away from the harbor. At the beginning of the port construction, when the piers were short, their effect on the configuration of the shoreline was limited; later on, with the expansion of the harbor and seaward prolongation of the jetties in the late 70 s, the seaward movement of the coastline continued with transects accreting at a rate of 7.42 m/year at the north side of the port over the second time interval (1972–1988). Noteworthy, the rate and extent of accretion appear to have decreased in recent years, probably related to cumulative effects of the reduced effective length of the piers of the port (Gambolati et al. 1998) and reduction of fluvial sediment sources to provide material for the beaches as stated by Cencini et al. (1988).

Implications for the past and current shoreline management

Over the last 60 years, Ravenna littoral experienced various forms of interventions to stabilize the shoreline. Revetments, semi-submerged detached breakwaters and series of groynes were a common protection approach until a 'Project plan for the defense of the Emilia Romagna Adriatic Coast' (Piano Costa 1981) was adopted (Coastance 2011). The plan moved away from traditional breakwater based defense structures and pointed to nourishment procedures as an alternative.

For the following decades, during the years 90's and early 2000's, nourishment practices were considered the best solution against erosion. Thus, the region managed to bring the total to 8.1 million m³ of sand onto nine different beaches along the Emilia Romagna coast by 2007 (ARPA 2009). The 'Stato del Litorale' report introduced in 2016 aimed at describing the status of the coast, verify the coast's evolutionary trends on 2012 and provide considerations for future coastal management policies (Aguzzi et al. 2016). Local authority (the Emilia-Romagna regional administration) later endorsed a "Gestione Integrata delle Zone Costiere" (GIZC) plan which led to the approval of specific guidelines on the mitigation of local climate-related risks with a special attention to the sea level rise issue. The recent document adopted by the Italian Environmental Ministry approved guidelines on coastal protection from erosion and climate change effects, delivered in accordance with the Floods Directive - Directive 2007/60/EC (European Parliament and Council 2007), also highlighted the importance of the long-term changes for the national and regional mitigation strategies (Perini et al. 2017).

With respect to local residents' response to coastal erosion problem and their attempts to control the shoreline, a common approach for beach operators to limit the damage from storms and erosion has been the construction of artificial sand barriers in front of their private properties (e.g., beach establishments, other beach facilities). Since a vast dune area (about 75%) has been damaged or even removed as a result of touristic activities over the last century (Sytnik and Stecchi 2014), and the coast can no longer be protected by them, these man-made sand barriers are seen as a forced protection measure against erosion, delaying flooding and damage to coastal infrastructure. Besides, during the months of October and April, private property owners use a heavy machinery (e.g., graders, bulldozers) to gather together sand from the beach itself. Beach bulldozing is a common method of seafront erosion management in the area, yet this an enhanced recreational beach may be achieved for the short term, and no new sand has been added to the system. This procedure obviously has a negative effect on the stability of the beach. Ideally, scraping is intended to encourage onshore transport of sand, but most of the sand 'trapped' on the lower beach is brought in by the longshore transport. Removal of this lower beach sand can interfere in their natural nourishment, damage embryo dune morphology and vegetation, and eventually alter natural integrity of the entire beach system.

Since shoreline displacement problem is site-specific, different solutions may be advised to mitigate erosion or control the shoreline position. An important principle in evaluation of suitable sustainable measures is to try to 'build with nature'. Regarding this, in one of the most recent efforts to respond to the threat of coastal flooding and erosion, the RIGED-RA project—"Restoration and management of

Coastal Dunes in the Northern Adriatic Coast, Ravenna Area—Italy" was carried out from 2013 to 2016. The aim was to identify dynamics, erosion and vulnerability of Northern Adriatic coast and associated residual dunes, and to identify intervention strategies for dune protection and restoration. A series of windbreak wooden fences parallel to the coastline were installed in the vicinity of river Bevano (sector 5) to promote the recovery of natural conditions, facilitate sand deposition and accumulation and to favor creation of embryo dunes. The project resulted in the dune progressively advancing seawards with nearby accumulation of sand deposits. As this natural dune-rebuilding process can take several years, the area is being actively monitored for geomorphological changes (Gambiastiani et al. 2016).

Solutions for current and future shoreline management must be thought principally over long-term rather than focusing on short-term period. This would mean perhaps that any current approaches to reducing risk of coastal erosion may no longer be practical at some time in the future. According to the Environment Agency report "Adapting to a changing climate" (DEFRA 2016) coasts should be managed for a 100 year time period, yet local solutions sensitive to coastal communities and theirs histories should nestle within a national strategic sustainability framework. For this reason, managing the shoreline should first reflect the lessons learnt from the numerous assessments performed in the study area to provide a credible basis for future policy decisions. To address this, some recommendations for mitigation should be considered:

- decisions on erosion-mitigation measures should be based on a good understanding of existing coastal processes and how they affect the area,
- forbid construction of the new buildings and other facilities on the beach and promote conversion of existing infrastructure into sustainable spaces,
- discourage and regulate inappropriate practices such as bulldozer beach cleaning and pedestrian trampling,
- map coastal risks and vulnerable spots and communicating results to the public,
- promote educational campaigns to raise public awareness regarding coastal risks and management,
- establish efficient and focused consultation with the local property owners who will need to consider how they will deal with these changes and consequences
- encourage sustainable 'building blue' and 'building with nature' practices,
- promote reconstruction and restoration of remaining dune bars.

The key conclusion drawn from the discussion is that there must be a profound public recognition of how and why coastlines are changing, what are the risks associated and the likelihood of these changes to get greater. This calls for an effective local policy and a wider framework of adaptive management tools to help both coastal system and communities to accommodate in the very long term to a changing coastline. For this reason, an effective local policy and adaptive shoreline management plan should serve as base-point to clearly define the implications of long-term coastal change when considering future development of the shoreline. This is particularly important in such highly dynamic areas as Ravenna where the scale of coastal changes is virtually unpredictable due to the complexity of the natural and anthropogenic processes acting in the area.

Conclusions

In this study, the emphasis was on quantifying rates of shoreline position based on historical data. A proposed graphical shoreline classification scheme showed to be effective at revealing different levels of shoreline displacement according to its long-term behavior and identifying most erosional units. Results also provided insights into the recent shoreline evolution of Ravenna coast and reflected the cumulative effects of the natural and man-induced processes simultaneously affecting the study area. The spatial and temporal variability of the local shoreline can be related to both the heterogeneity of the coast and to the diversity of factors contributing to erosion-accretion processes.

From the analysis of the areas affected by shoreline retreat, it can be concluded that the complex interactions of several human-induced and natural processes resulted in significant alterations in the shape of the Ravenna coast. As pointed out by previous researches, the shoreline position has been strongly affected by local land subsidence which accounts not only for direct shoreline retreat, but also for blocking of natural sand supply to the littoral and resulting in coastal instability. In addition, shoreline changes are greatly influenced by human factors such as installation of defense structures, harbor construction, water and gas extraction activities and tourism and urbanization expansion primarily responsible for converting the natural landscape into a densely developed area and increasing chances for erosion. At the same time, the lack of appropriate coastal management strategies contributes to worsen the effects of natural and anthropogenic forces responsible for coastal erosion. If the present trends are maintained, along with predicted global sea level rise and ongoing land sinking, coastal retreat in the Ravenna region is expected to accelerate, which will in turn increase the impact of other risks such as flooding and salinization. This trend represents a serious problem for tourism industry, which is of utmost importance for the regional economy.

The results of this work offer a synthesis of the shoreline characteristics and trends that may be likely to address coastal erosion problems in the area. Information on rates of shoreline change can be used to improve the understanding the relative importance of underlying causes and potential effects of coastal erosion to assist with future identification and selection of potential options to mitigate the risks arising from coastal retreat. The proposed shoreline classification can also offer an advantage from the perspective of regional consistency and the ability to facilitate comparisons with similar investigations in other coastal areas at the regional and national level. Proposed recommendations can serve as a support to local shoreline management plans.

In the future, the methodology adopted in this research could be expanded to include natural impacts on shoreline changes such as sea level rise and storm surge incidence. A further step would be to carry out analysis of coastal vulnerability taking into consideration to both natural and anthropogenic impacts as well as population exposure and adaptive capacity. In this way, a more comprehensive and integrated assessment would be obtained.

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