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A review of impact of subsidence induced by gas exploitation on costal erosion in Emilia-Romagna, Italy

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ABSTRACT During the last six decades, the Emilia-Romagna coastal plain underwent severe land lowering, as a consequence of groundwater pumping and gas production, that was pointed out as one of the main causes of beach erosion affecting extensively the coast. This paper aims to investigate the influence of gas fields exploitation on the beach erosion, through an analysis carried out in two critical sites: Reno River and Fiumi Uniti River deltas. The study is based on the comparison between the geomorphological evolution and the phases of the gas withdrawal. Main results highlight that, despite the gas exploitation cause subsidence, the strong coastal retreat has been much more dominated by morpho-dynamic processes associated with the decrease of river supply.

Key words: coastal erosion, subsidence, shoreline changes, gas exploitation.

1. Introduction

The Emilia-Romagna coast is exposed to beach erosion and inundation risk because of its geomorphological features (Fig. 1) and widespread urban areas that have increased by 400% in the last 65 years, particularly in the southern sector (Lorito *et al.*, 2010). Land loss and flooding are common matters to the overall coastal plains and, in the delta systems, due to the combined effect of sediment supply reduction, subsidence and sea-level rise (Syvitski *et al.*, 2009). Moreover, scenarios could be worst in the future, if sea-level rise will reflect the Intergovernmental Panel on Climate Change (IPCC) projections (Bondesan *et al.*, 1995; Perini *et al.*, 2017). This issue is strategic for the regional economy, above all as far as tourism is concerned, for which beach preservation is a central matter.

The protection of the coast was based on hard protections such as breakwaters, groins, and artificial embankments that have been constructed over the 60% of the regional shoreline (Perini *et al.*, 2008) but they have not solved the problem. In fact, beach erosion still affects over the 26% of the coastline (30.5 km) and the 21% of beaches (24.8 km) is in a precarious state despite the littoral is constantly fed artificially (Arpae - Regione Emilia-Romagna, 2020). Furthermore, coastal dunes, important sources of sand for the beaches and natural defenses against sea flooding, are limited to 30% of the regional coast and are often in a discontinuous and degraded condition (Perini and Calabrese, 2010).

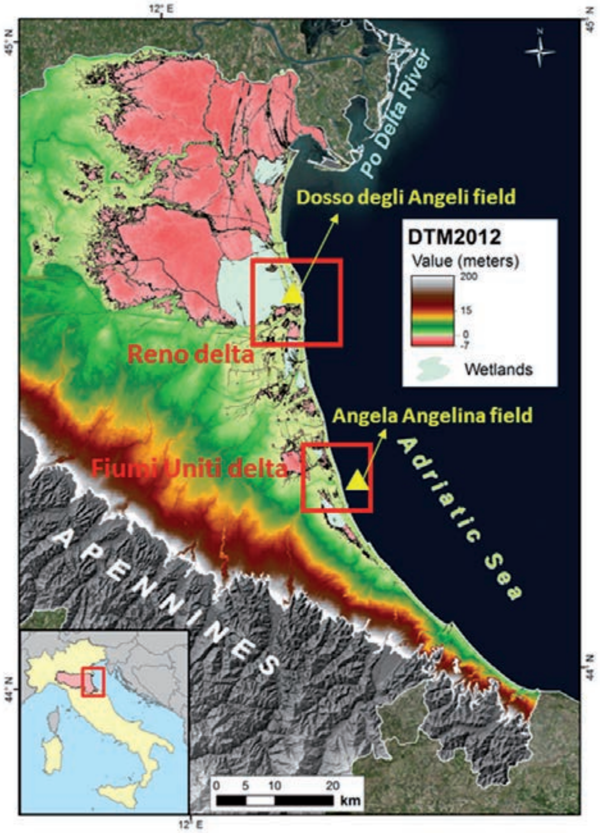

Fig. 1 - Elevation map of Emilia-Romagna coastal plain in which low laying areas and localisation of the gas fields depocentres Dosso degli Angeli and Angela Angelina are highlighted.

In order to understand coastal erosion and counter impacts, all driving processes have been investigated since the first ‘regional coastal plan’ (Idroser S.p.A. - Regione Emilia-Romagna, 1983): land subsidence, the reduction of sediment flux from rivers and the interference due the coastal engineering works were identified as the main causes of the shoreline retreat; furthermore, some areas of chronic erosion were identified in correspondence of gas withdrawal.

In recent decades, studies on subsidence have progressed considerably, several authorities have created specific monitoring networks and have applied measures to contrast it; on the contrary, little has been done to study and improve the sediment transport. The studies on subsidence point out that the lowering of Emilia-Romagna coastal plain is driven by the interplay between natural and anthropic components: the natural subsidence, depending on tectonics, sediment load and compaction, causes 2.0-2.5 mm/yr rates in the central sector (Ravenna area) and 0.5-2.0 mm/yr rates in the southern one (Gambolati and Teatini, 1998; Carminati and Di Donato, 1999; Teatini *et al*., 2005); major values can be reached in the northern sector (Po River delta area) because of the high compressibility of the recent Holocene deposits (Teatini *et al*., 2011). The anthropic subsidence is mainly dependent by groundwater withdrawals from the shallow multi-aquifer system and by gas extraction from inland and offshore reservoirs (Gambolati *et al*., 1991; Antoncecchi *et al*., 2021; Severi *et al*., 2021).

Water pumping led to over 1-2 m lowering with rates up to 5 cm/yr in Ravenna industrial district and in Cesenatico cities; in the Po delta, subsidence rates were up to 8 cm/yr due to methane and water pumping carried out in the period 1938 to 1961 (Caputo *et al*., 1970), with dramatic effects on the rivers and channels outflow to the sea and on the entire ecosystem (Corbau *et al*., 2019). Currently the combined effect of natural and anthropogenic subsidence locally reaches 10-20 mm/yr rates at Fiumi Uniti River mouth (Arpae - Regione Emilia-Romagna, 2018; Montuori *et al*., 2018) where gas exploitation of Angela-Angelina gas field is still dominant on the phenomenon. The reduction of subsidence rates is attributable to the national and regional laws that have been enacted in the 1980s with the aim of regulating and limiting water pumping.

The gas exploitation activities started in Italy since 1960 (Assomineraria - RIE, 2012) are currently in reduction even if Italy still represent one of the most important methane-producing countries (about the 80% of national hydrocarbon production) in southern Europe (Bertello *et al*., 2008, 2010; Fantoni *et al*., 2008).

The extraction activities have been also developed in the offshore, up to the 12 miles limit where there are still 24 oil and gas exploitation licences (Fig. 2), six of them no longer in exercise. The two largest gas fields are Garibaldi and Agostino, located in front of Ravenna at 8-13 nautical miles (NM) from the coast. Both reservoirs exploitation started on 1970, and the total production, updated to 2016 (mining is still active), reaches around 86 billion standard cubic metres (Sm3 - gas volume in m^3 in standard conditions of pressure and temperature), which represent about 30% of the overall regional yield in the period. Since 1980 the production in all gas fields (Fig. 2) was about 170 billion Sm3 whereas it was 257 billion Sm3 considering the previous period. Gas

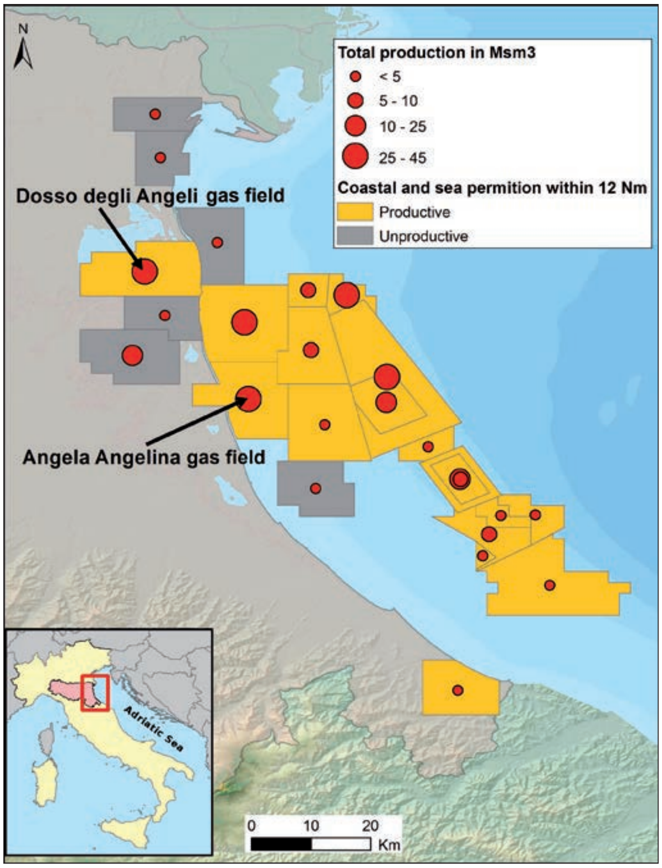

Fig. 2 - Gas exploitation licenses along Emilia-Romagna coastline and offshore within the 12 NM and total production.

exploitation is generally decreasing in the area since 1998, which represents the maximum peak after 1980 with an amount of 7.4 billion Sm3 extracted. Dosso degli Angeli is the most productive gas field inland with an amount of 31 billion of Sm3 extracted throughout the period of activity.

The relationship between subsidence induced by gas extraction and coastal erosion has therefore been hypothesised because of timing concurrence (Idroser S.p.A. - Regione Emilia-Romagna, 1981; Arpa Emilia-Romagna, 2009), but the actual dependence has never been demonstrated, nor advanced models for the simulation of interplay of these processes have been developed.

In this study, the available information concerning the mining activities is compared with the coastal dynamics, especially with the geomorphological modifications and the shoreline and sea-bottom changes, to highlight possible control or independent trends. The analysis regards the two most critical sites of Reno River delta, close to Dosso degli Angeli gas field, approximately 20 km north of Ravenna, and Fiumi Uniti River delta, close to Angela and Angelina gas fields, that is 10 km south of Ravenna (Fig. 1).

2. Data and methods

The study benefits from a large amount of cartographic material, of subsidence monitoring data sets and information on gas production and it focuses on their integration.

As first step, geomorphological features and coastal dynamics have been analysed in detail; secondly, the evolution of deltaic cusps and beaches has been compared with the timing of production activity, considering the variations in the volumes extracted and induced subsidence.

Most of the data is stored in regional archives and databases and available through web applications (https://geo.regione.emilia-romagna.it/geocatalogo/; https://geoportale.regione.emilia-romagna.it/catalogo/).

The main data used are briefly described below:

- historical topographic maps and aerial photos. In Table 1, basic characteristics of maps and images are summarised;
- shorelines of the last two centuries. The shorelines are digitised in vector format on the base of georeferenced historical maps and aerial images. The photointerpretation is carried out at a detailed work scale (1:500/1:2,000) according to the dry/wet principle (Moore, 2000), modified for Emilia-Romagna coast (Calabrese and Lorito, 2010a);
- bathymetric maps and depth measurements (20th and 21st centuries). The digital bathymetric models of the seafloor (DBM) of 1901 and 1953 years derive from historical nautical maps by Hydrographic Institute of the Italian Navy (Perini *et al.*, 2010). The DBM of 2012 has been processed from bathymetric data acquired by Eni S.p.A., Arpae (Regional Agency for Prevention, Environment and Energy of Emilia-Romagna), and Province of Ferrara (Table 2);
- subsidence monitoring data (from 1970 to 2016). The subsidence data sets were mainly acquired by Arpae that carried out six monitoring surveys on behalf the Emilia-Romagna Region. The first two surveys (1970-1999 and 1999-2005 periods) were performed by means of levelling method, while the following ones (1992-2000, 2002-2006, 2006-2011, 2011-2016) using the Permanent Scatterers Synthetic Interferometric Aperture Radar (PSInSAR) technique;
- production history of gas fields (from 1965 to 2018). The fields production data is made available from Ministry of Economic Development (MISE).

Table 1 - Historical maps and aerial images used in the study.

Name	Year	Scale	Geometrical resolution	Planar position accuracy
Austrian topographic map	1853	1:86,400		
Piedmont topographic map	1853	1:50,000		
Italian Military Geographical Institute (IGM) topographic map	1893-1894	1:25,000		
RAF aerial images (Royal Air Force)	1943-1944	1:30,000	0.5 m	6 m
GAI aerial images (IGM) - regional data set	1954-1955	1:30,000	0.5 m	6 m
Coastal aerial images (CGR)	1976-1978	1:25,000	0.5 m	< 3 m
Coastal aerial images (CGR)	1982	1:10,000	0.7 m	< 4 m
Coastal aerial images (CGR)	1991	1:10,000	0.5 m	< 3 m
Coastal aerial images (CGR)	1992	1:10,000	0.5 m	< 3 m
IT2000 aerial images - national data set	2000	1:10,000	0.5 m	< 10 m
Coastal aerial images (CGR)	2005	1:10,000	0.5 m	< 3 m
Agea 2008 aerial images - regional data set	2008	1:10,000	0.5 m	< 10 m
Coastal aerial images (Istituto Nazionale di Oceanografia e Geofisica Sperimentale)	2010	1:10,000	0.5 m	< 5 m
Agea 2011 aerial images - regional data set	2011	1:10,000	0.5 m	< 4 m
TeA 2014 aerial images - regional data set	2014	1:10,000	0.5 m	0,5 m
TeA 2017 aerial images - regional data set	2017	1:10,000	0.2 m	0.3 m
Regional CGR 2018 aerial images	2018	1:10,000	0.3 m	0.3 m

Table 2 - Characteristics of the digital bathymetric model (DBM) used in the study.

DBM (years of survey)	Geometric resolution; planar position accuracy; datum	Source
1901 (1880-1905)	50×50 m; 5 m; Genova - low tide level, corrected for medium tide.	Nautical map at 1:100,000 scale, survey at 1:30,000 scale, measurements with sounder with centimetre detail. Hydrographic Institute of the Italian Navy.
1953 (1953-1954)	50×50 m; 5 m; Genova - low tide level, corrected for medium tide.	Nautical map at 1:100,000 scale, survey at 1:10,000/20,000 scale, measurements with sounder with centimetre detail. Hydrographic Institute of the Italian Navy.
2012 (2012)	5×5 m; 5 m; Genova - medium tide level	Topo-bathymetric Lidar survey, single-multibeam surveys. Eni S.p.A., Arpae - Emilia-Romagna Region and Province of Ferrara.

The approach used to achieve both qualitative and quantitative information is based on spatial analysis techniques in a GIS environment. GIS analysis based on historical topographic maps and aerial images allows us to compare the position and evolution of river mouths at different times. The morphological data cover a longer time interval than the gas exploitation period, thus allowing us to identify any foregoing trends, independent of the processes triggered by the subsidence induced by the gas withdrawal.

The data concerning Reno and Fiumi Uniti deltas let to reconstruct the shapes changes and the timing of fore-stepping and back-stepping phases of the system.

A more detailed analysis is based on georeferenced shoreline position over time, which shows the tendency to advance, retreat and the stability of the coast. Such quantitative shoreline changes evaluation points out trends and rates, which are compared with subsidence variation. In the unprotected and relatively natural sandy sector in front of the Vene di Bellocchio lagoon within the Reno delta, 11 shorelines from the period 1943-2011 are analysed using the Digital Shoreline Analysis System tool (DSAS) for GIS (Thieler *et al.*, 2005).

The evolution of the sea-bottom is inferred from the analysis of different 3D bathymetric models. Raw data differ both in acquisition methods (from manual sounder to multibeam) and in the number and distribution of detected points. Due to the error associated with interpolation, the use of these maps is not appropriate for calculating volumetric variations of the seabed. The analysis of DBMs is very significant from a qualitative point of view, in fact, they testify to strong morphological changes in the seabed over time, as deepening or translation of the topo-bathymetric profile.

The subsidence monitoring data describe the differential vertical movements of the coastal plain, starting from the second half of the 20th century. Measurement techniques have evolved over time and have influenced the assessment of subsidence rates. In order to minimise the inherent differences in measurements, the published maps of spatial distribution of subsidence are used; these maps represent the ranges of values and not the single measurement points, providing valid information for the aims of the study. The subsidence rate referred to each survey or to a specific year corresponds to the minimum, the maximum or the average of the range values reported for the study sites.

Among the fields production data, the quantity of gas pumped expressed in standard cubic metres per year is used. The total gas volume extracted up to the 1980s is divided equally for each year of the period, lacking the specific information on the true volume extracted annually. For the following years, the exact quantity of gas extracted per year is reported.

3. The case studies

The case studies areas (Fig. 1) affected by chronic beach erosion and influenced by major gas field still in production, are:

- Reno River delta that hosts the Dosso degli Angeli gas field, located inland at a minimum distance of 2 km from the shoreline;
- Fiumi Uniti River delta next to the Angela Angelina gas field, located offshore at about 2 km from the shoreline.

In the two sites, well documented erosion processes are responsible for progressive back-stepping of the river mouths and rectification of the coastline, in a context of a general profound remodelling of the delta cusps (Calabrese *et al.*, 2012).

They suffer from high subsidence rates too, especially during exploitation time, whereas recently the phenomenon is decreasing sharply in the Reno delta and mildly in the Fiumi Uniti delta (Table 3).

The monitoring results show that up to 2006, the minimum and maximum subsidence values are respectively between 5-10 mm/yr and 15-20 mm/yr in both deltas; the data of partially overlapping surveys are comparable although they were acquired through different techniques (levelling and interferometry) and the years of the campaigns are not the same.

The more recent subsidence rates, related to the period 2011-2016 (Arpae - Regione Emilia-Romagna, 2018), show values ranging from 2.5 to 5.0 mm/yr at Reno River delta, while the Fiumi Uniti River delta is still affected by high rates up to 17 mm/yr (Fig. 3, Table 3).

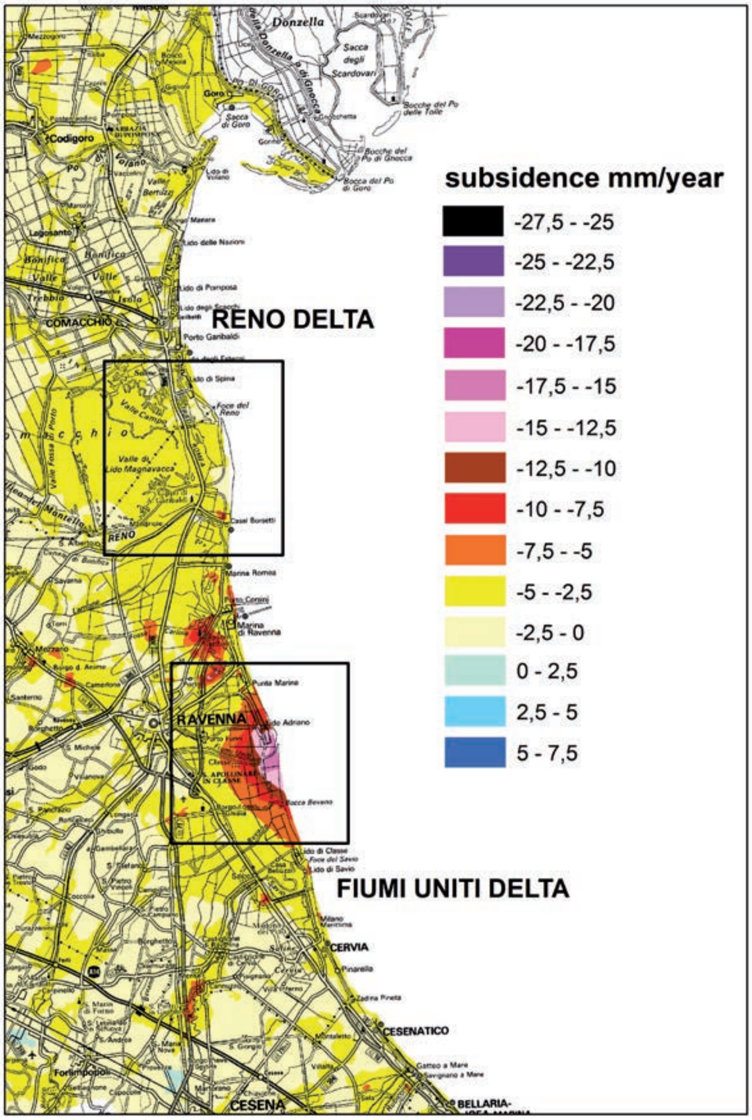

Fig. 3 - Isokinetic contours maps of land subsidence 2011-2016 and localisation the two sites of the Reno River and Fiumi Uniti River mouths (Arpae - Regione Emilia-Romagna, 2018).

Table 3 - Minimum and maximum subsidence rates recorded in correspondence of the two gas fields; data comes from Isokinetic cartography processed by ARPA-Emilia-Romagna starting from levelling and interferometric measurement.

Method and years	**Reno delta min rates (mm/yr)**	**Reno delta max rates (mm/yr)**	**Fiumi Uniti delta min rates (mm/yr)**	**Fiumi Uniti delta max rates (mm/yr)**
Levelling 1970-1999	10	20	8	16
Levelling 1999-2005	8	20	8	20
SAR 1992-2000	10	20	5	15
SAR 2002-2006	10	20	5	20
SAR 2006-2011	0	5	5	22.5
SAR 2011-2016	2.5	5	5	17

3.1. Case study 1: Dosso degli Angeli gas field and the Reno River delta evolution

Dosso degli Angeli gas fields, is one of the biggest in the northern Adriatic basin; the reservoir belongs to the pre-Quaternary succession and it is between 3000 and 3250 m deep. The field deployment started in 1971 and the maximum production was reached till 1992, with a cumulative gas exploitation of 26 MSm3 and a pressure drop of almost 300 kg/cm^2 in 1992 (Fig. 4). The peak of yearly production was reached in the 1987 (about 1600 MSm3), after that volumes extracted fell to around 200 MSm3 since 1997. Similar quantities were produced until 2004, subsequently the production was interrupted until 2010; in 2011, the activity was restarted with volumes below 200 MSm3 (update to 2018).

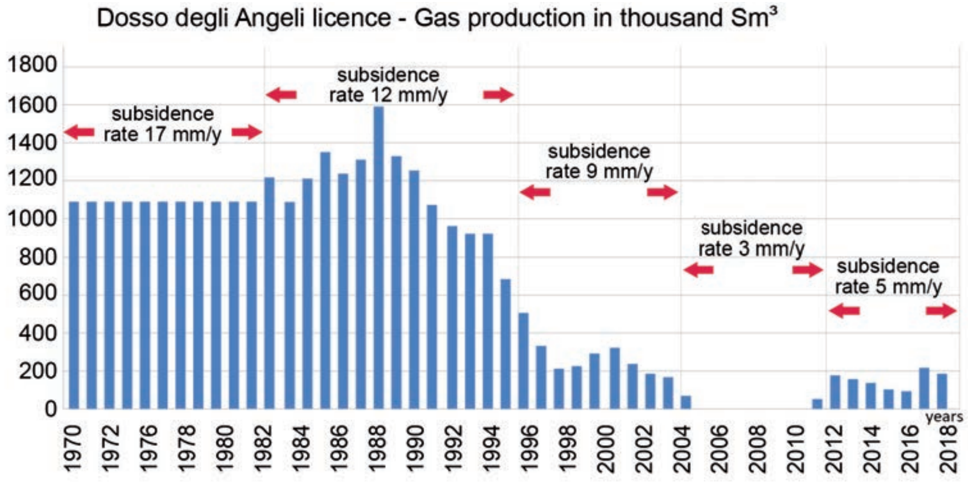

Fig. 4 - Yearly gas production of Dosso Degli Angeli gas field since 1970, data from MISE. Until 1980 the data represent an average of the total amount of gas extracted. The subsidence rates are the average over the licence surface on land, elaborated from the data sets for the main phases of extraction activity.

The Reno River delta experienced considerable growth until the early 20th century (Calabrese *et al.*, 2010a), the maximum accretion of about 700 m was observed in the period 1911-1950. The shape of the delta cusp was originally symmetrical (Fig. 5), followed by the northward deflection of the river channel; this brought to the development of a lagoon northwards (Vene di Bellocchio) and to an incipient erosion of the beaches southwards, due to reduced fluvial sediment supply (Simeoni, 2005; Billi *et al.*, 2007a, 2007b; Preciso *et al.*, 2012). The back-stepping phase and associated rectification of the shoreline occurred and still acting due to the strong reduction of sediment supply by rivers to beaches at the end of the climatic phase called "Little Ice Age" (about 14th-19th century A.D.) (Marabini, 2000; Calabrese *et al.*, 2010a).

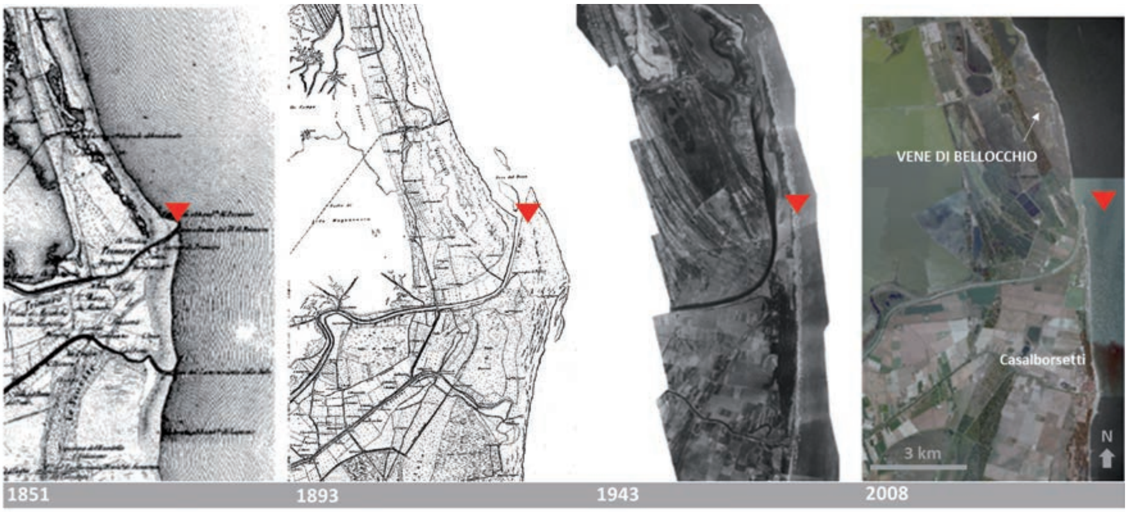

Fig. 5 - Evolution of the Reno River mouth during the last two centuries (Calabrese *et al.*, 2010a).

In this coastal sector, excluding the protection at the river mouth, few defenses have been erected over the time by government: a submerged mixed system (Longard tubes) installed around 1990 and overcome by the sea already at the end of the same 1990s and more recently beach nourishment. Because of this relatively low direct anthropic impact, this area preserves an evolutionary trend closer to the concept of naturalness with respect to the entire regional coast.

3.2. Case study 2: Angela Angelina gas field and the Fiumi Uniti River delta evolution

Angela Angelina gas field exploits a reservoir between 3000 and 4000 m deep in the pre-Quaternary succession; the production (Fig. 6) reached the peak in the1998 (over 1,700 MSm3), afterwards the extracted volumes progressively decreased to about 200 MSm3 since 2016.

The total volume pumped in the 1965-1980 period is equally spaced as there is no information on annual withdrawals. Until the 1995 the volumes extracted annually ranged from 400 to 200 MSm3 with a slight progressive reduction between the 1980s and the 1990s. A marked increase of production is recorded between 1995 and 1998.

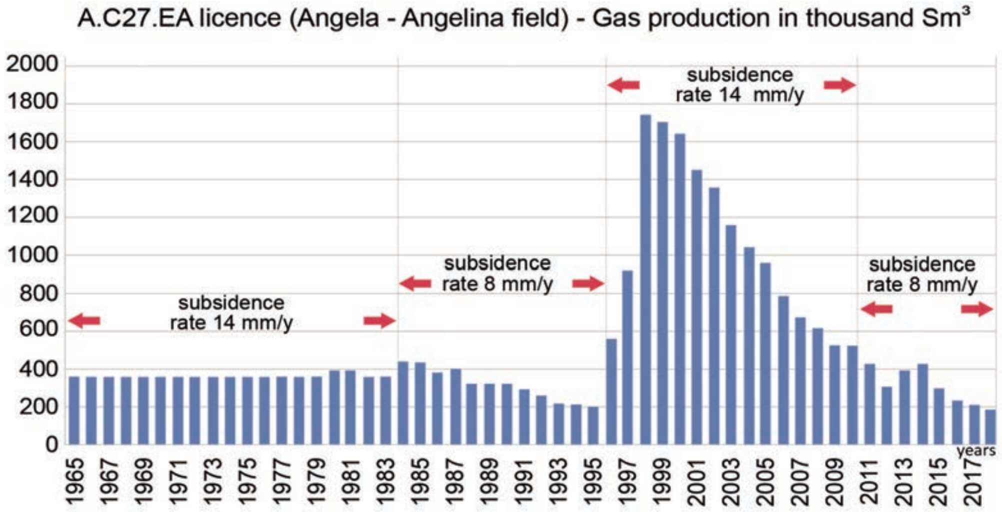

Fig. 6 - Yearly gas production of Angela-Angelina gas field since 1965, data from MISE. Until 1980 the data is the average of the total amount of gas extracted. The subsidence rates are the average over the licence surface on land, elaborated from the data sets for the main phases of extraction activity.

The Fiumi Uniti delta advanced symmetrically until the first half of the 19th century and the maximum accretion was reached before 1850, after which the delta cusp underwent similar changes observed at Reno River delta, such as the deflection of the river channel towards the north and the progressive erosion of the most advanced barriers (Fig. 7). This remodelling still acts today and gives the mouth the shape of a small estuary. The evolution of the mouth in the last century has been interpreted as the expression of the passage from an over-feeding condition (river-dominated phase) to an under-feeding condition (wave-dominated phase) (Calabrese *et al.*, 2010a, 2012).

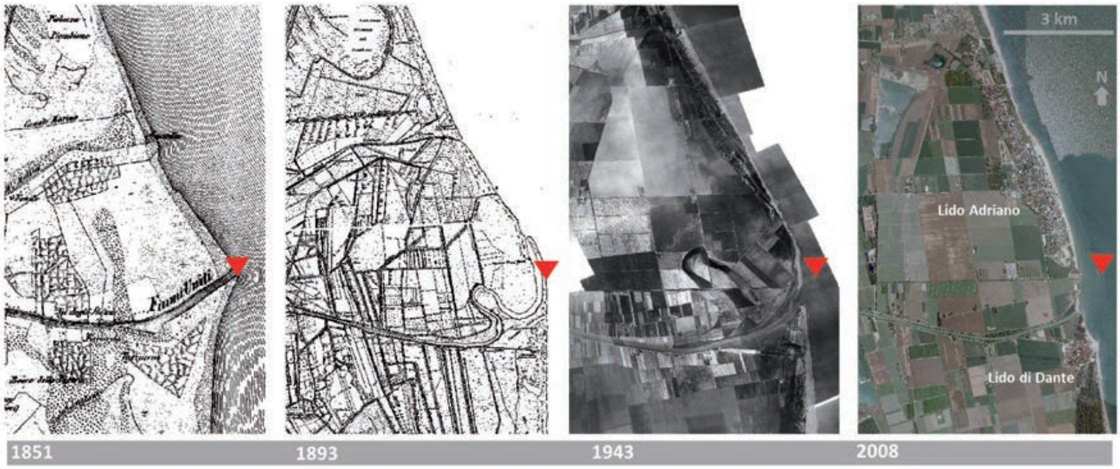

Fig. 7 - Evolution of the Fiumi Uniti River delta during the last two centuries (Calabrese *et al.*, 2010a).

The northward side of the estuary is protected by embankments, breakwaters, and submerged groynes, built over the last 30 years starting from the beginning of the 1970s. In the southern side of the river mouth, groynes were built in the 1990s, after the 2000s they were included in a multiple defense system closed by detached breakwaters.

The Fiumi Uniti River area is characterised by an intense urbanisation, which caused the flattening of coastal dunes, with important loss of sand reservoir for the beaches and an accelerated sediment compaction. In the northern sector of the mouth, Lido Adriano village was erected starting from the 1950s while, in the southern sector, Lido di Dante since 1958 with maximum development after the 1980s.

4. Analysis and results

Integrated analysis and data comparison are applied in the two case studies in order to assess a possible relationship between coastal erosion and subsidence induced by gas extraction.

4.1. Case study 1: Reno River delta

The re-analysis of historical cartography and aerial images confirms the occurrence of dismantling processes of the delta cusp and the rectification of the shoreline, with a progressive land loss starting from the first half of the 20th century. The erosion causes the consumption of the spit between the river channel and the sea and the rapid landward migration of the sand barrier protecting the Vene di Bellocchio area (Fig. 5). The regressive trend produced a maximum shoreline retreat of 1100 m in the last hundred years (average rate -11 m/yr).

The position of the shoreline progressively recedes with constant continuity, experiencing negligible deviations from this general trend. The long-term change rates are substantially constant over the last 60 years, although in the last few years the maximum shoreline retreat between the Reno River mouth and Lido di Spina shows a relative peak reaching values over 20 m/yr, the highest in the entire regional coast (Calabrese *et al.*, 2010b).

The linear regression of the shoreline data shows that the change in the position can be probably approximated to a continuous and linear process in the time interval considered (r-square equal to 0.99 in the proposed transect) (Fig. 8). This means that there are no substantial variations in the coastal retreat before and after the gas production period of the Dosso degli Angeli field; therefore, the long-term change rates (in the case of Fig. 6: -8.8 m/yr) can be considered valid for past and recent years into this coastal sector.

Differently, subsidence displays remarkable variations that deviate from the general linear trend of shoreline changes and that can be closely associated with the extraction activity. Fast land lowering occurs in the period 1955-1980, reaching velocities of 12-13 mm/yr and further increase are experienced during the maximum gas field activity with subsidence rates up to 20 mm/yr. Later, concurrently with the reduction in gas extraction, there was a gradually decrease of the subsidence rates, 5 mm/yr after 2004.

As shown in Fig. 8, data from the period 1982-1990 suggest that there may be a correlation between the slight increase of the shoreline retreat and the peak of gas production; similarly, the bland slowdown between 2002 and 2011 can be associated with the reduction and then interruption of the volumes extracted.

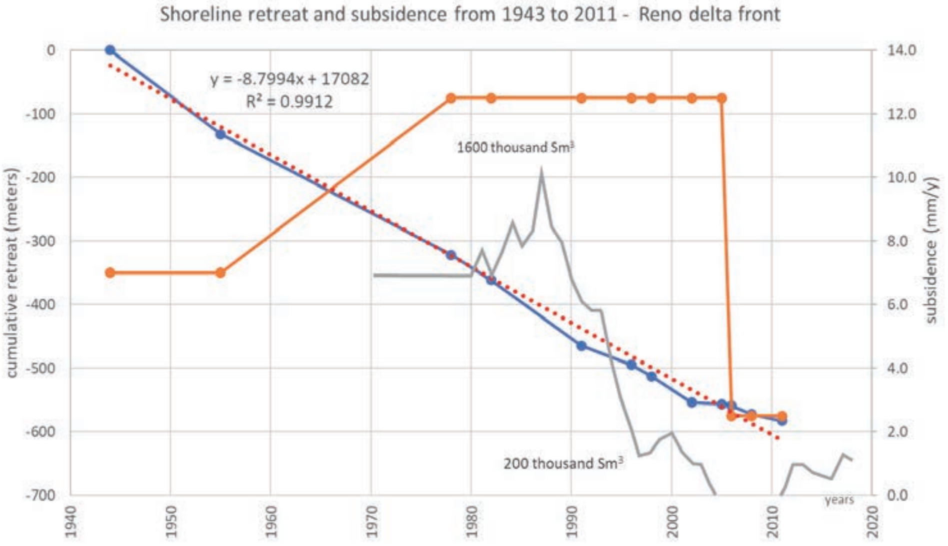

Fig. 8 - Shoreline changes (blue line) along a transect and subsidence (orange line) at Reno River delta front in the period 1943-2011; regression line equation for shoreline changes is reported. Gas production trend (gray line) is reported (see Fig. 8).

The fact remains that between 1943 and 1955 there is one of the highest retreat rates in the entire period considered.

Similarly, from the analysis of the sea-bottom evolution, a progressive and fast lowering during the period 1900-1950 is clear, before the beginning of gas field exploration (Fig. 9). The most pronounced deepening is localised at the delta fronts where, in this period, the seabed deepens up to over 4 m in the shoreface and 2 m in the offshore and quite equivalent values are confirmed in the following period (1953-2012), with rates between 4 and 8 cm/yr. Sea-bottom far from the river mouths does not show such marked dynamics. In more recent time, the seabed still deepens but at much lower rates.

The lowering of the seabed is associated with a strong retreat of the foreshore, which is over 500 m in the period 1901-1953, it is about 500 m in the period 1953-2012 and, then, it slows down in more recent time.

4.2. Case study 2: Fiumi Uniti River delta

The geomorphological evolution of the Fiumi Uniti delta, resulting from the analysis of historical maps and aerial images, is summarised in Fig. 7: the delta front, from the beginning of the 20th century to nowadays, is characterised by a progressive erosion and land loss. The analysis of the shoreline evolution (Fig. 10) highlights an incessant coastal retrogradation with average rates ranging from 2.2 to 5.0 m/yr in the period 1919-1967. From the beginning of mining activities at Angela Angelina gas field in 1965 until the maximum gas production after 1990, shoreline retreat rates are similar to the ones in the pre-production period (rates 4.0-4.5 m/yr).

Subsidence led to a local land lowering of about 30 cm in the period 1900-1950 and about 80-90 cm between 1950 and 2000 (Teatini *et al*., 2005). The acceleration of the phenomenon in the second part of the century has been related to gas exploitation activities, as confirmed a recent study (Arpae - Regione Emilia-Romagna, 2018).

The shoreline position in the last decades shows a general marked variability in space and time, mainly influenced by the coastal defense interventions; however, in the southern and unprotected

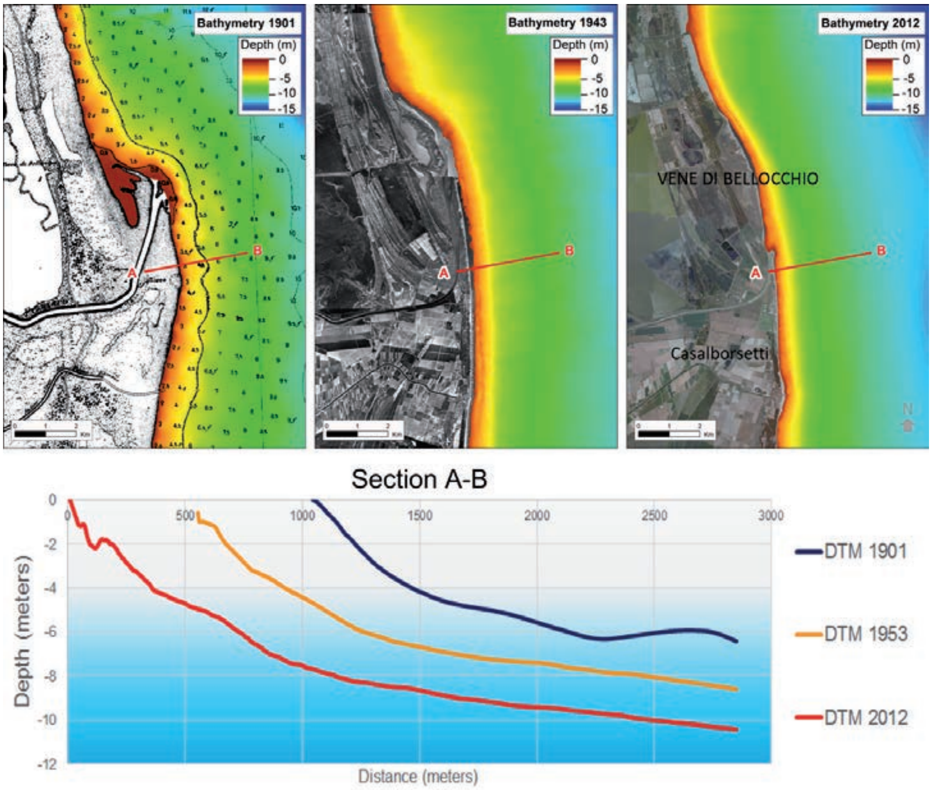

Fig. 9 - Sea-bottom evolution at Reno River delta front.

coastal sector of the Fiumi Uniti River mouth, beach evolves more naturally. In this sector, the shoreline retreat during the pre-production interval 1943-1955 is about 3 m/yr while the rates for the period 1955-1978, when gas exploitation began, it is approximately 4.5 m/yr (Fig. 11). This difference could be attributed to the effects of subsidence induced by extraction. Subsequently, however, this correspondence fails because there is higher shoreline retreat (about 7.3 m/yr) when production is at its lowest (1982-1991 period) and lower rates (about 2.5 m/yr) during the period of maximum production (1998-2005) (Fig. 11).

Sea-bottom evolution is quite analogous to Reno delta one, even if the deepening is generally less. The maximum deepening, about 4 m in the 1901-2012 period, is observed in the shoreface while it decreases towards the offshore, where sea-bottom lowers of about 2 m in the same period (with reduced drops in the 1953-2012 period). The relevant point is that the sea-bottom lowering occurs since the period 1900-1950, before the gas field exploitation (Fig. 12).

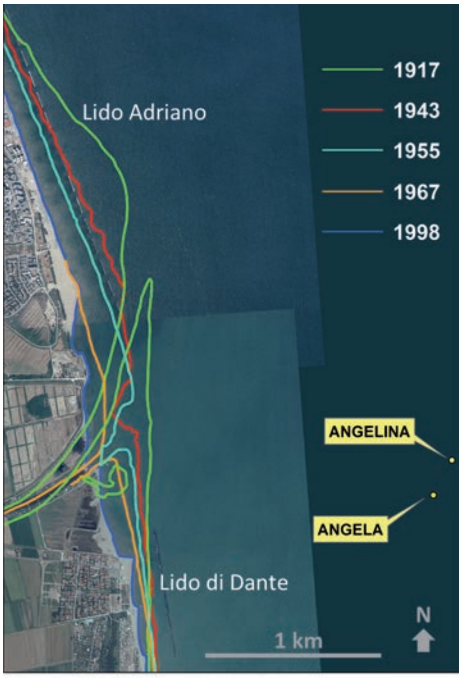

Fig. 10 - Shoreline position at Fiumi Uniti River in the period 1917-1998.

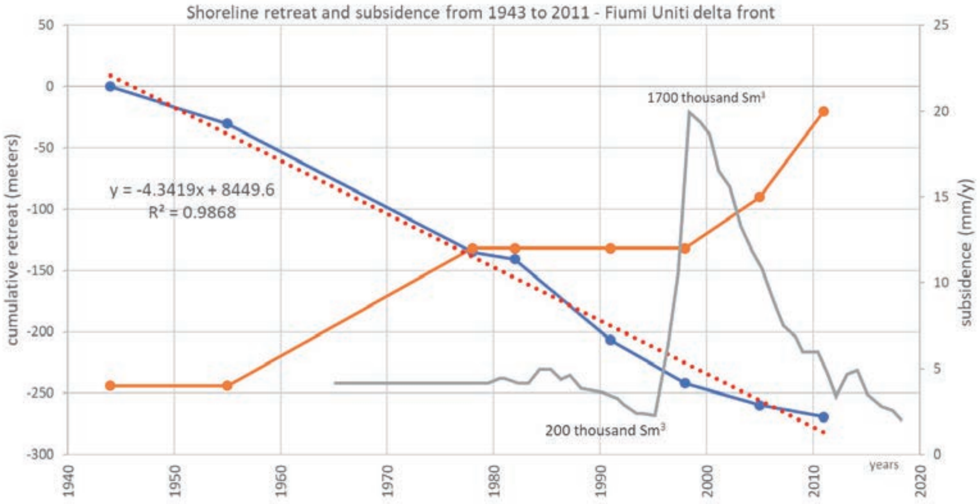

Fig. 11 - Shoreline changes (blue line) along a transect and subsidence (orange line) at Fiumi Uniti River delta front in the period 1943-2011; regression line equation for shoreline changes is reported. Gas production trend (gray line) is reported (see Fig. 4).

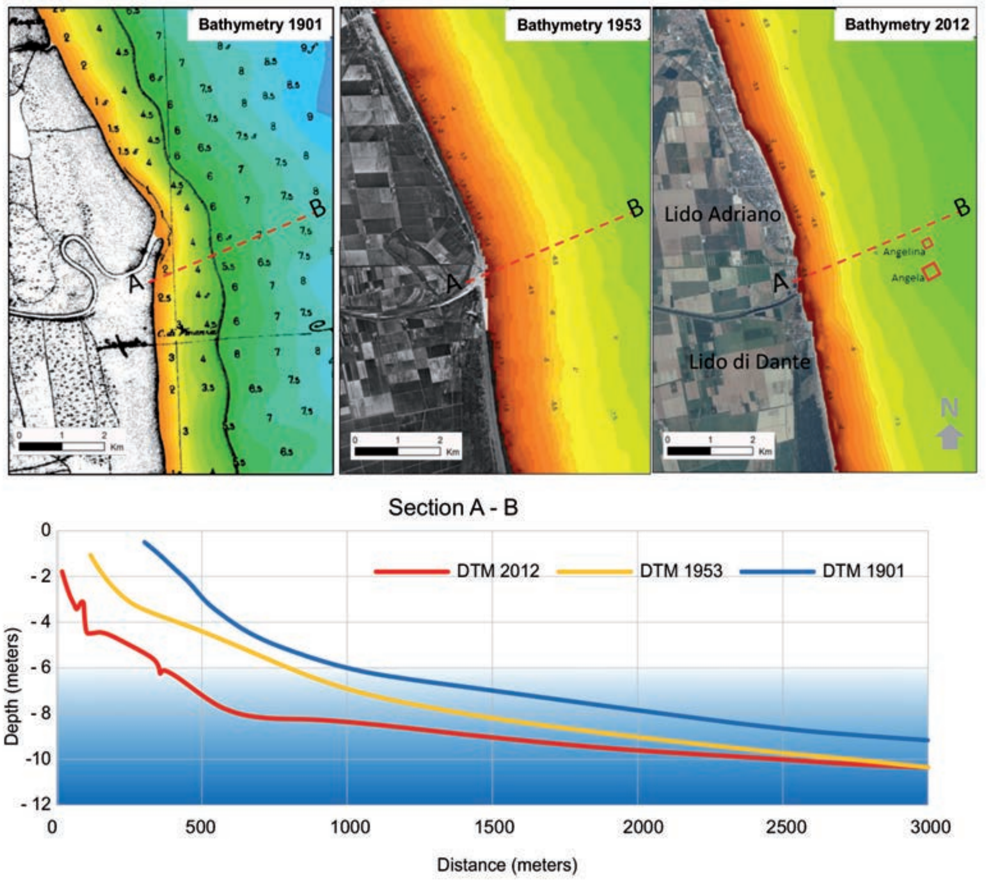

Fig. 12 - Sea-bottom evolution at Fiumi Uniti River delta front.

The data analysis introduced shows that both case study areas are characterised by a strong beach erosion even before gas exploitation. It is, therefore, evident that the subsidence induced by withdrawal overlaps with other long-term phenomena, without significantly increasing the erosive trends, contrary to what had been hypothesised so far in the Emilia-Romagna coastal area (Arpa Emilia-Romagna, 2009).

A rough test to assess how the choice to focus only on subsidence can be misleading is provided by Bruun's rule (Bruun, 1962); it is based on the assumptions that to maintain the equilibrium cross-shore profile under relative sea level rising, the coastline will move landwards a distance of approximately 100 time the vertical sea-level rise. In Fig. 13, two beach profiles dated 2006 and 2012 are shown, along a section crossing the beach system of Vene di Bellocchio, within the case study of Reno River delta. Starting from the 2006 cross-shore profile, using the Bruun's rule, the backward migration of the shoreline is calculated, resulting for a couple of scenarios of relative sea-level rise induced by subsidence (Fig. 13). This is obtained by applying respectively subsidence rates of 5 and 20 mm/yr, which are lowest and maximum rates measured in the area. In both cases, the shorelines move very little, if compared with the effective regression that is measured into 90 m; this means that the subsidence contributes for less than 15% to the inland shoreline migration. Considering the eustatic contribution quite comparable to the subsidence one, with sea level rising rates between 2.6 (best scenario) and 6.25 mm/yr (worst scenario) (Perini *et al.*, 2017), the theoretical shoreline retreat increases, almost doubling but it remains far below the real measures.

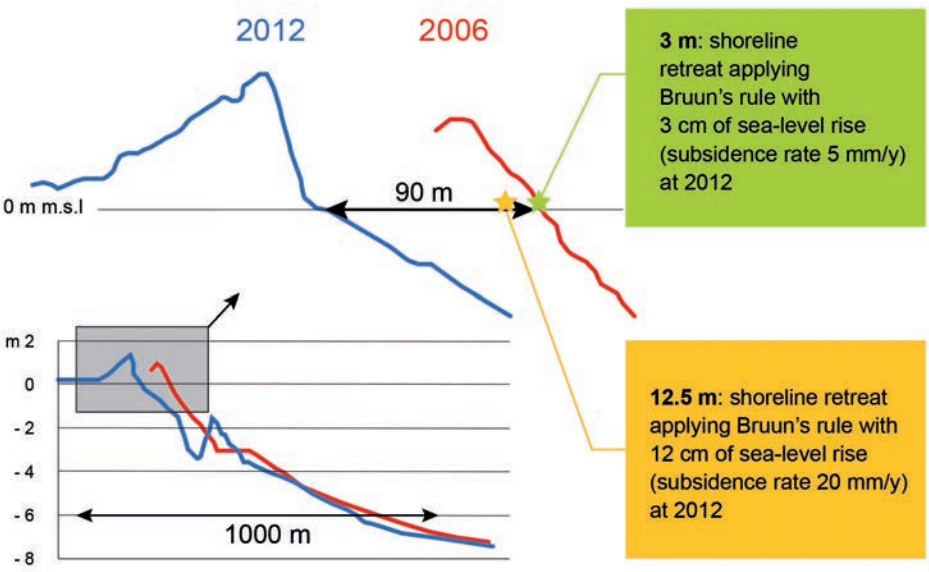

Fig. 13 - Measured beach profiles in 2006 and 2012 along the transect crossing the Sacca di Bellocchio. The positions of the shoreline according to Bruun's rule applying relative sea-level rise related to subsidence rates of 5 and 20 mm/yr are marked.

The Bruun's rule, however, does not consider several important geological and oceanographic principles (Andrew *et al.*, 2004) as the modification of beach profile due to the sediment flows. On the contrary, longshore and cross-shore transport are well documented (Bondesan *et al.*, 1978; Idroser S.p.A. - Regione Emilia-Romagna, 1983, 1996; Calabrese *et al.*, 2010b): the effectiveness of the long-shore transport is proved by the growth or erosion of the beach close to transversal hard defenses, while the landward cross-shore transport by washover fans in the study areas.

Moreover, as emerged by ongoing studies, sandy deposits beyond the closure point are evidence of seaward cross-shore flux.

Since the only extraction effect is not sufficient to explain the land loss, other factors are considered, such as reduced river supply, coastal artificialisation and impacts of the sea-storms.

In the international context, the insufficient sediment supply, associated with the sea level rise, has been indicated as the main cause of drowning and land loss in the Mississippi River delta (Blum and Roberts, 2009) and a general decline in fluvial load in this century has also been assessed for other major deltas of the planet, such as the Nile, the Indus, the Danube, the Yangtze, and the Rhone rivers (Giosan *et al*., 2014).

The change in the shape of the river mouths in the study sites is also symptomatic of progressive river supply decrease: the morphology ranges from symmetric to strongly longshore-deflected and asymmetric (see Figs. 5 and 7), as river influence becomes weakened and wave-induced longshore transport dominates (Calabrese *et al*., 2012; Anthony, 2015); the current configuration is the further evolution, delta destruction and an estuary-like shape occurs as the river supply is minimal.

The two diagrams of Figs. 14 and 15 summarise the evolutionary phases of the Reno and Fiumi Uniti deltas compared with the dominant processes in the territory, including those with impact on sediment supply.

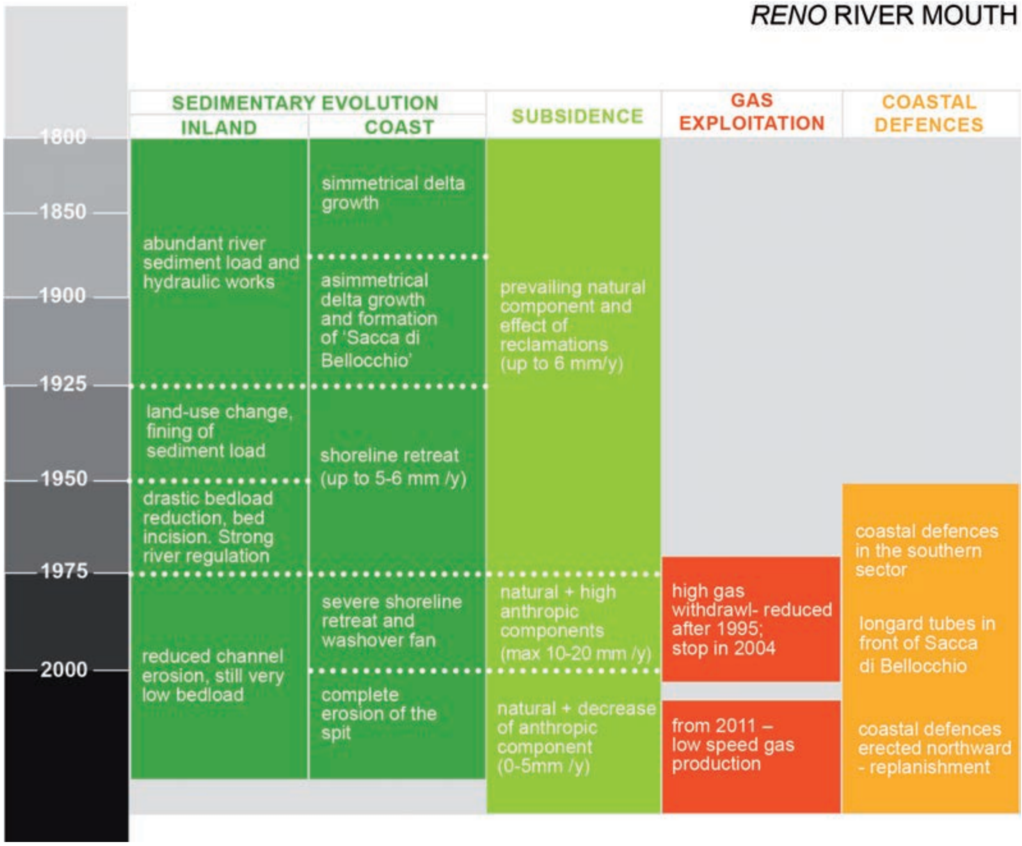

Fig. 14 - Reno River delta evolution and dominant processes in the territory.

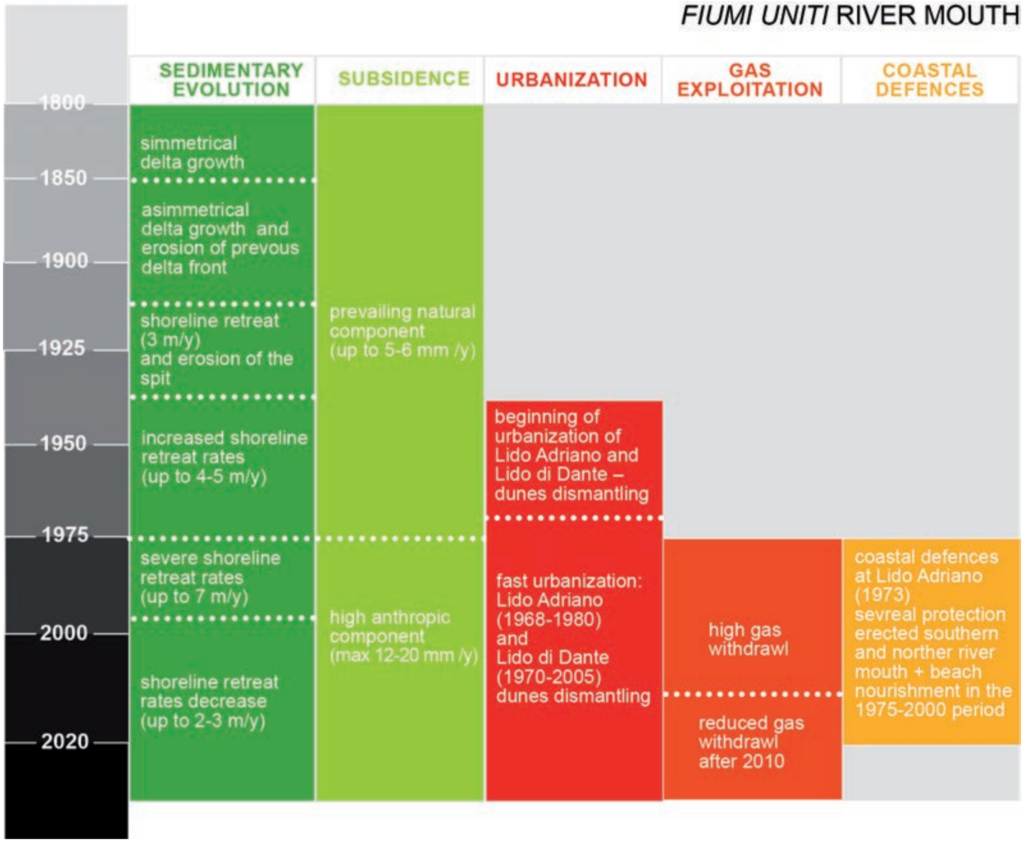

Fig. 15 - Fiumi Uniti River delta evolution and dominant processes in the territory.

For both areas, it is possible to define three main steps:

1. before the 19th century a strong delta growth phase starts and lasts to the end of the century (at Fiumi Uniti River) or the beginning of 20th century (at Reno River mouth). Delta fore-stepping testifies a strong contribution of sediment by rivers that compensates and exceeds the space created by subsidence, mainly natural at that time;
2. during the first half of the 20th century, the sediment supply is no longer enough to guarantee the previous straight progradation typical of the river-dominated delta. Marine processes control the sand redistribution along the coast and the erosion of deltaic cusps begins. This is related to changed climatic conditions and to anthropic actions inland, as the effective land use change along the rivers and the development of hydraulic control works;
3. after 1950 extensive sediment mining on riverbed, coast urbanisation and groundwater/gas exploitation are dominant.

During the last step, along the Reno River, significant land use changes in the catchment basins, dam construction, bed excavation, induce important channel morphology, and sediment water budget variations, which produce an almost null sediment transport by the river (Billi *et al.*, 2007b; Preciso *et al.*, 2012). The major role is certainly played by the intense and out of control sand mining in river channels that occurred between the 1950s and the late 1970s and causes a deficit of sediment for the beaches and a strong incision in the riverbed. Although the stop to such activity imposed by the regional government in the 1980s has reduced the riverbed degradation and favoured a new equilibrium state, the bedload yield of the Reno River is still very low (Preciso *et al.*, 2012). A specific study on the impact of land use changes is not available for Fiumi Uniti River, however some bed-load measurements and river runoff analysis document that a very reduced sediment transport still exists, not enough to maintain beach balance (Ciavola *et al.*, 2010; Billi *et al.*, 2017).

In a situation of insufficient sediment supply, the erosive effect produced by the waves during severe sea storms can produce morphological changes that are much more marked than those induced by the only coastal lowering due to the subsidence of the area. Furthermore, at regional scale, there is no direct correlation between the severity of impacts and the spatial distribution of subsidence: the erosional hot spots, in fact, do not necessarily correspond with the areas with the highest rates.

In the study sites, sea storms are responsible for sudden and intense changes in coastal morphology, as reported by several studies in other context (Roberts *et al.*, 1987; Pilkey *et al.*, 1989; Davis and Dolan, 1992; Morton *et al.*, 2003). Five major sea storms, documented in historical database (Perini *et al.*, 2011), have likely contributed to the sharp shoreline retreat in the 1955-1966 period. More recently, the greatest beach loss occurs as result of major events, such as that of February 2015 (Perini *et al.*, 2015), and this loss is not recovered in subsequent years (Fig. 16).

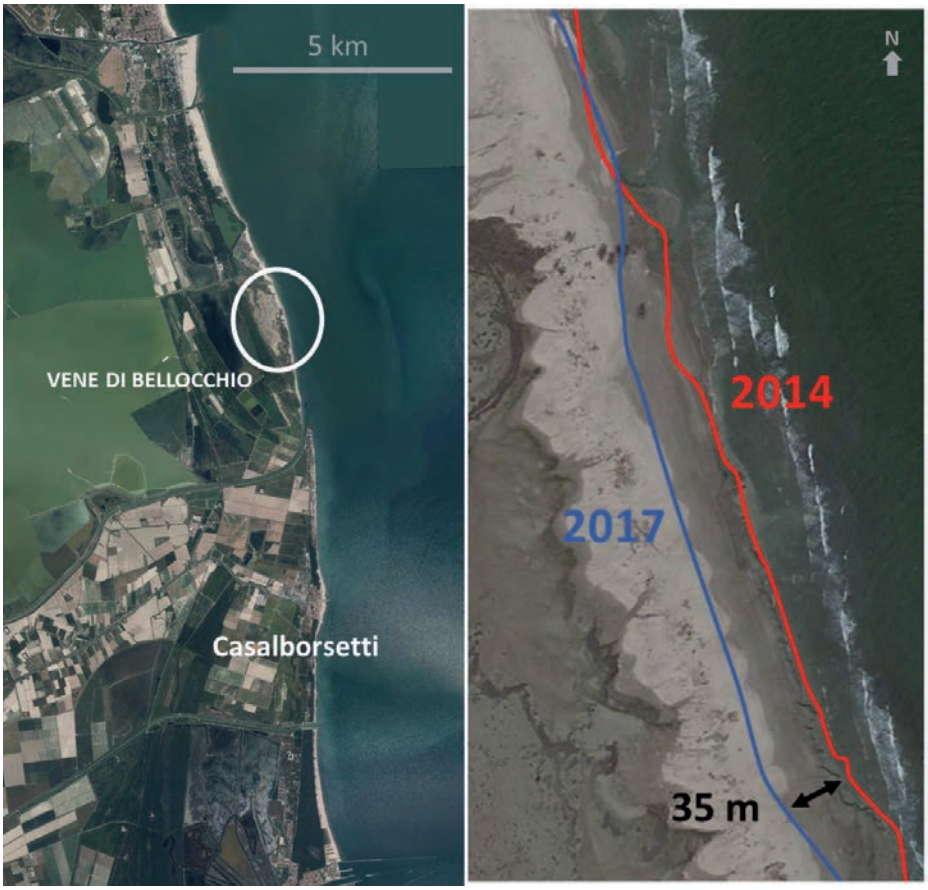

Fig. 16 - Aerial photo after big sea storm (February 2015) at Reno River delta front. Compared to July 2014 (shoreline drawn in red), the maximum retreat is about 35 m; after two years the shoreline (blue line) still corresponds approximately to that of 2015.

Another factor of strong impact on the coast in the last 50 years are hard coastal defences and jetties: large ports affect long-shore transport by acting as sedimentary traps in the over-flow side and subtracting sediment to the under-flow side (Idroser S.p.A. - Regione Emilia-Romagna, 1983; Calabrese *et al*., 2010b). The seawalls and banks fix the shoreline, the breakwaters partly stabilise the protected beaches but generate migrating erosional hot spots in the contiguous areas (Perini *et al*., 2008). This complexity has often masked what is the longer-term natural trend as the dismantling of delta apparatuses that possibly continues to make an important contribution to erosive processes, particularly in the study areas.

5. Conclusions

The aim of the study is to assess the impact of land subsidence induced by gas withdrawal on coastal erosion processes. The analysis is focused on the Reno and Fiumi Uniti deltas, which are respectively localised in Dosso degli Angeli and Angela Angelina gas fields. The work is based on the re-analysis, integration, and comparison of multiple data sets and cartographies concerning geomorphological aspects, as deltaic evolution, shoreline retreat, lowering of sea-bottom compared with gas production information, and land subsidence.

In both study areas it is confirmed that the subsidence is strongly affected by gas extraction causing unavoidable environmental impacts to the water circulation into the channels and lagoon and increasing the sea flooding risk inland (Perini *et al*., 2017); on the contrary, it seems that such phenomenon plays a secondary role in the beach erosion process if compared with other causes. Long-term processes, including the dismantling of delta front due to the reduced sediment supply and more recent morpho-dynamics processes, influenced by the engineering interventions, have, indeed, the main role on the coastal erosion in the study areas. The most direct evidence of this is that the shoreline retreat starts before the beginning of gas exploitation, it does not fit with the trend of subsidence rates and, therefore, it is difficult to correlate it with the different phases of extraction activities.

On the other hand, long-term processes are evident from the analysis of historical cartography and from the constant and linear shoreline change rates since the beginning of the 20th century. Coastal geomorphology studies and analysis of the impact of sea storm over the last 50 years show that the most critical areas due to coastal erosion are often associated with the local littoral configuration and dynamics as well as the presence of artificialisation of the coast.

In order to better understand coastal erosion and, therefore, to make the most appropriate choices to contrast its effects, a holistic vision of the problem is crucial and this means shifting the focus from subsidence to the other control factors that are currently lacking in relevant studies and monitoring data, especially at regional scale.

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