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Human impact and the historical transformation of saltmarshes in the Marano and Grado Lagoon, northern Adriatic Sea

Giorgio Fontolan [a,*], Simone Pillon [a], Annelore Bezzi [a], Renato Villalta [b], Marco Lipizer [b], Antonella Triches [b], Alessandro D'Aietti [c]

[a] Dipartimento di Matematica e Geoscienze, Università di Trieste, Via Weiss 2, 34128 Trieste, Italy
[b] Autorità di Bacino Regionale ABR-FVG, Contrada Savorgnan 9, 33057 Palmanova, Italy
[c] Osservatorio Alto Adriatico, Agenzia Regionale per la Protezione dell'Ambiente del Friuli Venezia Giulia (ARPA-FVG), Via Cairoli 14, 33057 Palmanova, Italy

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ABSTRACT

Historical transformations of the saltmarshes in the six sub-basins of the Marano and Grado Lagoon were analyzed using aerial photographs (1954, 1990, 2006), and the support of historical maps and topographic surveys. Analysis of the 2006 set of aerial photographs enabled the definition of the present extent and distribution of the saltmarshes inside the lagoon (760 ha), with a total reduction in saltmarsh area of 16% (144 ha) compared to 1954. Direct human actions played a significant role in the budget, since total loss due to land reclamation and dredging during this period amounted to 126 ha. After excluding the total loss due to direct human interventions, different erosional and depositional marsh types were recognized and associated with different forcing factors, based on morphological and geographical evidence. Over the 52-year period marshes were lost due to: (a) drowning – the combined effects of eustatism, regional subsidence and autocompaction (102 ha); (b) edge-retreat by wind wave attack (34 ha); (c) erosion by vessel-generated waves (37 ha); and (d) coastal dynamics and inlet migration (5.7 ha). Conversely, marshes gained in area due to: (a) fluvial input (63 ha); (b) tidal input (27 ha); (c) paralagoonal deposition (45 ha); (d) the re-opening of abandoned fish farms (18 ha); and (e) the dumping of dredged material (8 ha). Our analysis demonstrates that local and short-term forcing factors can obliterate or compensate the long-term ones, especially the relative sea-level rise. A test of the integrated sediment budget carried out on one third of the total lagoon, through a bathymetric comparison between datasets from 1964 to 2009, pointed out that conservation or slight expansion of the marshes inside these basins were linked to an overall positive sediment budget of 61,000 m^3/y. Nevertheless, significant morphological changes occurred in the submerged basin, which is affected by sustained deposition along the inner margins due to sediment supplies, by an overall erosion of tidal and sub-tidal flats far from the tributaries, and by an important infilling of the channels. The analyzed data, along with information available for the Venice Lagoon, highlights how the fate of open-water lagoons is to flatten whilst submerging because of the strong influence of wind waves, which tend to transform the lagoon into a marine embayment. This transgressive condition reduces, if not negates, the compensative effect of the sedimentation rate on wind-wave-induced shear stress excess, since supplies seem to contribute primarily to the morphological accommodation.

1. Introduction

Coastal lagoons are particularly unstable and fragile transitional areas, comprising a variety of different habitats of quite unique environmental and eco-systemic value. Their complex morphology is due to the balance and relationship between the supply of sediments from the sea or rivers and erosion by tidal or wave-induced currents. The evolution of lagoon morphologies depends upon the mutual interaction between these forces, but in the medium- to long-term the effects of relative sea level rise (eustatism + subsidence) must also be included. In this context, the saltmarsh represents not only one of the most important and evident morphologies from a morpho-dynamic point of view, but also a habitat of significant worth.

Rapid erosion of tidal saltmarshes, perhaps in response to the accelerating rise in global sea level, has been documented at many

* Corresponding author.
E-mail address: fontolan@units.it (G. Fontolan).

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sites around the world (Kearney et al., 1988; Reed, 1995; Day et al., 1999; Hartig et al., 2002; van der Wal and Pye, 2004; Baily and Pearson, 2007; Ravens et al., 2009). In other cases, the mutual balance between relative sea-level rise (SLR), sedimentation rate and autocompaction (Cahoon et al., 1995; Allen, 2000) has been found to make saltmarshes accrete at a rate equal to or greater than the historical rate of eustatic SLR (Orson et al., 1987; Reed, 1988; Nielsen and Nielsen, 2002). The erosion or accretionary feedback of marshes is greatly susceptible to local conditions and forcing factors (Reed, 1995; Day et al., 1998), both natural and due to the direct and/or indirect effects of human activity (Schwimmer and Pizzuto, 2000; Adam, 2002; Cox et al., 2003), with accretion processes even occurring in basins with a sedimentary deficit and diffused erosion processes (Reed, 1995). As a driver of conservation strategy, detailed knowledge of such phenomena is crucial, not only from a protection perspective, but above all in terms of management rules, which are necessary to minimize the direct impacts of human activity (navigation, excavations, reclamation and environmental restoration) on the sedimentary budget.

In Italy, lagoons (*stricto sensu*) are located exclusively along the northern Adriatic coastline, i.e. in subsiding areas with a very high rate of relative SLR (Kent et al., 2002; Lambeck et al., 2004; Antonioli et al., 2009). In terms of significant environmental transformations, the Lagoon of Venice stands out as an emblematic example of an area having suffered severe morphological deterioration due to the acceleration of transgressive effects caused by human activity during the last century (Favero, 1992; Day et al., 1998; Ravera, 2000; Pillon et al., 2003; Sfriso et al., 2005; Molinaroli et al., 2009; Sarretta et al., 2010). On the whole, the strong negative sediment budget of the lagoon has resulted in a simplification of its morphology, flattening and deepening the lagoon floor, along with a marked reduction in saltmarshes (more than 50% from 1927 to 2002) and an increase in the area of sub-tidal flats (0.75–2.00 m depth) (Sarretta et al., 2010).

In this study, the Marano and Grado Lagoon was chosen to obtain a more general picture of the situation in the North Adriatic. It is an interesting example due to the close interaction between natural and human forcing factors. Also, it has a pressing need for effective conservation and management, largely because of the existence of widespread mercury pollution in its sediments (Piani et al., 2005; Covelli et al., 2008, 2009, 2012), which means any prospective marsh reconstruction project becomes quite a delicate issue (the lagoon has been declared a Site of National Interest because of its high level of sanitary and environmental risk). At the same time, there is a paucity of physical data (wind, wave, climate, bathymetric maps), which has only very recently begun to be addressed. The study focused on an analysis of saltmarsh evolution through a comparison of aerial photographs, supported by historical maps, which are the only available data in this regard for the lagoon. The factors affecting saltmarsh surface changes were analyzed, with geographical, morphological and vegetation parameters investigated in order to understand the processes at work. In addition, a test of the sediment budget of two of the six basins through the bathymetric comparison of two datasets was carried out, leading to better knowledge surrounding the relationship between saltmarsh evolution and the whole basin.

2. Study area

The Marano and Grado Lagoon, located in the northern part of the Adriatic Sea, is an extremely important wetland (Fig. 1). It covers an area of 160 km^2, spanning a region between the Isonzo and Tagliamento River deltas, and is separated from the sea by a series of barrier islands divided by six tidal inlets. Seaward,

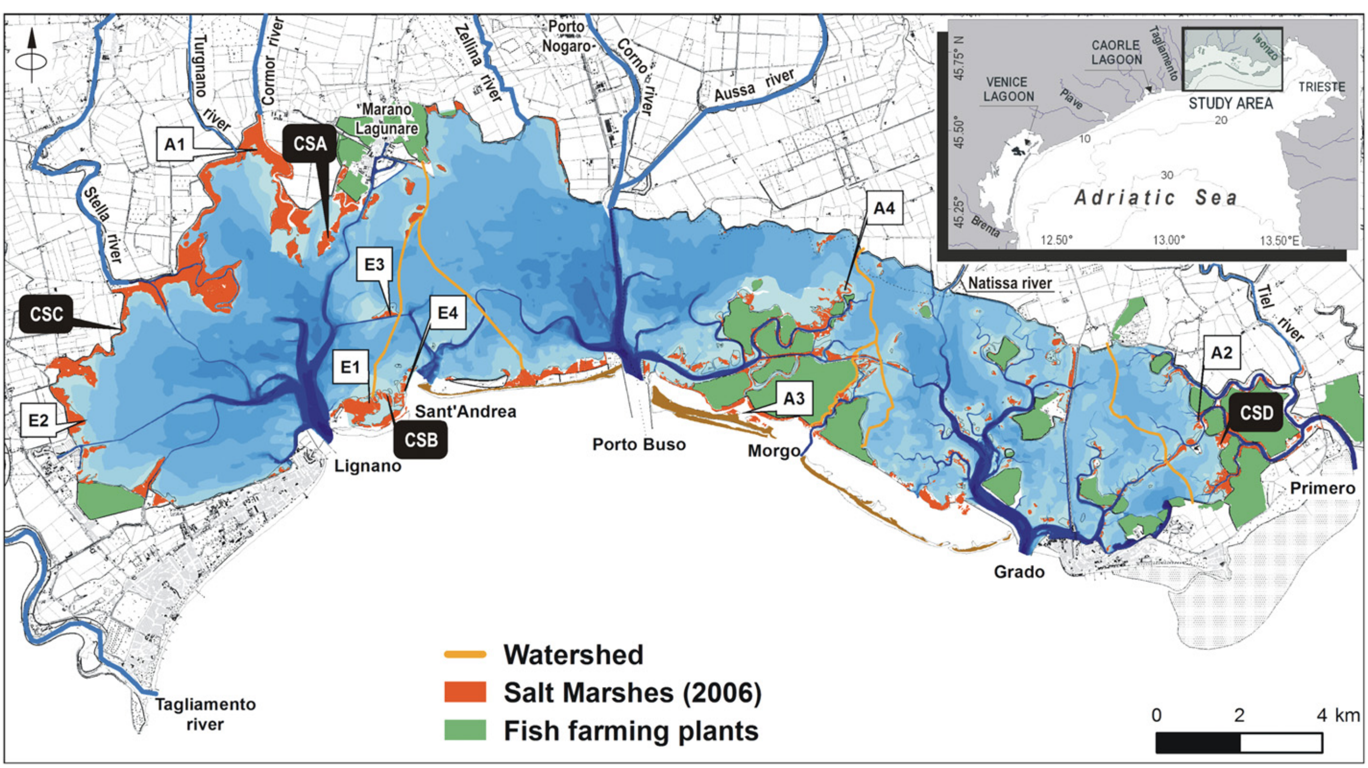

Fig. 1. Location of the study sites. The major cities, rivers and tidal inlets are indicated. The bathymetry of the lagoon is pictured in shaded colours (after Triches et al., 2011). Squared balloon callouts indicate the location of saltmarsh types, as identified in this study (see section 5.1). Rounded black balloon callouts indicate the location of the four case studies (see section 4.2, Figs. 3 and 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a series of new barrier islands extend 10 km from Porto Buso to the Grado inlet, alternating with tidal flats. These fast-evolving islands define a small (6 km^2) paralagoonal basin (Brambati et al., 1998).

The morphological and bathymetric features of the lagoon as a whole are known from a hydrographic map edited in 1966 (Dorigo, 1966) and from a new release edited at the end of 2011 (Triches et al., 2011; see background in Fig. 1). For the Grado Lagoon only, supplementary descriptions and historical maps are available (Dorigo, 1965; Brambati, 1969), as well as a geomorphological map (Gatto and Marocco, 1992). The information available regarding the hydrodynamics of the lagoon is also quite old (Dorigo, 1965), though partially revised by Brambati (1996). According to Brambati (1996), in 1989 there were six basins (Table 1): Lignano, S. Andrea, Buso, Morgo, Grado and Primero. The hydrodynamics of the lagoon have recently been modelled numerically (Ferrarin et al., 2010), although not yet updated with the new bathymetric data.

2.1. Forcing factors in the study area

To evaluate the rate of relative SLR in the study area, the only available continuous tide data comes from the Trieste tide gauge dataset, available since 1890. Sea level fluctuations are remarkable, particularly in the last ten years, reaching 15 cm. The transgressive tendency, calculated using a linear trend of mean annual values, is +1.35 mm/y for the entire 1890–2010 dataset. Considering the three sets of aerial images (1954, 1990, 2006) used for morphological analysis in this work, separate trends correspond to +0.63 mm/y during 1954–1990 and +5.27 mm/y during 1990–2006.

There are some data about subsidence in the lagoon, but the calculations have been made based on benchmarks located on top of the levees, which are subject to structural subsidence and are therefore not ideal for calculating natural subsidence. The only reliable data available come from a deep borehole drilled outside the lagoon on an area of reclaimed land about 1 km from the Secca Muzzana. From this site, a regional tectonic subsidence rate of 0.49 mm/y has been calculated (Antonioli et al., 2009). Tide gauge data series comparisons between Trieste and Grado give a difference value of 0.8 mm/y, which can be assumed as the subsidence value for Grado during the period 1994–2005 (Ferla et al., 2008). Tides are semi-diurnal, with a mean range of 0.65 m and spring and neap ranges of 1.05 m and 0.22 m, respectively (Dorigo, 1965), but data on tide propagation inside the entire lagoon are sparse and old. Ferla et al. (2008) confirmed the data of Dorigo (1965), who reported that there is good hydraulic efficiency in the lagoon due to the short propagation delays from the inlets to the lagoon margins, with preserved or sometimes increased amplitudes.

The main freshwater inputs are: the spring rivers (Stella, Turgnano, Zellina, Aussa-Corno, Natissa, Tiel) and the River Cormor, featuring a mountain watershed and the 30 drainage pumps of the low Friulian plain. In 2009 the Autorità di Bacino Regionale ABR-FVG calculated the mean discharge of the rivers alone as 81.5 m^3/s, of which the main contributors are the Stella River (36.1 m^3/s) and the Cormor (10.7 m^3/s). There are no data available regarding sediment load.

Wind is an important driving force for the lagoon, since it can form waves over the open-water exposed to a significant fetch (Fagherazzi et al., 2006). In terms of its frequency and intensity, the local wind climate is influenced by the prevalence of winds blowing from the first quadrant, mainly from the ENE (the Bora) (Carrera et al., 1995). Southeasterly winds (the Scirocco) are also important, but to a lesser degree due to the restricted lagoon fetches. Owing to a lack of recording stations inside the lagoon, there are no wave data available.

Vegetation distribution in the lagoon area is reported in a detailed GIS (Poldini et al., 2006). The richness of its present habitats is such that the lagoon has been declared a Special Protection Area and a Site of Community Importance following EU directives.

The complex human–environment relationship in the region has led to a transformation from the lagoon's original state to that which is present today. During the last two centuries, a variety of human activities have deprived the lagoon from evolving naturally, limiting it instead to developing within a controlled and constrained context. The range of human influence can be summarized based on the data reported by Dorigo (1965) and Gatto and Marocco (1992), as well as an analysis of historical IGM (Army Geographic Institute) maps available since 1891:

(1) The reclamation of perilagoonal lands starting from the early 1900s, resulting in the extensive loss of wetlands;
(2) The construction of levees (3 m above sea level) along approximately 65 km of the lagoon's border due to the devastating flood of November 1966;
(3) The dredging of a channel for ships to cross the lagoon, part of the Litoranea Veneta – a network of canals and navigable stretches of river in the region (1915–1916);
(4) The dredging of the Aussa-Mare channel for mercantile ships to cross from Porto Buso inlet to Porto Nogaro industrial harbour, in the Aussa River (1970s); the dredging of various other channels to aid navigability;
(5) The dredging of large marinas and associated shipways; for example, Marina Punta Faro on the western side of the Lignano inlet and Aprilia Marittima marina on the western side of the Lignano Basin (1970s);
(6) The armouring of tidal inlets (except the natural S. Andrea inlet); for example, the construction of the Grado (1928–1934) and Porto Buso (1960–1964) inlet jetties. The Lignano inlet has been fixed on the western side due to the construction of the Marina Punta Faro, but only inside the lagoon;
(7) Fish farming, which is carried out on embanked areas of the lagoon enclosed by sluice gates. Fish farms cover 1796 ha across the whole of the lagoon, mostly in Grado, Morgo and Primero.

Table 1
Saltmarsh area changes in the different time periods. The reference base is the saltmarsh extent of 1954.

Basin Name	Basin extent (ha)	Saltmarsh extent (ha) 1954	% of the basin extent	Change (ha) 1954–1990	Change (ha) 1990–2006	Change (ha) 1954–2006	Rate (ha/y) 1954–1990	Rate (ha/y) 1990–2006	Rate (ha/y) 1954–2006
Lignano	5050	488.1	9.66	32.2	−23.2	9.0	0.9	−1.5	0.2
S. Andrea	700	74.9	10.70	−35.7	−6.9	−42.6	−1.0	−0.4	−0.8
Buso	4500	162.6	3.61	−33.2	−8.1	−41.3	−0.9	−0.5	−0.8
Morgo	297	8.1	2.72	3.9	0.9	4.8	0.1	0.1	0.1
Grado	3314	114.8	3.46	−55.1	−8.4	−63.5	−1.5	−0.5	−1.2
Primero	1900	56.3	2.97	−14.9	4.1	−10.8	−0.4	0.3	−0.2
Total	15,761	904.7	5.74	−102.7	−41.5	−144.2	−2.9	−2.6	−2.8

3. Materials and methods

3.1. Aerial image analysis

The location, extent and evolution of the saltmarshes in the Grado and Marano Lagoon was defined by an analysis of aerial photographs, together with the support of a recent lagoon vegetation map (Poldini et al., 2006) and some fieldwork.

Three different sets of aerial photos were used, taken in 1954, 1990 and 2006:

(1) 1954: GAI flight (nominal scale 1:35,000), 20 black and white frames 23 × 23 cm, scanned at 600 dpi. In this set, marsh morphologies were not always easily identifiable because of the nominal scale, black and white format, poor sharpness, and reflection from the sun, which frequently obscured image details. Validation of the uncertain cases was carried out using historical IGM topographical maps (1:25,000, courtesy of the Centro di Rilievo, Cartografia ed Elaborazione CIRCE of Venice);
(2) 1990: CGR flight, commissioned to draw the Regional Technical Map of the Friuli Venezia Giulia (nominal scale 1:10,000, 134 true colour frames 23 × 23 cm, scanned at 600 dpi). In this set of images, marsh morphologies were easily identifiable, due to good sharpness, detail, and very favourable weather conditions at the time of shooting;
(3) 2006: Digital true colour aerial ortho-photos, available from the National Cartographic Portal (website) of the Ministry of the Environment and viewed in ArcGIS© as a remote ortho rectified and georeferenced dataset. The images in this set are very detailed (0.3 m pixels). Any uncertain cases were validated through a comparison with the 1990 set, as well as direct recognition during field visits.

The 1954 and 1990 aerial photo sets were georeferenced in ArcGIS© using the Digital Regional Technical Map (CTRN 1:5000 scale) to identify ground control points and by applying a second order polynomial transformation. The root mean square error (RMSE) was calculated to obtain the difference between the map coordinates and the corresponding points on the photographs. Due to nominal scale, image quality, and less control points available, the oldest photo set (1954) showed a greater error value with a maximum of 10 m, while the 1990 aerial photo set never exceeded 5 m. The marsh edge at each site was digitized on-screen from the mosaicked set for each available year. The marsh edge was defined as the limit of continuously vegetated marsh. This procedure requires a good level of experience and confidence in recognizing morphologies, taking advantage of in situ observations. As the aim of this study was to evaluate the evolution of the lagoon environment, only those marshes reached naturally by the tide were considered, with the embanked fish farming areas excluded. The 1954 set was the most challenging because of the visual quality of some of the frames. In these frames, it was quite difficult to discern vegetated from the non-vegetated parts, but the available historical topographical IGM maps were very useful to validate the choices made. The IGM maps were used to identify which shape to look for to distinguish real marshes in the critical frames.

Starting from the 2006 set, the saltmarshes were classified into groups, indexed with a number code and the extent calculated for each set. Thus, it was possible to quantify the loss and gain for each group, calculating the surface area changes.

3.2. Topographical survey

A set of detailed topographical surveys was carried out on selected sites showing interesting evolution phenomena (see location in Fig. 1). The saltmarshes and nearby tidal flats were surveyed in 2009 and 2010 using a total station Zeiss Elta3 with a pole-mounted prism. The surveys were linked to the network of benchmarks present in the lagoon, which are located on the bordering levees and in some concrete bases (Protezione Civile – Regione Autonoma Friuli Venezia Giulia, 2005).

3.3. Bathymetric survey and comparison

A map comparison was carried out in order to analyze the evolution of Lignano and S. Andrea basins during recent decades. The 1964 "Hydrographic map of the Marano and Grado Lagoon" (edited by the Magistrato alle Acque di Venezia; Dorigo, 1966) was compared to bathymetrical data surveyed in the same area in 2009. The 2009 dataset forms part of the bathymetric data gathered for the "New bathymetric map of the Marano and Grado Lagoon" (Triches et al., 2011).

The two digital bathymetric models were created in ArcGIS© 3DAnalyst© using a Triangulated Irregular Network (TIN). Two 10 m cell rasters were derived from the TINs in order to compute the depth statistics and to perform the comparison. The analysis was limited to the morphological evolution of the Lignano and S. Andrea basins, currently the only ones available for a complete comparison, and was performed on a common surface of 57 million m^2. This covered the complete area of saltmarshes and left out the beach and barrier islands, which were not recognized in the sediment budget. For sediment budget calculation, no corrections were carried out on original depth data since both maps refer to the same datum (mean sea level at Genoa, IGM42). Analogously, according to Sarretta et al. (2010), no further corrections were adopted for the morphological comparison (hypsometry) due to the negligible – either positive or negative – differences between the datum and mean sea level at the time of each survey.

4. Results

4.1. Morphological types and distribution of the saltmarshes

Analysis of the 2006 set of aerial photographs enabled the definition of the present distribution of the saltmarshes inside the lagoon (see Fig. 2). On the whole, the saltmarshes cover an area of 760 ha, with a different distribution in each basin (Table 1). Based on the geographical distribution and morphogenesis (Oertel and Woo, 1994), different types of saltmarshes can be recognized:

(1) *Fringing saltmarshes and fluvial delta inside the lagoon*. These marshes (455.7 ha) are located almost exclusively in the Lignano Basin, bordering the inner margin of the lagoon and forming an almost continuous edge, although varying in width. The importance of fluvial sediment is evident because this type of marsh formed significant fluvial deltas inside the lagoon. It is also supported by the salinity distribution (Ferrarin et al., 2010), as well as by the vegetation. For these marshes the vegetation map (Poldini et al., 2006) shows habitats with vegetation of brackish and/or freshwater dominated by *Phragmites australis* and halophile *Scirpus* beds; and, only for the areas farther from the rivers, salt soil meadows dominated by tall rushes;
(2) *Tidal channel-fringing saltmarshes*. Already identified in Venice by Albani et al. (1984) and in the Grado and Marano lagoon by Gatto and Marocco (1992), this type of marsh forms by sedimentation along the edges of the channel network as a result of abrupt morphological, and thus hydrodynamic, contrast between the channels and adjacent tidal flats. Second in terms of extent (142 ha), these marshes are evenly distributed

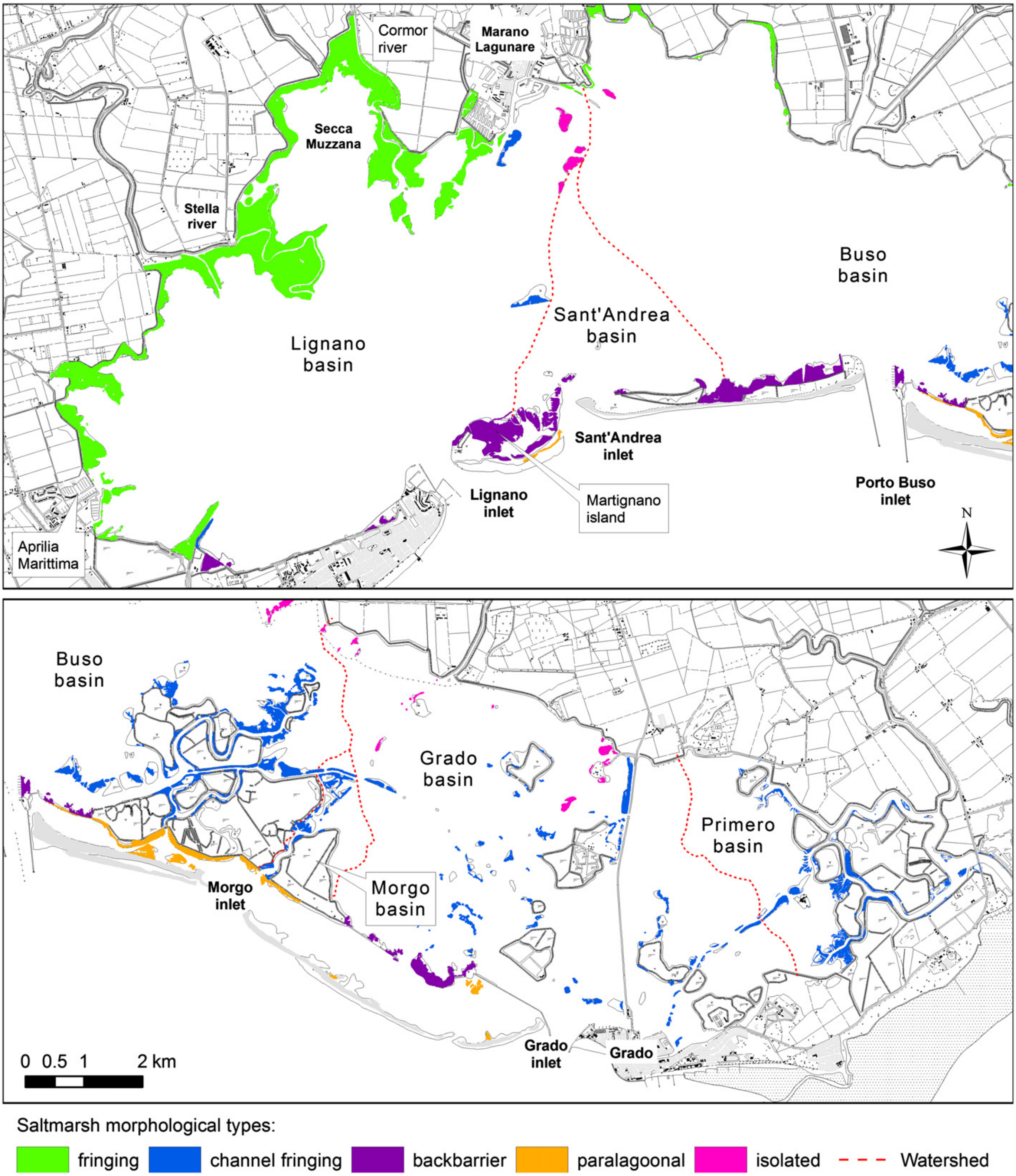

Fig. 2. Distribution of the identified saltmarsh morphological types (see section 4.1 for a description).

Table 2
Changes in the saltmarsh extent (ha) relative to each basin and the entire lagoon, during 1954–1990 and 1990–2006. Loss refers to negative changes, excluding direct human interventions (reclaimed); gain refers to positive changes either natural or man-induced. Net changes refer to the algebraic sum of loss and gain; total changes are the algebraic sum of net changes and reclaimed marshes. Detailed loss and gain are reported in the form of different erosional (E) and accretionary (A) saltmarsh types (see text and Fig. 7 for the acronym explanation).

	Lignano		S. Andrea		Buso		Morgo		Grado		Primero		Total lagoon		
Saltmarshes	1954–1990	1990–2006	1954–1990	1990–2006	1954–1990	1990–2006	1954–1990	1990–2006	1954–1990	1990–2006	1954–1990	1990–2006	1954–1990	1990–2006	1954–2006
Loss	−26.8	−16.4	−16.3	−8.6	−19.3	−8.3	−1.2	−0.9	−56.2	−9.5	−12.9	−3.2	−132.6	−46.9	−179.6
Gain	73.7	10.7	5.5	1.7	29.9	5.2	5.8	1.9	11.4	1.1	6.5	7.6	132.9	28.2	161.0
Net changes	**46.9**	**−5.7**	**−10.8**	**−6.9**	**10.6**	**−3.2**	**4.6**	**0.9**	**−44.8**	**−8.4**	**−6.4**	**4.4**	**0.2**	**−18.8**	**−18.6**
Reclaimed	−14.7	−17.6	−24.9	0.0	−43.9	−5.0	−0.7	0.0	−10.3	0.0	−8.5	−0.3	−102.9	−22.8	−125.7
Total changes	**32.2**	**−23.2**	**−35.7**	**−6.9**	**−33.2**	**−8.1**	**3.9**	**0.9**	**−55.1**	**−8.4**	**−14.9**	**4.1**	**−102.7**	**−41.5**	**−144.3**
Type E1	−13.2	−11.3	−9.7	−5.1	−7.0	−4.6	−0.8	−0.8	−35.7	−5.1	−7.4	−1.9	−73.8	−28.7	−102.5
Type E2	−13.6	−1.9	−0.8	0.0	−3.9	−1.6	0.0	0.0	−10.7	−1.8	0.0	0.0	−29.0	−5.3	−34.3
Type E3	0.0	−3.2	−3.1	−0.7	−8.5	−2.1	−0.4	0.0	−9.8	−2.6	−5.4	−1.4	−27.2	−9.9	−37.1
Type E4	0.0	0.0	−2.7	−2.8	0.0	0.0	0.0	−0.2	0.0	0.0	0.0	0.0	−2.7	−3.0	−5.7
Type A1	48.5	9.9	0.0	0.0	4.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	52.6	10.1	62.7
Type A2	2.4	0.0	0.0	0.0	2.3	0.8	2.2	1.2	3.7	0.8	6.2	7.6	16.8	10.4	27.2
Type A3	22.1	0.0	5.5	1.7	9.6	1.8	1.4	0.7	2.0	0.2	0.0	0.0	40.6	4.5	45.1
Type A4	0.0	0.0	0.0	0.0	13.7	2.4	2.2	0.0	0.0	0.0	0.0	0.0	15.8	2.4	18.2
Type A5	0.8	0.8	0.0	0.0	0.2	0.0	0.0	0.0	5.7	0.1	0.3	0.0	7.0	0.9	7.9

throughout all the basins, with the only exception being S. Andrea, and cover the greatest extent in the Buso and Primero basins (53 and 45.5 ha, respectively). Some of these marshes are actually artificial, as a consequence of a past dredging method which involved the dumping of sediment on the channel side. The habitat in these marshes comprise: Mediterranean saltmarsh scrubs; saltmarsh grass swards, dominated by *Puccinellia festuciformis*; salt soil meadows, dominated by tall rushes; and *Spartina maritima* pioneer saltmarshes. Many of these marshes, mainly the ones located along the ship canals of Grado and Primero, are degraded to patches embanked on the channel side and are frequently planted by *Tamarix* or invaded by *Rubus ulmifolius*;

(3) *Back-barrier saltmarshes*. These marshes develop in the lee of spits or barrier islands (Oertel and Woo, 1994), when the angle of the slope of the intertidal and immediate sub-tidal area is shallow. They are present (total surface area of 116 ha) on the lee side of the barrier islands inside the Lignano, S. Andrea and Buso basins. In the rest of the lagoon, back-barrier areas have been altered into embanked fish farming plants, and thus only a few examples remain near Grado. On the whole, these are “classic” marshes, with well developed creek networks and frequent salt pans. Their habitat can be described as: salt soil meadows, dominated by tall rushes; Mediterranean saltmarsh scrubs; and saltmarsh grass swards, dominated by *Puccinellia festuciformis*;

(4) *Saltmarshes in recent paralagoonal basins*. This type of marsh has formed in more recent decades in the shallow basins and swales located between the old barrier islands, partially embanked, and the new ones. These marshes (25 ha in total) are located in the Buso, Morgo and Grado basins. Their habitat comprises: Mediterranean saltmarsh scrubs; salt soil meadows, dominated by tall rushes; and *Spartina maritima* pioneer saltmarshes;

(5) *Isolated marshes*. These marshes (21 ha) are typically separated from other lagoon morphologies, in some cases connected with residual morphologies of the ancient submerged alluvial plain (Gatto and Marocco, 1992). Their habitat can be described as: salt soil meadows, dominated by tall rushes; and Mediterranean saltmarsh scrubs.

4.2. Evolution of the saltmarshes

Changes in the surface distribution of the saltmarshes in the lagoon were identified by analyzing the differences between the digitized photographic datasets from 1954, 1990 and 2006. The results are presented in Table 1. A general loss of marsh surface area throughout the entire lagoon is evident, amounting to 144 ha in 52 years (16% of the original extent), with the overall loss rate having slowed only slightly in the more recent period, from −2.9 ha/y during 1954–90 to −2.6 ha/y during 1990–2006. Some of the area variations for the lagoon basins are negative and some are positive, and all change significantly over time.

Because of the influence of human activity, as described above in section 2.1, a thorough analysis must be carried out in order to distinguish between natural and man-made transformations. Analysis of the aerial photographs clearly shows that in many cases the marshes have been reclaimed or occupied for agricultural, commercial and maritime development. Table 2 reports the amount of direct man-made changes responsible for marsh disappearance (“reclaimed” marshes), compared to the erosional and accretional changes. Human activity caused the loss of 103 ha of saltmarsh during the period 1954–1990, mostly in the Lignano, S. Andrea and Buso basins, and 23 ha during the period 1990–2006, only in the Lignano and Buso basins. Among the different types of human activity contributing to the loss of saltmarsh, the most relevant interventions are those on barrier islands, involving the significant reclamation of land for aquaculture plants and farmland (total of 73 ha). Second most significant (with a loss of 19 ha) are those activities related to fish farming (embankment and enlargement of existing plants), even though most of this activity took place before 1954. And finally (with a loss of 15 ha) there are the effects of dredging, carried out for the development of new marinas and channels.

Aside from the direct interventions of humans, the variation in marsh extent is the result of different erosional and depositional processes. Therefore, by analyzing extent changes in each group of saltmarsh it was possible to highlight the peculiarities of each basin. Table 2 reports the erosional and depositional changes for the marshes during the two time spans considered. The main result is the net loss of −18.6 ha of marsh area during the 52-year period, corresponding to 2% of total marsh extent in 1954. The overall budget is obtained by the algebraic sum of marsh changes that occurred in each basin, which could be of opposite sign. For instance, Lignano, Buso and Morgo feature a marsh area increase of 41.2 ha, 7.5 ha and 5.6 ha respectively during the entire time span; Grado, S. Andrea and Primero show an opposite trend, owing to the loss of 53.2, 17.7 and 2 ha during the same period. If we consider the two different time spans separately, the trends change further still: Lignano and Buso changed from a positive to a negative trend; Primero from negative to positive; S. Andrea and Grado conserved their negative trends, and Morgo its positive trend.

Clearly, trends and rates change significantly across the basins, also when two basins seem to behave similarly, thus implying that several driving forces play different roles according to each individual basin's configuration and level of exploitation.

In order to highlight the erosional and depositional characteristics of the marshes, a number of relevant cases (see Fig. 1) were studied through detailed cross-sectional topographic surveys:

Case study A (CSA) (Fig. 3): An eroding saltmarsh located in the Cormor River delta (Lignano Basin). This group of saltmarshes has eroded from 22.3 ha in 1990 to 20.9 ha in 2006, mostly on the side facing the Marano ship channel, which is also exposed to the Bora fetch. The cross section has a regular profile with a mean elevation of 0.5 m, quite high for the marshes in the North Adriatic. The southern margin, which faces the Marano channel, is a clear erosion cliff connected by a gentle slope to the nearby floor.

Case study B (CSB) (Fig. 3): An eroding saltmarsh located near to the S. Andrea inlet. It is part of a group of marshes superimposed on a relict barrier island, now relegated to the lee of the active barrier island. The old beach ridge is visible in the cross section (reaching an elevation of 1.18 m). Towards the inner part of the lagoon, there is a subsided zone with some creeks and extended salt pans. The typical marsh vegetation in this area has been degraded and is now covered by *Spartina maritima*, which is typical of almost permanently flooded areas.

Case study C (CSC) (Fig. 4): This is a typical fringing saltmarsh, located in the Lignano Basin, covered by thick vegetation dominated by *Phragmites australis*. The surveyed area was partially excavated in the 1990s and subsequently covered by the fast expansion of *Phragmites*. It shows an abrupt cliff-like edge directly connected to a sub-tidal flat.

Case study D (CSD) (Fig. 4): An expanding saltmarsh located near the watershed between the Primero and Grado basins. In this area, the tide expands where the channels are not confined by the embanked fish farming plants, forming delta-like fans of saltmarshes, which tend to grow towards the tidal flats (+3.5 ha from 1954 to 2006).

4.3. Sediment budget of the Lignano and S. Andrea basins

The sediment budget of the Lignano and S. Andrea basins was produced based on the topographic and bathymetric map comparisons between 1964 and 2009 (Fig. 5). The analysis involved the computation of quantities of eroded and settled sediment, discerning two morphological groups: channels and marshes + tidal flats. In the channels, the total budget was found to be positive ($7.875 \cdot 10^6$ m^3 in 45 years), as a consequence of natural silting ($8.318 \cdot 10^6$ m^3) and the dredging of two new canals (a canal connecting the Aprilia Marittima marina with the Litoranea Veneta, and a canal in the Marano Lagunare Harbour; $-0.443 \cdot 10^6$ m^3). The total budget in the saltmarshes and tidal flats was found to be negative, amounting to $-5.119 \cdot 10^6$ m^3. The overall net budget was positive ($2.756 \cdot 10^6$ m^3 in 45 years), suggesting a deposition rate of ca. 61,000 m^3/y. Apart from the channels, the marshes and tidal flats that border the Stella River delta in the west and the Cormor River delta in the east were found to be the most significant sites for deposition. A calculation was performed in the GIS to obtain the volume of sediment deposited in these two areas, and this came out as $1.032 \cdot 10^6$ m^3 (a rate of ca. 23,000 m^3/y) in the Stella River delta and 412,000 m^3 (rate of ca. 9000 m^3/y) in the Cormor River delta.

A more accurate interpretation of the transformations that have taken place in this environment can be obtained through an analysis of the surface variations in the bathymetric classes (hypsometry), which represent the morphologies of the lagoon. Fig. 6 shows the hypsometric distribution of the Lignano and S. Andrea basins for the years 1964 and 2009. As can be seen, while the saltmarshes (the class above mean sea level) have been generally well preserved (supporting the evidence set out in the previous section, albeit over a different time span: 0.45 ha/y in 1954–2006), tidal and sub-tidal flats (−0.75/0 m) have been reducing more and more in surface area, promoting a significant increase in all classes deeper than −1 m. This process is visible in Fig. 6 as a horizontal translation of the envelope towards greater depth, up to the modal value in the −0.75/−1.00 m class. From there on, the deeper classes have increased their surface area, although not enough to show the significance of the process. The channel silting in fact, due to morphology, involved comparatively small area changes, being mostly a vertical process.

Hypsometry is an effective tool to obtain an immediate picture of the morphological structure of the lagoon basin and its transformation, but does not help distinguish the precise processes that involve one or more elevation classes. A better explanation can be obtained by comparing the elevation mean changes that have occurred to given depth ranges during the observed time span, i.e. using a 20-cm depth-interval distribution. These data have been obtained through specific queries using the spatial analysis and have been compared to the spatial distribution of the erosion, stable and depositional areas (Fig. 5).

Using 1964 as the reference baseline, we observe a flattening of the lagoon floor as a general morphological pattern, similar to that already found in the Venice Lagoon (Sarretta et al., 2010). The depth that separates negative to positive elevation changes (mean fulcrum depth) corresponds to −1.3 m (the midpoint of the −1.2 to −1.4 m depth class). Erosion mostly affects the tidal and sub-tidal flats, although constrained on average to a thickness of about 10 cm, with a maximum of 16 cm in the −0.40/−0.60 m depth class. On the other hand, the silting up of the channels is definitely shown as a process involving greater values (deposit thickness of >1 m), which tend to grow with depth up to a maximum average silting of 2.7 m for the channel more than −3 m deep.

The cross section reported in Fig. 5 highlights the above mentioned phenomenon of flattening of the channels within the main hydrographic network in the central part of the lagoon, and

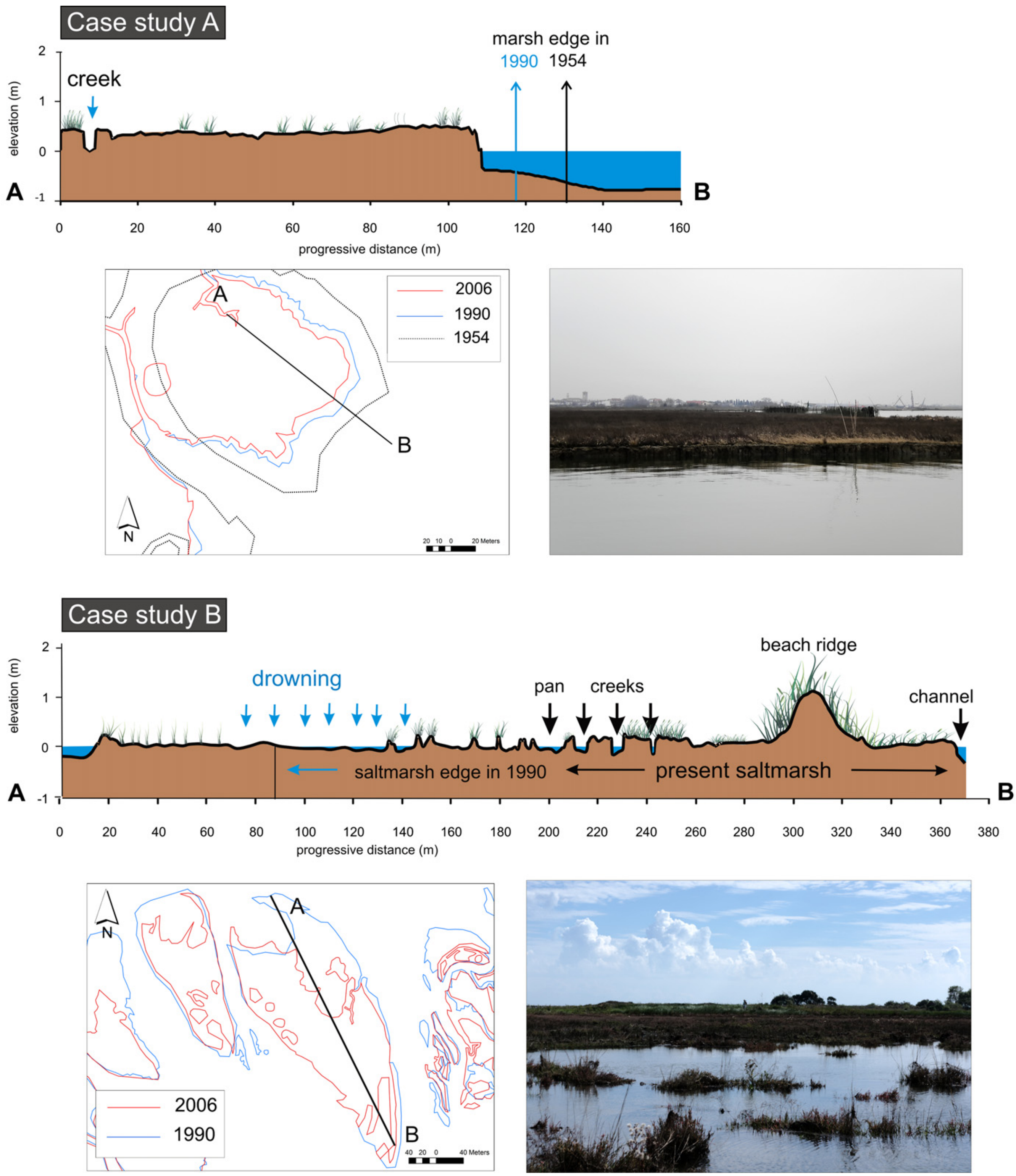

Fig. 3. Case studies A and B: cross section (surveyed in October 2010 and September 2010, respectively), evolution map, and sample photograph.

the erosion that affected mostly those tidal and sub-tidal flat that are confined within the same network. Otherwise, tidal and sub-tidal flats locally show a sustained process of sedimentation along the inner edge of the lagoon, due to the direct input of fluvial sediment. Bifurcation between erosion and deposition is clearly marked in Fig. 5 by the grey area that represents the equilibrium depth. This varies according to the proximity to the sediment source: it corresponds to ca. −0.70 m along the cross section reported in Fig. 5 and can reach a value of around −1.00 m close to the tributaries.

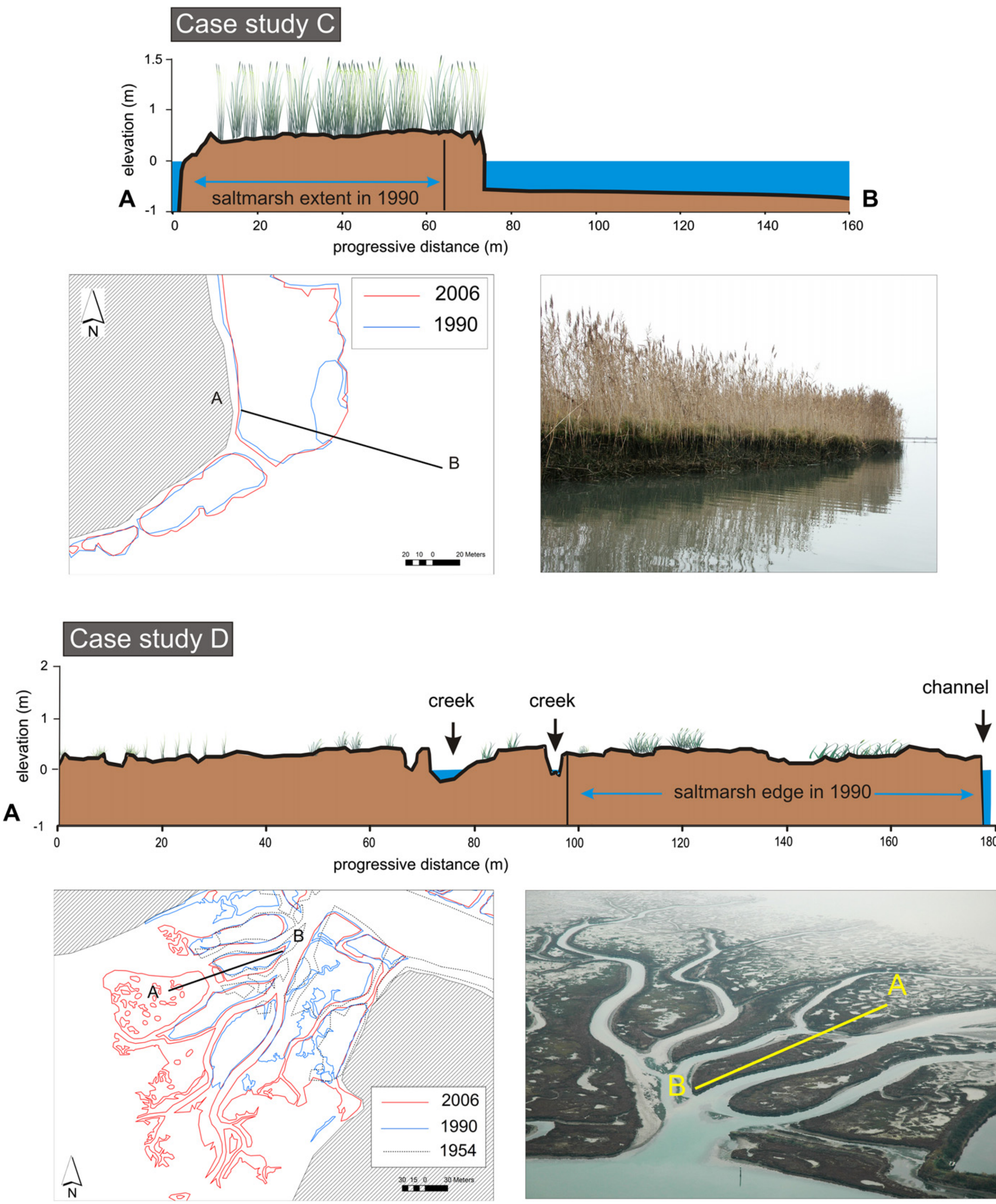

Fig. 4. Case Studies C and D: cross section (surveyed in June 2010 and November 2009, respectively), evolution map, and sample photograph.

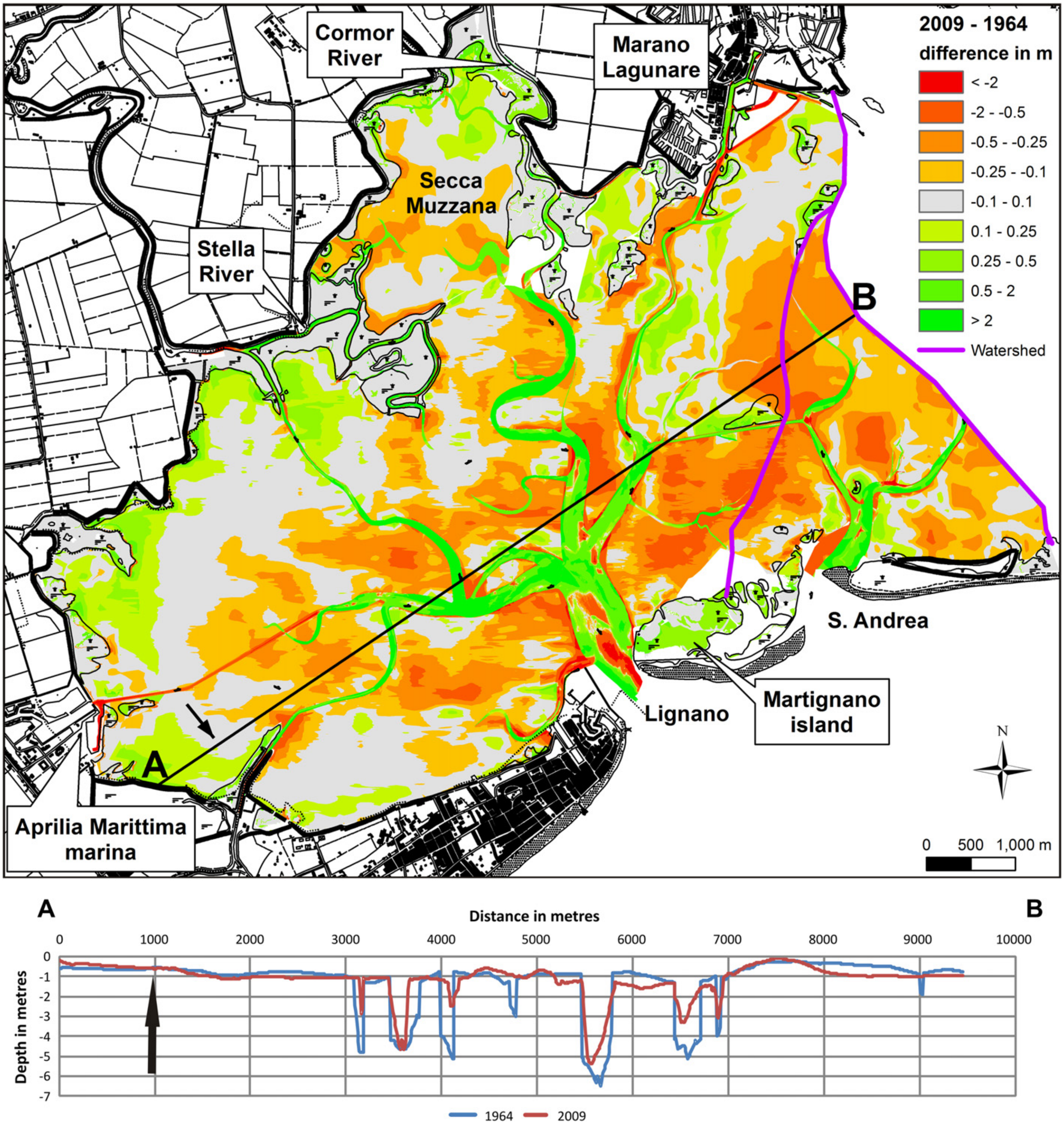

Fig. 5. Depth difference map between the 1964 and 2009 surveys in the Lignano and S. Andrea basins. The depth changes are pictured in colour shades from red to green. In the bottom of the figure a sample section is reported, showing the sedimentation and erosion processes that occurred in the two basins. The arrow on the map and section indicates the bifurcation between erosion and deposition, corresponding to a depth of −0.7 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

5. Discussion

5.1. Saltmarsh evolution and forcing factors

Besides direct human interventions, changes in the distribution of saltmarshes have resulted from the combined action of different forcing factors, both natural and man-made. According to Tonelli et al. (2010), marsh survival depends on a delicate balance between mineral and organogenic sediment accumulation and trapping coupled with stabilization due to halophytic vegetation on the one hand, and degradation-erosional forces due to SLR, subsidence and autocompaction, direct wave attack, and a decrease in sediment supply, on the other. The negative effect of these forcing factors may be enhanced indirectly by human action, as in the case

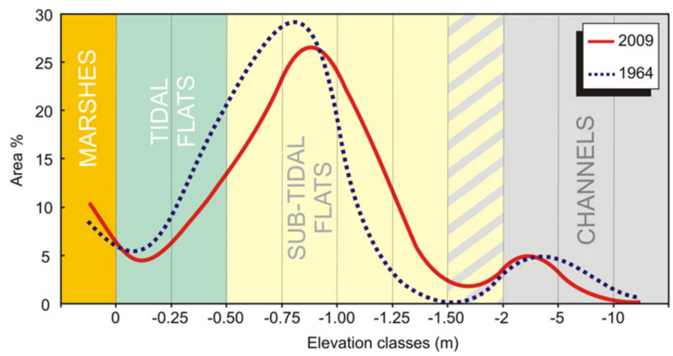

Fig. 6. Hypsometric distribution of the Lignano and S. Andrea basins for the two bathymetric datasets (1964, 2009).

of the well-known accelerated subsidence of Venice, due to extensive water extraction from the subsoil (Sarretta et al., 2010), or the water-sediment flux control in the rivers (Simeoni et al., 2007).

Owing to the complex interactions and feedback mechanisms among these driving forces (van der Wal and Pye, 2004), an understanding of the systematic relationship between each forcing and marsh response is still lacking. The erosional and depositional processes affecting the saltmarshes in the various basins of the Marano and Grado Lagoon are related to different geographical settings (sheltered or exposed settings, proximity to sediment sources, presence of human activity, marsh position relative to the other lagoon morphologies), sometimes featuring specific marsh-edge morphologies and vegetation, as found by the analysis of aerial photographs, maps, vegetation maps (Poldini et al., 2006), and through fieldwork. Putting to use the data available through the digitization and classification work, an attempt has been made at furnishing an interpretation of the ways in which the various processes have played out, correlating the morphological, geographical and evolutionary features with one or more prevalent forcing factors for each saltmarsh classification group (Table 2, Fig. 7).

5.1.1. Erosional marshes (type E)

5.1.1.1. Type E1: drowning marshes due to relative sea-level rise. The imbalance between SLR, deposition rate and autocompaction is one of the processes that has led to the disappearance of saltmarshes (Cahoon et al., 1995; Allen, 2000). In this study, we have frequently observed a reduction in saltmarsh surface area (Fig. 7), along with a progressive retreat of the marsh-edge facing the mud flat, or pond enlargement, as well as vegetation loss or low-marsh communities replacing mid- or high-marsh vegetation, without evidence of cliffed edges. These signatures of deterioration represent a drowning process, as also reported by Nyman et al. (1993).

Drowning due to relative SLR is suggested here to be responsible for the loss of 102.5 ha of saltmarsh from 1954 to 2006, mainly on channel margins and in the back-barrier, with a greater erosional rate in many basins during the period 1990–2006 (Table 2). This fact should confirm the importance of the eustatic component during the latter time span, with a mean sea level that increased with a rate eight times as much than during the former period (see section 2.1). A similar effect has already been observed by Downs et al. (1994) at Blood sworth marshes, Maryland, where the initiation of marsh inundation by non-channel ponds coincided with a short-term acceleration in SLR from 1930 to 1948.

In the Marano and Grado Lagoon the process is less evident, since it is highly variable in terms of trend and morphological evidence, both at the basin- and single-marsh group scale, thus confirming that drowning is the result of a complex interaction among the direct driving forces (i.e. eustatism and regional subsidence) and local phenomena (sedimentary rates, autocompaction).

As an example, the different genesis, and therefore different sedimentary nature and structure, of the marshes (back-barrier, fringing, deltaic etc.) leads to a different proneness to autocompaction processes, typical of clay and peat terrains (Cahoon et al., 1995; Allen, 2000). If the sediment supply is scarce, the marshes tend to subside and degrade, as observed along many back-barrier marshes of this lagoon. On the contrary, as in the case of the back-barrier of Martignano (see Case B in Fig. 3 and case E1 in Fig. 7), the survival of some areas, as the most elevated marsh edges and the old beach ridge zones, could be related on the one hand to the sediment supplied by the embracing channels, which flow directly from the S. Andrea tidal inlet, or on the other hand to the minor autocompaction of the sandy sediment of the old barrier morphology.

5.1.1.2. Type E2: marsh-edge retreat by wind waves. Wind-generated wave action is a common forcing factor in open lagoons (Cavaleri, 1980; Arfi et al., 1993; Fagherazzi et al., 2006, 2007; Defina et al., 2007). In this case study, the Bora (ENE) wind fetch is particularly important: the most exposed basins for fully developed wind waves are the Lignano and Buso, a small part of the Grado basin. In the Lignano basin, the process involves mostly the marshes that fringe the western border of the lagoon (Fig. 7), as well as the eastern margin of the marshes of deltaic origin (Fig. 3; Case A). The marshes show spurs and furrowed edges, identified by Allen (1993) as "typical marsh fronts with episodic erosion under relatively high wave energy conditions". Edge-retreat is continuous from 1954 onwards, reaching values of 30 m in some places. As observed by Reed (1988), Day et al. (1998), and Rizzetto and Tosi (2011), the sediment eroded from the saltmarsh edge can redeposit landward, thus promoting the sedimentation observed in small protected bays and the filling up of some creeks.

In the Buso and Grado basins, wave action erosion involves mostly isolated marshes, which develop edge-retreat, fragmentation, and the disappearance of small patches, as also reported by Day et al. (1998) and Baily and Pearson (2007). The effect of wind waves and waves generated by vessels is often difficult to distinguish, as both could be responsible for the degradation of the eastern edge of those marshes also facing the channel network, in the absence of other physical limitations to the fetch exposure (i.e. marshes, islands, or fish farmings) in the eastwards direction.

5.1.1.3. Type E3: marsh-edge retreat caused by vessel-generated waves. Vessel-generated waves are often indicated as a cause of resuspension in estuaries (Schoellhamer, 1996) and saltmarsh edge-retreat, particularly where commercial and recreational boat traffic is frequent (Castillo et al., 2000), as in the Lagoon of Venice (Amos et al., 2010). Vessel-induced erosion is typically associated with a retreating saltmarsh scarp, with subsequent undercutting and toppling of the scarp, leading in the worst cases to marsh fragmentation.

In this case study the process is remarkable, greatly evident in some spots, with a total loss of 37 ha. The most involved basins are Primero, Grado and Buso, while Lignano, though crossed by important shipways with significant pleasure and fishing boat traffic, is less affected because of the lesser presence of channel-fringing saltmarshes. The only exceptions are the marsh fringing the Litoranea Veneta canal (Fig. 7), and those located on the Marano Lagunare Harbour channel, where the erosion processes are clearly evident, with a retreat of 22 m in 52 years and 16 m in 16 years, respectively. In these areas, redeposition of the eroded sediment has occurred, thus causing the expansion of the marsh on the opposite side.

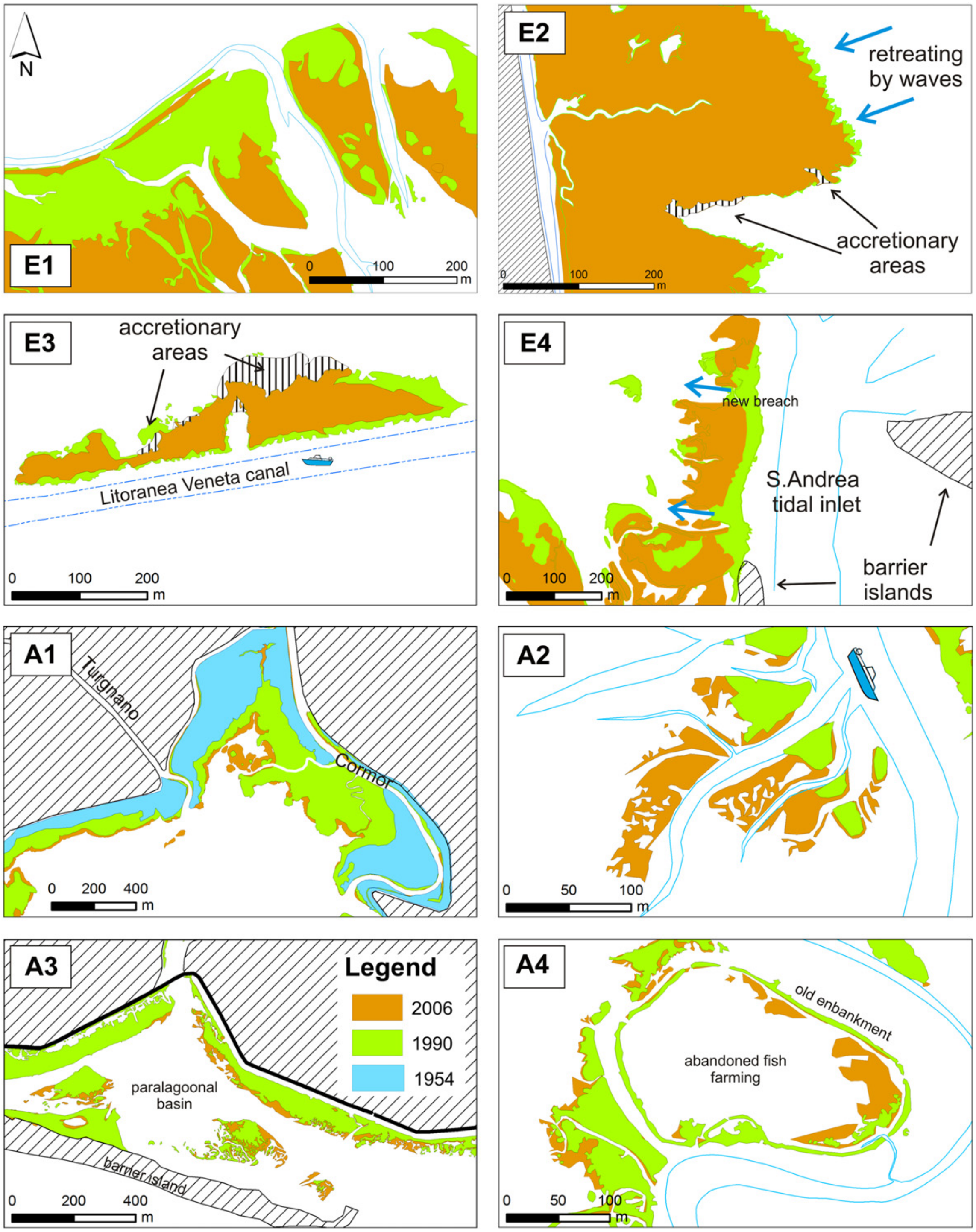

Fig. 7. Different erosional and accretionary saltmarsh types. In each picture, the change between 1954 and 1990 or 1990 and 2006 is derived from aerial photographs. Erosional marshes, type E1: drowning marshes due to relative sea-level rise; type E2: marsh-edge retreat by wind waves; type E3: marsh-edge retreat caused by vessel-generated waves; type E4: marsh erosion due to coastal dynamics (inlet migration). Accretionary marshes, type A1: marsh accretion due to direct fluvial input; type A2: marsh accretion due to tidal input; type A3: marsh formation in recent paralagoonal basins; type A4: marsh formation and accretion in abandoned fish farms.

5.1.1.4. Type E4: marsh erosion due to coastal dynamics (inlet migration). Processes related to coastal dynamics may involve the saltmarshes, where the unconstrained behaviour of an inlet affects an adjacent marsh, e.g. when a back-barrier marsh is directly exposed to erosion, due to a significant offset in the alignment of two adjacent barriers, in the absence of jetties or other fixed defence structures.

This phenomenon has been observed in the present study area; specifically, in the back-barrier marsh facing the western side of the S. Andrea natural inlet (Fontolan et al., 2007), which is still involved in a progressive retreat. This retreat, which causes marsh loss (5.5 ha during the period 1954–2006), is due to the migration of the main tidal channel westwards, as a response to the high sediment load on the depositional updrift side.

Marsh erosion at the ends of a barrier island close to an inlet is also common at the shoreward termination of a jetty structure, and is known as "inner bank erosion" (Seaberg, 2002). Although this was not observed in the Marano and Grado Lagoon, due to the complete revetment of the ends of the barrier island close to the jettied inlet, the shape of the unabated eroded area is parabolic, similar to that which occurs on the coast downdrift of headland features, i.e along the neighbouring Caorle Lagoon (Fontolan, 2004).

5.1.2. Accretionary marshes (type A)

5.1.2.1. Type A1: marsh accretion due to direct fluvial input. Although there is an almost total absence of data about the sediment load of the rivers flowing into the Marano and Grado Lagoon, the morphological expansion of the edges of the fringing marshes in areas of brackish and freshwater influence (Ferrarin et al., 2010) is evidence in itself for the existence of river transport. This expansion occurs almost solely in the Lignano Basin, where the river load is testified by the positive sediment budget of the basin (see section 4.3), which shows extended sedimentation areas on the tidal flats during the 1964–2009 period. This confirms the geochemical and sedimentological data of Marocco (1995), who reported a mainly fluvial origin of the Lignano Basin sediments.

As a general rule, according to Day et al. (2011) river waters directly enhance wetland vertical accretion via sediment deposition, and indirectly via enhanced root growth and organic soil formation. The primary features of the accretionary fringing marshes of riverine influence in the Lignano Basin are: the dominance of *Phragmites*; the presence of an abrupt edge, sometimes with a narrow frontal talus that connects with the facing tidal flat; a quite compact meadow-like appearance in aerial photographs, with few channels and ponds. The river deltas have preserved their extent almost unchanged, while there are wide areas of expanding marsh edges in the protected bays formed by the delta lobes (Fig. 4; Case C).

The most significant expansion took place during the first period (52.6 ha during 1954–1990), mostly along the eastern margin of the Secca Muzzana Bay (+36 ha; Fig. 7), due to the embankment and land reclamation (at the beginning of the 1950s) of a vast area of marsh close to Cormor River. Following the embankment, an expansion of the marshes occurred over the pre-existing tidal flats by sediment dispersal through a couple of new channels that substituted the old main course, currently filled at the southernmost branch outflow. After 1990, accretion of the marshes has greatly reduced, with a budget of only 10.1 ha. This is the net result of a larger sedimentary transfer due to small-scale erosional and depositional adjustments. However, the decreasing rate of accretion refers only to marsh extension. Volume changes are obviously different, since the space needed to accommodate sediment deposition over the facing tidal flats is progressively increasing, due to the natural hypsometry of the lagoon basin, which deepens towards the center.

5.1.2.2. Type A2: marsh accretion due to tidal input. The complex hydrodynamics of the lagoon, dominated by tides, allows the transport and deposition of sediment during tidal cycles, similar to the Lagoon of Venice (Albani et al., 1984). A proportion of this sediment probably comes from the discharge of the Isonzo and Tagliamento Rivers, outside the lagoon, and is transported through the inlets during flood tide (Brambati, 1970; Gatto and Marocco, 1992; Marocco, 1995), allowing the channel-fringing and back-barrier saltmarshes to react to SLR (Gatto and Marocco, 1992). Another proportion of the sediment probably comes from erosion processes at work in nearby areas (Day et al., 1998).

In some cases, sedimentation and the colonization of vegetation are sufficient to build new saltmarsh surfaces, through the silting up of creeks and ponds and through lateral expansion. These are phenomena of a certain significance (16.8 ha during the period 1954–1990, and 10.4 ha during 1990–2006), which show a general trend that remains almost unchanged throughout the entire time span considered in the study.

The development and growth of marshes due to tidal input refers to those marshes clearly formed at the bifurcation of channels, which cause the flow expansion and deceleration, thus enhancing sedimentation. Similar phenomena are due to the abrupt change in channel orientation, with subsequent lateral spreading of the effluent outside the levees or embankments, and are responsible for the formation of a dissected structure of delta-like fans (see Fig. 4, Case D, and Fig. 7). The feeding of such marshes appears to occur mainly in those basins that have a complex morphology, either for the inherited antecedent alluvial forms (Oertel and Woo, 1994), or for the fixation of the channel network inside the articulated system of fish farming plants. For this reason, sedimentation works mainly in protected areas in the Primero and Morgo basins. Morphologically, these basins feature a well developed network of secondary channels and shallow tidal flats, with fish farming plants covering a significant area (388 ha in Primero, 85 ha in Morgo). In the Grado Basin, this process is relevant in percentage terms; although, due to small values of sedimentation, the actual extent of surface increase is small, amounting to 3.7 ha in the first period and 0.8 ha in the second.

A similar situation has been observed in the Treporti Basin in Venice, the only basin that has experienced a preserved net positive sedimentary budget during recent decades (Sarretta et al., 2010). Conversely, open fetch conditions and the dominance of wind waves inhibit the development of marshes inside the lagoon basin, as well as at the bifurcation of channels. Our data on the Lignano sediment budget and related morphological signatures seem to confirm this hypothesis, and suggest that resuspension wind-induced phenomena also prevail for a positive mass balance, thus tending to flatten all the sub-tidal morphologies through the deepening of mud flats and channel filling.

5.1.2.3. Type A3: marsh formation in recent paralagoonal basins. The recent paralagoonal basins, formed after the abandonment of the former barrier island system between the Grado and Buso inlets and the formation of new bars and spits seawards, are potential sedimentary sinks, where calm conditions and sediment supply (mainly from the sea through ephemeral breaches and wash over phenomena) promote the formation of new saltmarshes. In these basins, accretion appears to be significant, showing for the whole lagoon a value of 40.6 ha during the period 1954–1990, and only 4.5 ha during 1990–2006. However, the data from the first period are due to human intervention in the form of coastal stabilization, carried out on the barrier island of Martignano, which favoured the greatest expansion of the marshes in its back-barrier, and accounting for more than 50% (+22 ha) of the total estimated accretion. Owing to their external marine nature and the specific feedback with the beach of the fore barrier, these environments need to be considered separately from the lagoon basins, either for the environmental and sediment budget, or for management purposes.

5.1.2.4. Type A4: marsh formation and accretion in abandoned fish farms. Marsh accretion has been observed in peculiar cases, for example where fish farming plants have been abandoned and re-opened to tidal currents. Mainly in cases where marshes were already present, this re-opening has led to natural sedimentary feedback with the adjacent channels, thus inducing a net increment of marsh area during the examined period. This type of event was most apparent during the 1954–1990 period in the Buso and Morgo basins (+15.8 ha), but in some sheltered areas inside the old embankment the sediment supply caused accretion after 1990 (+2.4 ha) as well, demonstrating that accretion continues long after the initial abandonment of the plant. Although this process is a relatively small contributor in terms of the overall quantity of marsh formation, it is significant from a management perspective. It demonstrates the lagoon's capability of morphological and ecological self-restoration in the presence of a sheltered environment and shallow water. Consequently, owing to the large number of fish farming plants in northern Adriatic lagoons, as well as their prevalent and extensive management methods, the partial or complete re-opening to tidal flows following the abandonment of such plants can be considered a potential high-impact soft practice for the conservation of the natural morphology and biodiversity of the lagoon.

5.1.2.5. Type A5: artificial marshes created by the dumping of sediment. The dredging of channels and the associated dumping of material on the channel sides was a common practice in the lagoons of Venice, Marano and Grado (Gatto and Marocco, 1992). If the amount of sediment is sufficient, the dumped bank can be colonized by vegetation and gives birth to new saltmarshes. Gatto and Marocco (1992) pointed out the existence of this type of marsh (called "pseudo-marshes"), which were already identifiable in the 1954 aerial photographs, often featuring rock revetments on the channel side. However, quantifying this dredging practice is impossible, and only in very few places was the formation of such marshes evident during the examined time period.

5.2. Sediment budget and lagoon morphological response

Similar to the Venice Lagoon (Sarretta et al., 2010), one of the main characteristics of the Lignano and S. Andrea basins is the present great extent of the sub-tidal flats (69% of the total basin area, with depths of between −0.50 and −2.00 m). This represents a 10% increase in their distribution between 1964 and 2009. A tendency towards a flooding state is reflected by the 8% loss in the area of tidal flats during the same period, largely occurring adjacent to the main channels. The increasing influence of wave activity (Fagherazzi et al., 2006; Defina et al., 2007) is recognized as the main factor responsible for the erosion, enhanced during submergence of open-water lagoons (sensu Oertel and Woo, 1994). The morphological response is a general tendency of the lagoon floor to flatten, either by erosion of the tidal flats, or through siltation of the channels, which in some cases have completely filled and disappeared. Flattening in this context effectively means morphological simplification, resulting in lagoons losing their typical shallow-estuarine characteristics and changing into marine embayments (Cooper, 1994).

Despite the evident contribution of sediment from the Stella and Cormor Rivers, their influence appears constrained to the innermost lagoon. Therefore, the reasons for the sedimentary surplus measured in the Lignano and S. Andrea basins remain hypothetical. In fact, an analysis of the morphological changes in the remnant basins is needed to explain possible sediment advection from the adjacent wind-exposed basin, as Buso is supposed to do, following the first preliminary unpublished data. According to Marocco (1995), a significant part of the fine sediment load could also enter the lagoon from plumes of the Tagliamento River, mainly after the typical floods during autumn and spring, easily enhanced by flood tides or waves and storms from the southeast (Scirocco). However, data are not yet available, although monitoring via direct and indirect continuous measurements of the sedimentary fluxes are in progress at the Lignano tidal inlet by the ABR-FVG.

In the Lignano and S. Andrea basins, most of the saltmarshes demonstrate a capability to react against SLR, but a significant decoupling of the morphological evolution is also observed, due to the progressive erosion of those tidal and sub-tidal flats not directly fed by fluvial sedimentary supplies, and mainly distributed around the channel network.

The state of disequilibrium of the basins also occurred in the presence of a significant positive sediment budget of 61,000 m^3/y, which is very close to the hypothetical sedimentary rate necessary for the morphological accommodation due to SLR recorded during the period 1964–2009. This implies that the simple relationship and feedback between sediment supply (marine, fluvial and internal erosion) and relative SLR is complicated by the intrinsic anisotropy of both variables inside a lagoon. Moreover, the open lagoon inherited hypsometry of the basin drives the subsequent morphological changes during submergence, according to a critical shear stress feedback mechanism linked to wind waves, as suggested by Fagherazzi et al. (2006). The contribution of our data to the above mentioned model is the possible set up of different sedimentary inputs that counterbalance the shear stress erosion, thus making it possible to test the stability of the model (see Fig. 4 of Fagherazzi et al., 2006) and the subsequent morphological response.

Considering that a positive sediment budget is a matter of fact, we can use the measured mean fulcrum depth value (−1.3 m) as the *mean current stable equilibrium point*, and the variable values of changes from erosion to deposition (−0.7 m far and −1.0 m close to the tributaries) as the *unstable equilibrium depth* of Fagherazzi et al. (2006). Using the same parameter as Venice and the unlimited fetch configuration, the erosion effects due to critical shear stress excess are very limited, involving only the sub-tidal flats, between −0.7 m and −1.3 m. This therefore confirms the morphological evidence of maximum erosion occurring in the starved sub-tidal flats around and close to the channels, although limited to the lower boundary depth of the model.

6. Conclusions

In this study, a spatial analysis of changes in saltmarsh area using aerial photographs taken in 1954, 1990 and 2006 for the entire Marano and Grado Lagoon was carried out. In addition, the sediment budget over a 45-year period was computed and obtained through a bathymetric comparison of the years 1964 and 2009. Hydrographic maps of two (Lignano and S. Andrea) of the six lagoon basins were used for this purpose. Altogether, the results revealed the following:

(1) A significant decline in the total area of saltmarsh in the lagoon, corresponding to 144 ha (16% of the original extent). Direct human impact has played a primary role (−126 ha) in the disappearance of saltmarsh through the processes of dredging and land reclamation;
(2) Aside from direct human impact, the overall extent of saltmarsh loss has been minimal. Where such changes have occurred, this has been a result of significant gains and losses to the marsh surface owing to the contemporary occurrence of depositional and erosional phenomena. This demonstrates the resilience of the marsh system on the whole, which is still able to react and counterbalance the external erosional forcing factors;
(3) Compensation between erosion and sedimentation, as well as the role and relative importance of the identified main forcing factors (SLR and sediment autocompaction, wave action, vessel-generated waves, coastal dynamics, and sediment supply), vary according to the particular basin;
(4) In the Lignano and S. Andrea basins, marsh conservation over the decadal timescale is the main result of significant

sedimentary inputs. This is also confirmed by the positive (61,000 m^3/y) sediment budget calculated, an amount that compensates for the accommodation due to submergence that occurred during the 45-year period. Despite this, the altered hypsometry during the period 1964–2006 demonstrates that sediment inputs are not sufficient to avoid the natural evolution of this type of open lagoon, where the wind-wave-induced bottom shear stress exceeds the erosion threshold on the subtidal flats between depths of −0.7 and −1.3 m around the channel network, far from the tributaries;

(5) With the current sedimentary and SLR regimes, the Lignano and S. Andrea basins will evolve further through a morphological decoupling and flattening. This will take place due to the aggradation of the inner fringing marshes and tidal flats, the deepening of tidal and sub-tidal flats far from the margin, and the continuous filling of the channels.

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