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Abstract: Comparison of 1927, 1970 and 2002 bathymetric surveys in the Lagoon of Venice was used to reconstruct historical changes in sedimentation. A detailed GIS-based analysis of the charts revealed the timing and pattern of geomorphic changes and allowed calculation of sediment deposition and erosion for the lagoon as a whole and each of its four sub-basins: Treporti, Lido, Malamocco and Chioggia.

Two main developments are discernible from comparative observation of the areal distribution of the main elevation ranges: the collapse of the saltmarshes, which decreased by more than 50%, from 68 km2 in 1927 to 32 km2 in 2002, and the progressive deepening of the lagoon, with a huge increase in the area of subtidal flats (between -0.75 and -2.00 m depth), from 88 to 206 km2 during the same period.

On the whole, the lagoon showed a clear-cut shift in the most frequent elevation (modal depth) from a value of -0.62 m in 1927 to -0.88 m in 2002. The deepening of the lagoon affected mostly the lagoon sub-basins south of the town of Venice, where modal depth increased from -0.65 m to -1.12 m in Lido, from -0.64 to -1.75 m in Malamocco and from -0.39 m to -0.88 m in Chioggia.

Large changes in lagoon morphology were caused by human-induced subsidence, the dredging of navigation channels between 1927 and 1970, and intense natural erosion enhanced by sediment re-suspension due to Manila clam fishing between 1970 and 2002. There was a net loss of about 110 Mm3 of sediments from the lagoon, most of which (73 Mm3, ca.70%) was in the earlier period. A significant amount was lost by dredging and direct disposal outside the system, either on land or at sea, and there was a net loss of 39 Mm3 from the lagoon to the sea through the inlets, at an annual rate of 0.5 Mm3.

Comparison of erosion rates in the two periods highlighted an alarming acceleration, from a net sediment loss of 0.3 Mm3y-1 in the period 1927-1970 to 0.8 Mm3y-1 in 1970-2002. Deterioration caused a shift from a highly differentiated lagoon morphology in the 1930s to a sediment-starved and subsidence-dominated structure in the 1970s, and from there to the high-energy and marine-like lagoon of today.

The results demonstrate the potential application of GIS to reconstructing the recent chronology of sediment distribution and improving our understanding of the geomorphic processes shaping the seafloor, while providing insight into the possible impacts of environmental changes brought on by natural and anthropogenic forcing

Sediment budget in the Lagoon of Venice, Italy

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Abstract

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deposition and erosion for the lagoon as a whole and each of its four sub-basins: Treporti, Lido, Malamocco and Chioggia.

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Comparison of erosion rates in the two periods highlighted an alarming acceleration, from a net sediment loss of 0.3 Mm^{3}y^{-1} in the period 1927-1970 to 0.8 Mm^{3}y^{-1} in 1970-2002.

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The results demonstrate the potential application of GIS to reconstructing the recent chronology of sediment distribution and improving our understanding of the geomorphic

processes shaping the seafloor, while providing insight into the possible impacts of environmental changes brought on by natural and anthropogenic forcing.

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1. Introduction

The saltmarshes of the Lagoon of Venice (LV) have experienced intense and varied human impacts that range from reclamation, waste disposal and livestock grazing to less obvious, more modern activities such as restoration efforts, which reflect a new appreciation of natural ecological services (Silliman et al. 2008). Large expanses of mudflats and open saltmarshes near cities were converted to port and industrial complexes, resulting in their permanent loss (Pinder and Witherick, 1990) and the disappearance of the ecosystem services they once generated.

The substantial changes that have taken place in the morphology of the Lagoon of Venice (LV) during its history result from a combination of natural processes, human activities, and sedimentological responses to those activities. Although knowledge of long-term trends in deposition and erosion are important for proper management of coastal ecosystems, it is difficult to gain this knowledge from short field experiments or other traditional methods. A long-term, large-scale perspective of the sediment system may be obtained, however, by analyzing a long sequence of bathymetric surveys (Jaffe et al., 2007). Understanding how lagoons have responded to past modification is necessary in order to prevent further degradation in response to future environmental pressures (Higgins et al., 2007), including invasive species (which fundamentally alter saltmarsh community structure) and the relatively unexplored and multifaceted effects of climate change (Bromberg Gedan et al., 2009).

This paper presents a history of bathymetry, deposition, erosion, and morphological changes (affecting saltmarshes and tidal flats) in the LV from 1927 to 2002, and relates them to changes in land-use and the main physical and sedimentological drivers affecting the lagoon environment during the last few decades. This represents a preliminary attempt to provide an overview of the situation and analyse the relationships between land-use and the response of sedimentological compartments at large spatial and temporal scales. The history was reconstructed using computer analysis (Longley et al., 2001) and hydrographic and topographic surveys conducted by the Venice Water Authority (*Magistrato alle Acque di Venezia*, MAV). This study is not the first to address bathymetric changes in the LV (MAV-CVN, 1999; MAV-CVN 2004; Pillon et al., 2003; Molinaroli et al., 2009) but is the most comprehensive to date.

Recently, Molinaroli et al. (2009) performed a precise division of the LV into four sub-basins using GIS-based techniques (see Fig. 1): Treporti (A), Lido (B), Malamocco (C) and Chioggia (D). The authors also demonstrated that the morphological and sedimentological variations between 1970 and 2002 were different in each sub-basin. In this paper we used their partitioning to follow the historic evolution of the bathymetry of the four sub-basins over more than 70 years, in order to construct two sediment budgets, one for the period 1927-1970 and another for 1970-2002.

2. Study area and historical background

The Lagoon of Venice is the largest lagoon in the Mediterranean. Like many other coastal areas around the world, it has been subject to transformations and intense anthropogenic pressure over the past few decades which have deeply modified the natural environment. The construction of breakwaters at the lagoon inlets during the period 1808-1927 and the dredging of lagoon channels for navigation purposes (in 1926 and 1970) have had a significant impact on the lagoon's morphology.

Riverine sediment input into the lagoon has been almost completely eliminated, and the breakwaters constructed to defend the inlets have greatly reduced the input of coarse marine sediment into the lagoon (Day et al., 1998). As a consequence, erosion and subsidence, particularly during the last century, have caused a three-fold reduction in the area of saltmarshes in the Venice Lagoon to about 35 km^2 at present. In the past 15 years or so, projects have been undertaken to arrest marsh loss and promote restoration (Scarton et al., 2000).

Insert Table 1

Various events can be recognized as drivers affecting structures and processes in the morpho-bathymetry of the LV between 1927 and 2002, and are listed in Table 1, chronologically subdivided in terms of the two periods considered for the bathymetric comparison (1927-1970 and 1970-2002):

1. Saltmarsh destruction from 1927 to 1960 to reclaim land used for the construction of the industrial zone (a total of 22 km^2), together with Venice airport and urban development on the lagoon-side of the city of Mestre (S. Giuliano), the latter two occupying a further 5 km^2
2. Modification of hydrodynamic conditions as a result of the dredging of the Malamocco-Marghera ship canal (the “Oil Canal”), in the central part of the lagoon in the 1960s. This work affected the first period of our study due to the disposal on land of the dredged material (more than 40 Mm^3), and the second period by influencing lagoon morphology (e.g. saltmarsh distribution and bathymetric features, such as texture, grain size, depth, and erosion rate) (Ravera, 2000);
3. Increased nutrient and pollutant (trace metals and POPs) loads in the 1960s and 1970s, in relation to inputs from the industrial area and the catchment basin, and urban waste from the city of Venice (Cossu and De Fraja Frangipane, 1985; Donazzolo et al., 1982). Those activities produced several million m^3 of material with various levels of contamination; the new regulatory framework established by the Ministry of the Environment in the 1990s

(Ministero Ambiente, 1993; Apitz et al., 2007) imposed strict guidelines regarding the disposal of this material.

4. Dredging for maintenance purposes carried out in the last decade by the MAV and the Port Authority, amounting to an average of about 1 million m^3 y^{-1} (MAV/CVN 2004), which was disposed of outside or re-used inside the lagoon.

5. Mechanical clam harvesting by local fishermen since the early 1990s to exploit the newly-formed banks of Manila clams (Provincia di Venezia, 2000; Pranovi et al., 2004), an alien species, intentionally introduced in the lagoon in the middle of the 1980s for aquaculture purposes, subsequently becoming widespread throughout the lagoon (Cesari and Pellizzato, 1985; Pranovi et al., 2006).

3. Materials and Methods

Insert Figure 1

3.1 Bathymetric datasets

The bathymetric datasets used for assessing historical changes in the LV derive from three maps published by the MAV after survey campaigns conducted in 1927, 1970 and 2002. The “1927” bathymetric maps were published by the MAV in 1934. They come from a detailed survey carried out between 1922 and 1933 (central year 1927) and consist of 134 elements on a scale of 1:5000. The survey was conducted by performing precise tacheometric measurements and manual soundings. A precise altimetric network covered the entire lagoon surface. These maps have recently been digitized by the Venice municipal Tide Forecast Centre as high resolution TIFs.

The “1970” bathymetric maps were published in 1971 by the MAV. They come from surveys carried out from 1968 to 1971. Bathymetric data were collected by multiple sampling methods: echosounding, tacheometric measurements and stereophotogrammetric analysis.

The “2002 dataset was collected from the end of 1999 to June 2002, further data being collected in spring 2003. A “Multibeam” bathymetric acquisition system was used for the main channels (depth >5 m) and the three seaward inlets (Lido, Malamocco, Chioggia). For shallow waters and secondary channels (depth <5 m), a single-beam echo-sounder was used. At shallower depths near saltmarshes and mudflats, data was collected by the traditional topographic method (stadia rods coupled to a GPS). The distribution of natural and artificial saltmarshes was surveyed by stereo aerial photography.

Digital data for both the 1970 and 2002 maps were provided by the MAV.

3.2 Sea-level reference datum and adopted corrections

Comparison of surveys and their related morpho-bathymetric maps requires consideration of the reference datum used during each survey. For sediment budget calculation, each vertical movement (of land and sea) also has to be considered, in order to distinguish actual from apparent sediment loss, since the latter reflects eustatism and local subsidence as well as erosion/deposition.

The datum used in the 1927 map is the National Altimetric Network Zero (NANZ), established in 1910 by the IGM (the Italian Military Geographical Institute) with reference to the tide gauge at Campo S. Stefano (CSS), Venice. The NANZ corresponds to the average of the high and low tides recorded from 1884 to 1909, assigned to the central year 1897 (Dorigo, 1961). In 1923 the reference tide gauge of Venice was transferred to Punta della Salute (PdS). Elevation differences between benchmarks associated with both CSS and PdS are negligible, in the order of 3-4 mm, thus within the tolerance errors for levelling between two geodetic elements.

The hydrographic maps of 1970 and 2002 both refer to the datum established in 1952 (and still in use), corresponding to the mean sea level recorded at Genoa in 1942 (IGM42). Altimetric measurements were carried out in 1968 in order to control and position the new datum with respect to the NANZ at Venice. Using the PdS benchmark as the reference control, the IGM42 datum was found to be 23.56 cm higher than the NANZ (Cavazzoni, 1977; Ferla et al., 2006). This value accounts for both the eustatism and subsidence, natural or human-induced (Gatto and Carbognin, 1981) which had occurred since the beginning of the last century.

Reference data and sea-level time series are shown in Fig. 2. Mean sea-level data are available for both Venice and Trieste, which is a tectonically stable maritime town located 115 km from Venice, on the eastern side of the northern Adriatic. A graphic indication of the subsidence which occurred in Venice during the examined period is given by the differing rates of apparent sea-level change in the two towns (Fig. 2b). This was about 10 cm greater in Venice than Trieste during the critical period 1927-70, when there was intensive water extraction from the deep aquifers underlying the former to supply industries centred on Marghera. According to Gatto and Carbognin (1981) the relative level of the soil fell by a total of 23 cm over 100 years: ca. 3 cm are due to natural (geological background) subsidence; ca. 9 cm to anthropogenic subsidence; and 11 cm to the rise in mean sea-level. Mean sea level is still rising, with absolute values currently up to 27-28 cm above the NANZ.

Considering the above data and the values shown in the graph (Fig. 2), we are now able to specify the correction to use when analysing topographic variation over time.

The distribution of lagoon morphologies and their spatial partitioning is the result of adaptation to (i.e., establishment of equilibrium with) morphodynamic and hydrodynamic processes. The latter are related to the tidal prism, hydroperiod and tide- and wind-induced currents, all strongly affected by lagoon depths. When sea-level changes, hydrodynamic forcing also changes, and the lagoon reacts in order to achieve a new equilibrium. Therefore, each map needs to take account of the mean sea-level at the time of the surveys, in order to obtain the correct distribution of the different morphologies and bathymetric categories.

The differences between mean sea levels measured during the period of survey (or immediately before) and the reference datum were calculated for each map, using the long term sea-level time series (Fig. 2).

The depth correction for the 1927 map, surveyed during 1922-33 (central year = 1927) is 6 cm, to compensate for the rise in mean sea level compared to the NANZ value (i.e., the relative sea level rise which occurred between 1897 and 1927). The average sea level measured during the period 1922-33 was adopted as the 1927 mean sea-level.

Analogously, considering the mean sea level in both the 1970 and 2002 charts as the mean sea level calculated over the 10 years before the last year of each survey, no correction is needed for either of the maps, since the reference datum (IGM42) is only 1.4 cm higher than the 1970 mean sea-level and roughly the same as the mean sea level in 2002.

Calculation of the sedimentary budget requires a more accurate knowledge of the depth values, in order to identify the “real” depth changes, i.e., those that are due to erosional or depositional processes.

Thus, the lagoon mass balance can be obtained only by eliminating vertical movements of both land and sea occurring between each pair of comparison maps.

For the sedimentary budget 1927-70, the depth correction to adopt is 23 cm, as the approximation of the absolute difference between the IGM42 and NANZ levels (23.56 cm), measured at the reference PdS benchmark, which is the product of both eustatism and subsidence. Unfortunately, in this comparison it was not possible to use differential subsidence values for the individual sub-basins of the lagoon, since a precise topographic network for monitoring land displacement is available only for the more recent period. Given the use of the same reference datum and the small variations in sea level, the 1970-2002 mass balance was calculated from original elevation data corrected only for the differential subsidence occurring in the lagoon sub-basins during the time span, available from spatial data reported by Brambati et al. (2003) and Carbognin et al. (2004).

Insert Figure 2

3.3. Sedimentology

Sedimentological information contemporary with the bathymetric chart of 1927 is very scarce. The few papers from that time dealing with surficial sediment characteristics mainly focus on benthic communities (Vatova, 1940, 1949), and only a rough description of sand/mud ratios in a few sub-areas was reported. In contrast, two sampling campaigns performed in the 1970s and in 2000s provide us with much more information (Molinaroli et al., 2009). The samples from the first campaign were collected between 1976 and 1978 by the Sezione Geo-Mineralogica of Ca' Foscari University in Venice: more than 200 sediment samples (~10 cm thick) were collected with PVC pipes. Samples were collected from tidal and subtidal flats, at water depths of between 0.1 and 2.4 m. The second set of samples was collected in the year 2002 by the Institute of Marine Sciences of Venice: 140 bottom sediment samples (~8 cm thick) were collected with a PVC pipe from lagoon flats at depths of between 0.2 and 2.2 m. Molinaroli et al. (2009) showed that in both cases samples were taken from all over the lagoon with the exception of fish farms and reclaimed areas; the authors discuss in detail the sample treatment methods and analytical procedures used for the two sampling campaigns and find that they were practically the same. Textural characteristics analysed by the same methods and subsequently processed by identical computational procedures can be meaningfully compared (Flemming, 2007) and are thus useful in studies of morphological variations, rises in sea level and physical changes.

3.4. GIS and spatial analysis

3.4.1 Map georeferencing and digitizing

The three bathymetric datasets (1927, 1970, 2002) were processed to produce three bathymetric models of the LV. Every single step in the analysis was performed using the ESRI ArcGis and QGIS-GRASS environments.

The datasets were of two types: the 1927 one was supplied in raster format maps (TIFs) by the Venice municipal Tide Forecast Centre, while the other two datasets (1970, 2002) were already in ESRI shape format, as supplied by the MAV.

The 1927 TIFs were georeferenced using control points recognized on a digital map, the Technical Regional Map in Autocad format, nominal scale 1:5000, based on the Gauss-Boaga Projection (Italian National Coordinate System). Although the original coordinate system adopted in 1927 was different, because the national coordinate system was changed in 1952, a previous comparison between the 1927 and 1970 maps, performed by the same institution which had published them, stated that the difference was not relevant at the scale involved (Rusconi, 1987).

Once georeferenced, the TIFs were mosaicked to check for perfect overlapping. Where the overlapping rasters did not match, a check for georeferencing errors was performed.

The subsequent phase was the digitalization of the morphological objects composing the lagoon. The dataset included three different geometric types of object: points, polylines and polygons.

Points were used to represent spot elevation data, while polygons were used to contour the saltmarshes. Polylines were used as an aid in the process of building the surface.

The total geometric objects created or processed were as follows:

for 1927: 77,537 points, 191 polylines (channel axes), 1829 polygons (saltmarshes);

for 1970: 72,472 points, 773 polylines (channel axes), 6419 polygons (saltmarshes);

for 2002: 138,697 points, 202 polylines (channel axes), 8208 polygons (saltmarshes).

3.4.2 Bathymetric models

To create the lagoon morphological models, a TIN (Triangulated Irregular Network) interpolation type was chosen, because it is precise (it maintains the original data at the sample points) and varies its precision in accordance with data density. The lagoon was subdivided into three morphological categories (saltmarshes, mudflats and channels) using specific vector layers provided by the MAV. Each zone was interpolated individually, to avoid the problems associated with abrupt changes in slope. After a number of tests were conducted, the TIN processed using the whole dataset experienced some interpolation problems, located at the transitions between the three categories. The interpolated surfaces did not respect the real transition between different morphologies, thus introducing errors of volume calculation. A channel axes object was created by connecting the deepest data points in each channel with a polyline in order to give continuity to the channel models. Channels are commonly sounded through cross sections; where these sections are too far apart, the interpolation produces interruption errors, because the 3D triangles connect the nearest three points.

The three datasets cover different areas, that of 1927 having the widest coverage. This is because the area of the lagoon open to tidal circulation varied during the period in question. Therefore an analysis mask was used to study the evolution on a common surface. The mask represents the open lagoon surface as it was in 1970 without the fish farming and unfinished reclamation areas. The analysis mask was supplied by the MAV, which had already used it for similar calculations. All three TINs were checked for interpolation errors, which were often caused by errors in the digitalization process. Those errors were of two types: positive-to-negative inversion and misplacement of data points, i.e. channel data points placed inside saltmarsh polygons. Those errors occurred particularly on the first two datasets (1927, 1970) because they derived from paper maps. The datasets were thoroughly analyzed to find and correct these errors. Once the TINs were validated they were converted to Grids (ESRI raster format) with 10m cells. The cell dimension was chosen to produce as detailed a representation of the models as possible while keeping the required processing power within manageable limits.

Rasters cannot represent vectorial models in detail, because they are quantized, and therefore limited to describing features bigger than the cell’s dimensions. This means that the raster surface area is smaller than the TIN surface area, though the difference amounts to 0.1%. This problem was particularly evident when the three rasters (saltmarshes, flats and channels) were combined to build the lagoon model. The resulting raster presented “no-data” cells at the borders of the three original rasters. This problem was solved by a Map Algebra operation which assigned to these no-data cells a mean value calculated from the 8 adjacent cells.

Although the same analysis mask was used, the three raster models had different total surface areas. This is due to a problem inherent in the modelling method used (TIN), because it produces a model connecting the data points, or polyline vertices, with 3D triangles, and therefore the interpolated surface is limited to the area covered by the dataset. The difference is small and amounts to 0.2% of the total lagoon surface area.

Some considerations have to be made concerning the saltmarshes. Analysis of the data points falling within the polygons of this morphological category gave different mean elevations for each dataset: 0.24 m, 0.22 m and 0.30 m for the 1927, 1970 and 2002 surveys respectively. While the decrease occurring between the first two surveys is plausible, the increase seen in the 2002 survey is not; such an increase conflicts with the fact that the relative sea level is rising. Saltmarshes can react to submergence; if a sedimentary input is available they tend to maintain their typical elevation, tied to tidal range, but they are very unlikely to increase it. The elevation of the marshes was sampled with different methods in the three surveys. Despite being older, the 1927 survey turned out to be more accurate, because the marshes were surveyed with tacheometric methods whereas in the two more recent surveys the stereo photogrammetric method was applied. Several recent studies attribute to North Adriatic vegetated marshes a typical elevation of between 0.25 and 0.30 m, comparable to the mean value of the 1927 survey (Favero et al., 1992; Albani et al., 2001; Bonometto, 2005; Silvestri et al., 2005; Marani et al.,2007). The elevation of the saltmarshes is important for the volumetric calculations. However, given the lack of consistency in the altimetric measuring techniques used in the three surveys, the saltmarshes were converted to rasters with a constant elevation equal to the mean value of the 1927 survey, i.e., 0.24 m.

The three rasters were then reclassified to analyze the frequency distribution of the bathymetric categories. Fourteen classes were chosen following a classification used by Rusconi (1987) in his analysis of the 1927 and 1970 maps. To perform these analyses the three bathymetric maps were considered as “photographs” of the lagoon at the time, so they were corrected only for differences between the sea-level reference datum used and the mean sea level at the time of the soundings. Only the 1927 map was corrected, by 6 cm. To calculate volumetric changes, two difference rasters were produced by a MapAlgebra operation using the ArcGIS “Raster Calculator” tool. The bathymetric values of the 1927 grid were subtracted from the 1970 values and the values of the 1970 grid were subtracted from the 2002 values, generating two raster maps of depth differences with the same resolution as the input maps, enabling a detailed assessment of the morphological changes occurring during the last 75 years. The final maps were corrected for datum and subsidence for 1927 and only for subsidence in the period between 1970 and 2002 as calculated by Brambati et al. (2003).

3.4.3 Geostatistics of sediment data

The 1970 and 2002 sedimentological datasets (paragraph 2.3) consisted of two vectorial (point) layers containing 17 intervals of grain-size. An IDW (Inverse Distance Weighted) interpolation was executed for each interval, obtaining 34 grids with 10m resolution cells, representing the spatial distribution of specific grain-size dimensions throughout the lagoon. Differences between the sedimentary maps of 2002 and 1970 were obtained by subtracting each 1970 map grid from its corresponding 2002 map grid.

4. Results and discussion

4.1 Morphological transformations

The morphological structure of the Venice lagoon in 1927, 1970 and 2002 is shown in Fig. 3. The structure is typical of a coastal lagoon, where water exchanges with the sea occur through three main seaward inlets. A complex network of channels has developed on the lagoon side of each inlet beginning with a main channel and reaching the inner lagoon through secondary and then higher order channels (creeks). Marshes are found mainly in the inner parts of the lagoon; a significant amount of marsh sediment in the northern basin is the result of rapid settling of suspended particles in estuarine areas characterised by freshwater inputs (the Silone, Dese and Osellino tributaries), which account for about 46% of the total riverine inputs of suspended matter to the lagoon (Zonta et al., 2001). A significant quantity of marshes have also arisen from sedimentation along the edges of the channel network, as a result of the abrupt morphological, and thus hydrodynamic, contrast between the channels and the adjacent tidal flats.

Insert Figure 3

Two main phenomena are easily discernible from comparative observation of figure 3 and the surface area occupied by each of the main elevation categories (Table 2 a, b ,c): the collapse of the saltmarshes, which decreased by more than 50% from 68 km^2 in 1927 to 32 km^2 in 2002, and the progressive deepening of the lagoon, with a huge increase in the area of subtidal flats between -0.75 and -2.00 m deep, from 88 to 206 km^2, during the same period. Evidence of transgressive effects is seen in the enlargement of mudflats deeper than -1.2 m (Fig. 3), which represent the remnant of the ancient depressions and ponds of the former Venetian alluvial plain, over which the embryo lagoon formed during the mid-Holocene highstand (Fontana et al., 2004). In 1927 these depressions had an area of up to 23 km^2 and a mean depth of -2.1 m. By 1970, relative sea-level rise had caused this area to double in size, though the average depth fell to -1.6 m. This was because ca. 22 km^2 of subtidal flats formerly between -1.00 m and -1.25 m deep “morphologically shifted to elevations of < -1.2 m. In 2002, the mean depth was still 1.6 m, although the area of subtidal flats deeper than -1.2 m was 105 km^2. Since relative sea level did not change significantly between 1970 and 2002, this further doubling of the area of deep subtidal flats indicates erosion due to enhanced hydrodynamic forcing, in turn due to the increased mean depth of the LV and to the hydraulic efficiency of the artificial channel network in the Malamocco sub-basin.

The deepening of the lagoon affected mainly the southern sub-basins C and D, and a part of basin B, south of the town of Venice, as already highlighted by Molinaroli et al. (2009) for the 1970-2002 period.

The distribution of area changes (losses and gains) of the different elevation categories within the lagoon (Table 2 b, c) and within each sub-basin was significantly different in the two periods.

During 1927-70, the greatest area reductions were seen in the saltmarshes and elevations above -0.75 m. The expansion of the other categories of mudflat (below -0.75 m) is related to depth increases, as for the subtidal zones. For the channels, due to the effects of the large-scale excavations carried out in the industrial area, 0.75 m is the fulcrum depth of the morphological adaptation of the lagoon to relative sea-level rise caused by the combined effects of eustatism and subsidence.

The following period (1970-2002) saw the enhancement of erosional process, leading to an expansion of subtidal flats below -1 m. In contrast, the categories affected by losses were mainly subtidal flats at a depth of between -0.5 m and -1 m, the latter depth becoming the new fulcrum of morphological adaptation of the lagoon system.

For sub-basin C, erosion gave rise to an increase of 26.7 km^2 in the area of subtidal flats below -1.5 m, which is currently the greatest modal depth of the four sub-basins of the LV, and more than 75 cm deeper than the modal depth of the same sub-basin in 1927.

In order to emphasize changes in morphology, we represented the distribution of the areas as a function of the elevations in 1927, 1970 and 2002, calculated for the whole lagoon and for each of the sub-basins A to D (Fig. 4). The frequency curves of the three periods for the whole LV showed a clear-cut shift in the most frequent elevation from a value of -0.62 m in 1927, to -0.87 m in 1970, and -0.88 m in 2002.

A similar shift in bathymetry was observed by Fagherazzi et al. (2006) when comparing the 1901 and 2000 lagoon morphologies. Their data refer to the southern lagoon, which was not clearly defined by the authors, but is likely to include the Chioggia and Malamocco sub-basins, as well as the southern part of the Lido sub-basin.

Those authors showed that shallow tidal basins (such as the Lagoon of Venice) are characterised by extensive tidal flats and saltmarshes that lie within specific ranges of elevations, between which intermediate elevations (± 0.25 m) are less frequent due to their inherent instability, strongly dependant on fetch conditions (Fagherazzi et al., 2007). With high deposition rates – such as those of 1901 – the most frequent tidal flat elevation was around -0.50 m, which tended to shift towards lower elevations when sediment availability was reduced (Fagherazzi et al., 2006; Marani et al., 2007).

According to Fagherazzi et al. (2006) the peak depth of -0.50 m which separates morphological stability from instability in tidal flats characterized the southern lagoon in 1900 as well as the present northern lagoon, thus confirming the significance of either riverine inputs that compensate for submergence or morphological complexity that inhibits the formation of wind-induced waves.

Despite the difficulties of comparison between Fagherazzi et al. (2006) and our own frequency analysis of lagoon elevations (since the studied surfaces are not coterminous), we also observed a modal elevation for the entire lagoon of ca. 0.6 m in 1927. The slight shift from the previous value of -0.50 m during 1901, whether significant or not (considering the uncertainties), may reflect reduced sediment input due to reclamation activities for the first industrial zone and the damming of rivers in the 1920s.

The significant additional shift towards -0.87 by 1970 is related to several reclamation activities (the 2nd and 3rd industrial zones, airport and housing in Mestre), together with the dredging of sediment for the Malamocco-Marghera ship canal, mostly disposed of on land.

The final shift towards the value of ~ 0.90 (seen in 2002) is not so evident as in the previous period, but looking at the evolution of the individual sub-basins, it coincides with the tidal flat erosion phase proposed by Defina et al. (2007). According to these authors, in a “starved” lagoon the instability of the subtidal flats inside basins with large open fetch will ultimately lead to a smooth horizontal bottom with increased depths of up to 2.0 – 2.5 m.

This is clearly seen in the Malamocco and Lido sub-basins, where the modal depth is 1.75 m and 1.12 respectively, both significantly deeper than 1970. This means that abrupt change has taken place since the large-scale submergence of the largest open basin of the lagoon, which caused increased erosion due to wave-induced currents during *Bora* wind events (Cavaleri, 1980; Fagherazzi et al., 2007).

In contrast, during the period 1927-1970, the mean depth in basin A saw change of the same order as the relative sea-level rise. After 1970 no significant morphological changes occurred, thus confirming that complex and mature lagoon morphology inhibits the effect of wave-induced currents by *Bora* winds, which are thus no longer able to generate significant wave disturbance over the irregular distribution of shallow flats and transverse saltmarshes.

Insert Table 2

Insert Figure 4

4.2 Historical deposition, stability and erosion

The processing of bathymetric data described in paragraph 2.4 was aimed at calculating the differences in elevation between pairs of datasets.

For description purposes a simplification was made in the classification of the elevation data. In figure 5 the difference rasters are presented in the form of erosion maps subdivided into four categories: strong erosion, moderate erosion, stability and deposition. Strong erosion corresponds to cells with erosion values greater than 0.5 m, and moderate erosion from 0.5 to

0.1 m. Stability corresponds to the range ±0.1 m, and deposition corresponds to cells with deposition values greater than 0.1 m.

Insert Figure 5

4.2.1.Bathymetric chart comparison: 1927-1970

15% of the lagoon is characterized by strong erosion, 29% by moderate erosion, 34% is stable and 22% is depositional (fig. 5). The areas affected by strong erosion are concentrated mostly in the channels, mainly the Malamocco-Marghera ship canal (the “Oil Canal”) and the whole of the industrial area with its canals and docks, which were excavated in the late 1960s. The areas affected by moderate erosion are mostly tidal and subtidal flats. Stable areas are evenly distributed across saltmarshes and tidal flats. Deposition is seen in many channels and some mudflats.

A - Treporti basin: Areas of strong erosion account for 13% and are located mostly in the Treporti Channel, saltmarshes and many secondary channels near depositional areas. Areas of moderate erosion account for 24% and are located mostly in mudflats and saltmarshes. Stable areas account for 39% and are located mostly in mudflats and saltmarshes. Areas of deposition account for 24% and are located in mudflats and channels.

B - Lido basin: Areas of strong erosion account for 17% and are located mostly in the Giudecca – Lido Channel, the Marghera docks, and many saltmarshes. Areas of moderate erosion account for 35%, and are evenly distributed across mudflats throughout the area, except a thin belt on the north-west landward side of the basin. This belt and some saltmarshes are stable, together accounting for 27% of the sub-basin’s surface area. Areas of deposition account for 22%, and are concentrated in some channels, a wide area on the north-west side of Venice, the convergence of the Treporti and Lido channels and some patches of the tidal flats.

C - Malamocco basin: The sub-basin appears to be divided into two zones: the eastern part with the Oil Canal and the other main channels, and the western part with almost all the saltmarshes and small channels. Areas of strong erosion account for 17% and are clearly concentrated in the eastern part of the basin, occurring mostly in the Oil Canal and Vittorio Emanuele Canal, excavated in the late 60s, and in some mudflats around the mouths of the northern tributaries. In the western part, the areas affected by strong erosion are almost all saltmarshes. Areas of moderate erosion account for 31%. In both parts of the basin these areas correspond to mudflats, large patches in the eastern zone and small patches in the western zone. Stable areas account for 29%. In the eastern zone the stable areas are mudflats, mostly concentrated in the southern part, whereas in the western zone they mostly correspond to saltmarshes but also to mudflats. Areas of deposition account for 22%. In the eastern zone they correspond to channels in the northern part and mudflats in the southern part. In the western zone the channels are almost all characterised by deposition, as are all the central mudflats.

D - Chioggia basin: Areas of strong erosion account for 12%. The main areas are the Chioggia inlet channel with a nearby artificial canal, a wide portion of mudflats in the northern part of the basin and some saltmarshes. Areas of moderate erosion account for 25% and correspond mainly to mudflats and to some saltmarshes in the south-western part of the basin. Stable areas account for 42% and include mainly mudflats and most of the saltmarshes. Areas of deposition account for 21% and include mainly mudflats, particularly in the north-western and southern parts of the basin. There is also a large deposition area in the convergence zone near the Chioggia inlet.

The dominant factor driving morphological transformation in the 1927-1970 period was subsidence, which had a significant human-induced component (c.f. 2.2 and 3.1). Most of the areas of strong erosion coincide with the Oil Canal, Vittorio Emanuele Canal and the industrial docks, from which about 40 Mm^3 was dredged. The remaining areas are saltmarshes, which by 1970 had been reduced to about half the surface area they had in 1927, with a loss of 25 Mm^3. A common phenomenon throughout the lagoon is the erosion of the main channels while the secondary channels are characterised by deposition, with some of the material coming from the erosion of the nearby flats and saltmarshes suffering moderate erosion. This process is mainly visible in the open lagoon, especially in the Lido and Malamocco sub-basins (B and C), while in the more protected areas where saltmarshes prevail (the Treporti and western Malamocco sub-basins), the movements of sediment are more complex. In the lagoon as a whole, mudflat erosion involved the movement of 66 Mm^3, of which 17 Mm^3 was deposited in the channels. On average, the mudflats deepened by about 7 cm, while the mean depth of the channels decreased by 5 cm.

The individual sub-basins evolved differently. In the Treporti basin (A), mudflats and channels were almost stable (-1 cm and 0 respectively), in the Chioggia sub-basin (D), both mudflats and channels deepened (by 4 and 5 cm respectively). The Malamocco (C) and Lido (B) sub-basins suffered the highest erosion of mudflats (deepening by 10 and 9 cm respectively). Sub-basin C also saw the highest rate of deposition in channels (15 cm) followed by sub-basin B (7 cm). In the Malamocco sub-basin (C), the high rate of deposition in channels is due to the filling-in of the Spignon channel, which was abandoned after the dredging of the Oil Canal.

4.2.2.Bathymetric chart comparison: 1970-2002

The activities that caused significant subsidence during the 1950s and 1960s were stopped but natural subsidence continued to influence the morphology of the lagoon.

Erosion was strong in 69 km^2 (17% of the total area), concentrated particularly in the area around the Malamocco inlet (sub-basin C, 38 km^2) and Chioggia inlet (sub-basin D, 16 km^2). Moderate erosion affected 32% of the lagoon, especially large areas to the north and south of the city of Venice (sub-basin B). Deposition and stability (affecting 28% and 23% of the entire lagoon respectively) prevailed in the Treporti and Lido sub-basins and were concentrated especially in the inner part of the lagoon, saltmarshes and surrounding mudflats (fig. 5).

A - Treporti sub-basin: this is the most stable sub-basin, with 75% of its area in a stable or depositional condition, confirming the trend of the 1930-1970 period. Strong erosion (affecting less than 1%) is concentrated in dredged channels, and moderate erosion (25%) in mudflats.

B – Lido sub-basin: most of this basin (35 km^2, corresponding to ~40 %) is affected by moderate erosion, with an average deepening of ~13 cm. These areas are located around Murano and south of Venice island. The city of Venice divides the Lido sub-basin into two parts: a southern area which is mainly affected by erosion and a more complex area to the north. Stable and depositional areas (26% and 24%) are located in the inner part, near the industrial area and Tessera airport, and other depositional areas are found inside the main channels.

C – Malamocco sub-basin: areas affected by erosion account for ~64% of the sub-basin as a whole, with almost 40 km^2 of strong erosion localized around the Oil Canal and the seaward inlet. This is the most compromised area of the lagoon, with mudflats deepening by an average of ~40 cm, mainly due to the hydrodynamics generated by the navigation channel dredged in the previous period. Stable areas account for 16% and are found in the inner part of the basin, behind the unfinished landfill islands. Depositional areas (20%) are concentrated mostly in a few channels and around saltmarshes.

D – Chioggia sub-basin: strong erosion expanded to 15% of the sub-basin, affecting mudflats around the artificial channels dredged in the previous period. Mudflats are generally characterised by moderate erosion (30% of the sub-basin), while stable areas, accounting for

30%, are located around saltmarshes. Depositional areas account for 25% and are concentrated in the channels and in the western and southern parts of the sub-basin. Another depositional area is located between the Malamocco and Chioggia sub-basins.

To summarise, the main morphological process in the 1970-2002 period was an extensive deepening, driven not by subsidence, but by serious erosional processes. The entire area from the island of Venice to the Malamocco inlet was characterised by widespread erosion of tidal flats, corresponding to ~40Mm^3 of sediment (~70% of total erosion), concentrated around the previously dredged Malamocco-Marghera ship canal. Throughout the lagoon, channels (especially the minor ones) experienced depositional processes involving ~20Mm^3 of sediments from adjacent eroded mudflats, producing a simplification of the lagoon's morphological structure. The seaward inlets showed a tendency to erosion at Malamocco and Chioggia and deposition at Lido. The process of saltmarsh erosion, significant during the 1927-1970 period, continued in the following 30 years with a loss of ~7 km^2 (~ 9 Mm^3), partially compensated by the construction of ~4 km^2 of artificial saltmarshes (~3Mm^3). As in the 1927-1970 period, the sheltered areas on the landward side of the lagoon were the most stable, characterised by both stability and deposition.

Mudflats deepened by an average of ~19 cm in the lagoon as a whole, with significant differences between sub-basins. Sub-basin A was almost stable, whereas B, C and D saw average depth differences of -9 cm, -40 cm and -13 cm respectively. Almost 15 km^2 of channels accumulated sediments, becoming ~90 cm shallower than before on average, while 8 km^2 of shallow flats were dredged. Channels were characterised by both deposition and erosion, resulting in an average deposition of ~40 cm of sediments.

4.2.3 Continuity of erosion/deposition processes during the whole period (1927–2002)

The sediment volume changes described above were combined in order to calculate the average rates of deposition and erosion and evaluate the continuity of deposition and erosion processes through the two examined periods (Fig. 5).

The 75-year area-weighted mean erosion rate for the entire Lagoon is 0.35 cm y^{-1}, while that of the Malamocco-Marghera sub-basin is twice as high (~ 0.7 cm y^{-1}).

Comparison of the two difference maps highlighted approximately 90 km^2 of the LV with continuous erosion (~1.5 cm y^{-1}) throughout the 75-year period, and 135 km^2 of permanently stable or depositional areas. In contrast, 180 km^2 of the LV saw a change in tendency in the second period, either towards instability or stability. Thus, almost one-half of the lagoon experienced continuously high erosion, with a marked increase in the last thirty-two years. More than 35 km^2 of tidal flats situated around previously dredged channels in the Malamocco and Chioggia sub-basins passed from stable or depositional conditions (0-1 cm y^{-1}) to high erosion (3.4 cm y^{-1}), with a total deepening of ~50cm. In contrast, nearly 30 km^2 of channels characterised by high erosion or dredging during the 1927-1970 period showed strong deposition in the following 32 years, with erosion rates changing from -3.5 cm y^{-1} to +3 cm y^{-1}.

The acceleration of erosion in the central part of the lagoon is a known fact, although there is debate as to the causes. The already-mentioned hypothesis of Defina et al. (2007) regarding the natural deepening of lagoons with long wind fetch when lacking new sedimentary inputs could be right about the principal cause, but it does not explain the acceleration. A concomitant factor is suggested by Sfriso et al. (2005), who highlight the extraordinary and progressive increase in sediment suspension and removal in the mudflats of the LV since the early 1990s due to the large fishing effort involving mechanical dredging for Manila clams. Continuous re-suspension and alteration of the physical properties of the bottom sediment, i.e. compaction and erosion of the critical threshold, could be responsible for erosive processes causing loss of fine material from the mudflats. These processes have markedly accelerated the deepening and the trend towards marine evolution in the central lagoon. The reduction of the macroalgal beds – both before and after the start of clam fishing by means of disruptive techniques – has also significantly contributed to the increase in sediment re-suspension and redistribution, favouring a loss of material and homogenisation of the grain-size and dry density of the surface sediment.

4.3 Sedimentary budgets and the mass balance of the lagoon

Studies of the evolution of recent sediment deposits in the LV are fragmented and provide information which is not readily comparable. In some cases, the erosion/sedimentation data are ambiguous since they do not make a distinction between the current status of the phenomenon and/or its evolution over the past few decades (Degetto and Cantaluppi, 2004). In addition, several sources of uncertainty occur when attempting to calculate sediment budget on decadal time scales using different methods, concerning diverse temporal scales, accuracy, etc.

MAV-CVN (1996) reported an average sediment loss of about $1x10^6$ m^3 $year^{-1}$, by analysing variations in lagoon sediments over the previous 20 years, excluding eustatism and subsidence. Pillon et al. (2003) compared bathymetric maps from 1930, 1970 and 1990, and showed a similar average yearly sediment loss (~$1x10^6$ m^3 $year^{-1}$). Sarretta (2007) calculated a net removal of sediments of $0.9 \pm 0.1x10^6$ m^3 y^{-1} between 1970 and 2000, and Molinaroli et al. (2009) have recently made a detailed comparison of 1970 and 2000 bathymetric charts, together with a comparison of sediment grain sizes, showing marked changes in both morphology and sedimentation.

4.3.1 Volumetric differences through bathymetric comparison

Using the maps in Fig. 3 a detailed calculation of the sediment budget was made for the two periods 1927-1970 and 1970-2002. The digitized bathymetric data were used to directly calculate the sediment volume changes between the surveys in each of the subareas. Table 3 shows all relevant data for calculating the sediment budget of the LV in the two studied periods, and Fig. 6 shows the eroded and deposited material, together with an estimate of the sediment disposed of either outside the lagoon or lost through the three inlets. Uncertainty in budget calculations derives primarily from survey and datum errors, since only overlapping prisms from consecutive surveys were used. Even in areas with perfect overlap between surveys, the lumping of all saltmarshes at 0.24 m above MSL leads to underestimates of shoaling.

Insert Figure 6

Insert Table 3

In the first period (1927-1970), dredging operations moved an estimated 60 Mm^3 of material, and erosion of saltmarshes and mudflats moved an additional 34 Mm^3 (18+16), making a total of 94 Mm^3. All the dredged material was disposed outside the lagoon, approximately 35-45 Mm^3 on land and the remaining 15-25 Mm^3 dumped in the sea. Of the eroded material, 21 Mm^3 was sedimented inside the lagoon, either in channels (17 Mm^3) or on saltmarshes (4 Mm^3) and the remaining 13 Mm^3 were lost though the inlets. The total sediment removal from the lagoon in forty-three years was thus 73 Mm^3 (~ 1.7 Mm^3 y^{-1}), of which the flux to the sea through the inlets was 13 Mm^3, i.e. ~0.3 Mm^3 y^{-1}, almost equally distributed among the four sub-basins.

In the second period (1970-2002) dredging operations moved an estimated 11 Mm^3 of material, while erosion of saltmarshes and tidal and subtidal flats moved an additional 61 Mm^3, making a total of 72 Mm^3. Approximately 3 Mm^3 of the dredged material was re-used to construct artificial saltmarshes and the rest (8 Mm^3) was disposed of outside the lagoon (on land). Of the eroded material, 35 Mm^3 sedimented either in channels (32 Mm^3) or on saltmarshes (3 Mm^3). The total sediment removal from the lagoon in thirty-two years was thus 34 Mm^3 (~1 Mm^3 y^{-1}), of which the flux to the sea was 26 Mm^3 , i.e. ~0.8 Mm^3 y^{-1}, two-thirds of which was from sub-basin C. In this period sub-basin A experienced a net gain in sediments, either from the small rivers or from the Treporti channel at the Lido inlet.

Insert Figure 7

To summarise, the last 75 years have seen extensive dredging and relocation of dredged material. Between 1927 and 2002, dredging operations and erosion moved an estimated ~170 Mm^3 (94+72) of sediments in the seaward inlets, mudflats and channels. An unknown but considerable portion of this volume represents winnowing of the same material. About 40 Mm^3 have been removed from the system and disposed of on land since 1960; another 20 Mm^3 of dredged material were disposed of at sea. The quantity of dredged sediment disposed of on land prior to 1960 cannot be estimated but was probably substantial. Since 1970 another ~10 Mm^3 of the material has been dredged from the inlets and inside the lagoon, in part re-used for artificial saltmarshes and sand-banks. An unknown portion of this material was also handled more than once.

The remaining volume, representing the net loss of material from the lagoon to the sea (approximately 40 Mm^3) is estimated to correspond to an annual rate of ~0.5 Mm^3.

The two budgets indicate that dredging and disposal of dredged material are important factors in the sediment budget of the LV. In fact, if we look in detail at the erosion and dredging of lagoon flats as shown in fig. 7, we see that of a total of 129 Mm^3 in the two periods (66+63 Mm^3), the dredged fraction was a little less than one-half (57 Mm^3). Most of the dredging took place before 1970, whereas in the more recent period erosion prevailed, moving 54 Mm^3. Concerning the relative importance of the two processes in the four sub-basins, the data indicates that more than one-half of the total occurred in sub-basin C, where 66 Mm^3 of sediments were moved, mostly due to dredging in the earlier period and erosion more recently.

4.3.2. Lagoon/sea exchanges

Direct measurements of the total mass of sediment input and output through the inlets have a high level of uncertainty .Contrasting data has recently been published, ranging from ~300 $*10^3$ ton y^{-1} (Bianchi et al., 2005) to ~4–500$*10^3$ ton y^{-1} (Zaggia et al., this issue) to ~600$*10^3$ ton y^{-1} (Chiarlo and Fornasiero, 2005). Those estimates refer to the present situation and although they are not very useful for a historical reconstruction of budgets, they could be very interesting in terms of comparison with the past.

Table 4 shows the sediment budget subdivided for the four sub-basins; as with Fig. 6, it is derived from bathymetric chart comparison. The rate of sediment loss to the sea has been transformed from m^3 to tons, assuming a uniform density of 2,650 kgm^{-3} and 50% porosity, in order to compare it with published flux data. Data on riverine input are also listed, but only for the more recent period, since no useful data are available prior to 1970.

From Table 4 it can be seen that not only was the average yearly loss from the lagoon as a whole quite different in the two periods (~400 and ~1100$*10^3$ ton y^{-1}), but the relative rate of loss from the four sub-basins (through the three seaward inlets) was also very different. In fact, loss rates were fairly evenly distributed across the sub-basins in the period 1927-1970 (between 30 and 150 $*10^3$ ton y^{-1}), whereas approximately 80% of all losses from the LV in the period 1970-2002 (~ 1100 $*10^3$ ton y^{-1}) were accounted for by the Malamocco sub-basin alone (~ 900 $*10^3$ ton y^{-1}), while the northern sub-basins (A and B) were almost stable. In the latter period, river input was negligible for the LV as a whole (less than 3%) but significant for sub-basin A, which seems to be the only one not losing sediments and where river input may positively affect sedimentation.

Finally, our historical data matches quite well with the estimates of Degetto and Cantaluppi (2004), who recently used radiochemical methods based on ^{210}Pb and ^{7}Be to obtain the mass balance of particulate material exchanged at the seaward inlets of the LV. The two radionuclides were assumed to give different temporal indications, i.e., longer for ^{210}Pb (decades) and much shorter (one-two years) for ^{7}Be. The results obtained with ^{7}Be were considered reliable enough, albeit strictly limited to the period investigated (1999-2000), and showed an average yearly imbalance (sediment loss) of ~ $800*10^3$ ton (range 300-1300) for the lagoon as a whole. The central-south lagoon was found to be the most highly eroded (~ $1100*10^3$ ton y^{-1}), while an accumulation of ~ $300*10^3$ ton y^{-1} was calculated for the northern lagoon.

According to Zaggia et al (this issue), the present situation seems to have changed, since their recent surveys suggest that most of the particle exchange between the LV and the sea (~ 600 $*10^3$ ton y^{-1} in total), is through the Lido inlet (~ 400 $*10^3$ ton y^{-1}), leaving Malamocco and Chioggia only 10% and 25% of the total budget respectively.

Insert Table 4

4.4. Relationship between variations in sediment texture and erosion/sedimentation patterns

Recently, Molinaroli et al. (2009) made a detailed comparison of LV sediment grain-size data from 1970 and 2000. The surficial sediments of the lagoon consist predominantly of clayey silts in both datasets (mean mud content was 75% for 1970 and 68% for 2000, dry weight) (Molinaroli et al., 2007).

In both datasets the silt fraction dominates over other fractions, but with a general tendency to decrease between 1970 and 2000, with the exception of basin C. In all sub-basins, the 1970 samples have a lower sand content than the 2000 samples. The 1970 and 2000 samples have similar clay content, except for sub-basins A and D, where slight differences between the two datasets are observed (Table 4).

The authors showed that there was a clear increase in sand content from 1970 to 2000 throughout sub-basins C and D, especially towards the landward side. Very high sand content is also evident in the 2000 samples from sub-basin B and around the city of Venice. Sub-basin A does not show significant variations (see Fig. 8 in Molinaroli et al., 2009).

The authors also presented data on surficial sediments in the form of ternary diagrams based on Flemming's sand/silt/clay ratios (2000). The location of data points within the diagram reflects specific hydrodynamic energy conditions. The sediment composition of the LV is described by a diagonal band that gradually expands towards the silt-clay axis. The textural gradient in sub-basin A shows a shift towards higher silt/clay content between 1970 and 2000, indicating a general decrease in energy in this sub-basin. In sub-basin B, most of the sediments have become richer in sand, while those of sub-basins C and D have become richer in silty sands and very silty sands (see also Fig. 7 in Molinaroli et al., 2009), indicating a general increase in hydrodynamism.

In order to understand the relationships between erosion/sedimentation patterns and sediment texture we calculated the raster differences of sand (>63μm) and clay (<2μm) between 2000 and 1970) (Fig. 7). The spatial distribution of differences in sand content shows the greatest increases around the city of Venice, especially on the southern side, between the city and the industrial area of Porto Marghera and between the city and the Lido inlet. Significant sand enrichment was also found in the southern part of the lagoon around the watershed between sub-basins C and D .

The spatial distribution of differences in clay shows the greatest enrichment in the northern part of the lagoon and towards the landward side, from the airport to the industrial area. Other spots in which remarkable enrichments are found are located in the southern lagoon. (Fig. 7).

Insert Table 5

Insert Figure 8

In order to explore the relationship between variations in sediment texture and erosion/sedimentation patterns we selected six representative sub-areas with different erosion/deposition characteristics and calculated the average grain-size data for each of them (Fig. 8). The average differences between three grain size intervals (<8, 8-63, and >63 μm) in 1970 and 2002 were calculated and represented by histograms (Fig. 8). The six selected areas cover more than 120 km^2 and have a volume of moved sediment of 26 Mm^3, accounting for almost one-third of the area and sediment budget of the LV.

Sub-areas I, II and V are characterised by stability/deposition. The first two are located in the northern lagoon (sub-basins A and B-north) and the third in the southern part, along the watershed between sub-basins C and D. Grain size data show a 5% gain in aggregate mud (<8 μm fraction), in the sub-areas located in the northern part of the lagoon (I and II) and a 30% gain in sand in sub-area V.

Sub-areas III, IV and VI are characterised by moderate/strong erosion processes. They are located in the southern part of the lagoon. Sub-area III, located to the south of the city of Venice (sub-basin B) is characterised by moderate erosion, while sub-areas IV and VI, located in sub-basins C and D respectively, are characterised by strong erosion over the last thirty-two years. Grain size data show a 15% and 6% loss of aggregate mud in sub-areas III and IV respectively and a 10% loss of sand in sub-area VI.

Insert Figure 9

Insert Table 6

To summarise, we have deposition of fine particles in the northern sub-basins (A and B-north) where there is still some riverine input, and deposition of sand in the watershed between sub-basins C and D. The calculated sedimentation rates are ~ 0.3-0.4 cm yr^{-1}. Erosion of fine-grained material was observed in sub-basins B-south and C, and erosion of sand in part of sub-basin D, around some of the channels excavated in the 1980s in connection with the Chioggia inlet. In this case the erosion rates range from 0.7 to ~2.5 cm yr^{-1}.

Those data are in agreement with radiochronological investigations conducted in the 1980s and 1990s, which highlighted a sedimentation rate of 0.3–0.5 cm y^{-1} in the more recent deposits (Donazzolo et al., 1982; Battiston et al., 1985, 1986). Evidence of erosive phenomena was reported in the early 1990s for the southern lagoon and more recently for the central lagoon, between the industrial area and Venice (Degetto, 1997; Degetto and Cantaluppi, 2004).

Bellucci et al (2007) studied five saltmarsh sediment cores taken from all around the LV and found that the inventories of excess ^{210}Pb were slightly higher than those expected from atmospheric deposition, due to some contribution from sediment re-suspended from mudflats or eroded from marsh borders. Average accumulation rates were ~ 0.3 cm y^{-1} (range: 0.1-0.4 cm y^{-1}), comparable to the average rate of mean sea level rise in the last century in Venice.

The erosion or sedimentation rates at three stations in sub-basin B and one in C were studied by Sfriso et al (2005) in the period 1989-1999. The authors showed that all stations in sub-basin B were affected by sediment losses, with mean erosion rates of between 0.5 and 3.6 cm yr^{-1}, while the other, despite being in the most unstable sub-basin of all (C), did not show any significant bathymetric change, due to the sea-grass growing on the bed. The authors stated that their data agreed with the previous indirect estimation of sediment loss, which was based on the number of fishing boats operating in the lagoon on an annual basis.

5. Conclusions

A detailed GIS-based analysis of bathymetric surveys carried out in the Lagoon of Venice in the periods 1922-1933, 1968-1971 and 1999-2003 was used to reconstruct historical sedimentation patterns. Analysis of available data on bathymetry, morphology and grain-size reveals that large-scale morphological changes have been directly and indirectly caused by human actions, including navigational improvements (docks, dredged navigation channels), urban settlement, industry (water extraction for industrial plants and subsequent subsidence, filling of wetland areas) and exploitation of natural resources (fish-farming, harvesting of clams with mechanical dredges). Lesser changes are attributable to natural erosion and sedimentation.

The main results are as follows:

1. Saltmarsh areas decreased by more than 50%, from 68 km^2 in 1927 to 32 km^2 in 2002.
2. The Lagoon is progressively deepening, with the modal depth shifting from a value of -0.62 m in 1927 to -0.87 m in 1970 and -0.88 m in 2002. The final change seems negligible for the lagoon as a whole but is the result of a compensation effect between the erosional southern part and the stable-depositional northern part.

3. The deepening is mostly due to the areal expansion of the deepest subtidal flats (between -0.75 m and -2.00 m in depth), from 88 to 206 km^2 during 1927-2002.
4. Depth increases in the 75 year-period mainly affected the Malamocco sub-basin, which went from -0.64 to -1.75 m on average, followed by Chioggia, from -0.39 m to -0.88 m, and Lido, from -0.65 m to -1.12 m.
5. There has been a net loss of about 110 Mm^3 of sediments from the LV, the majority of which (73 Mm^3, about 70%) occurred during the first period. A significant amount was lost by direct disposal of dredged sediments outside the LV, either on land or at sea, whilst 39 Mm^3 was lost from the lagoon to the sea throughout the inlets, at an annual average of 0.5 Mm^3.
6. Considering only the net export of lagoon material to the sea, sedimentary budget calculations highlighted an alarming acceleration of erosive phenomena, from a net sediment loss of 0.3 Mm^3y^{-1} during 1927-1970 to 0.8 Mm^3y^{-1} in 1970-2002. As a consequence, the lagoon was transformed from a highly complex, well-developed microtidal lagoon during the 1930s, to a sediment-starved and subsidence-dominated lagoon in the 1970s, and then to the high energy-dominated and marine-like structure of today.

Deterioration of the lagoon in terms of morphological and thus ecosystem complexity is mainly due to the transgressive effects of human-induced subsidence, superimposed on the natural sea-level rise. It has been demonstrated that in a sediment-starved lagoon like the Lagoon of Venice, tidal flats are characterised by instability due to the effect of wave-induced currents caused by wind acting on large-fetch basins. When morphological complexity and saltmarshes are lacking, this will ultimately lead to a smooth horizontal bottom of 2.0 – 2.5 m deep (Defina et al., 2007; Fagherazzi et al., 2006, 2007).

Nevertheless, it is our opinion that this phenomenon alone cannot account for the critical erosion of the Malamocco sub-basin, where the recorded modal depth in 2002 was -1.75 m, more than one metre deeper than 75 years before.

The southern lagoon experienced the intense impact of clam fishing with illegal mechanical harvesting during the 1990s due to the introduction and spread of the exotic Manila clam. In addition, the Malamocco basin also contains legal Manila clam fishing concessions, which were granted in order to control farming and exploitation. The practice has serious consequences, due to the high number of fishing boats dredging the lagoon bed, causing re-suspension and alteration of the physical-mechanical properties of the sediment. Thus the combination of increased susceptibility to sediment erosion due to clam fishing/harvesting and the enhanced strength of bottom shear stress due to wind waves could easily explain the unexpected deepening of the southern lagoon.

The results shown here call for a review of practises that are not compatible with current highly expensive efforts aimed at morphological reconstruction.

Insert Fig.10

Comparison of the area distribution of elevation categories in the four sub-basins today highlighted striking similarities between the A, B and D sub-basins and the LV as a whole in 1927, 1970 and 2002 respectively (Fig. 10). The current state of the different sub-basins (ontogenesis) reflects the historic evolution of the lagoon as a whole (phylogenesis): thus sub-basin C possibly indicates the future trend of the entire lagoon.

While this is a relatively comprehensive study of historical physical changes, it is incomplete in that the sediment budget is still uncertain. More precise quantification of the modern lagoon sediment budget will require both a better understanding of fluvial input and dredging export and a sediment transport model designed to explain historical changes in the sediment budget. The combination of cartography and modelling used in this study should be applicable in other systems where large changes in morphology have occurred on historical time scales.

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FIGURE CAPTIONS

Figure 1 – Lagoon of Venice and four sub-basins (A to D), separated by broken lines.

Figure 2 – (a) Mean sea level for Venice and Trieste compared to reference *datum*. Moving averages (11 years) are in bold. (b) Absolute difference in mean sea level between Venice and Trieste. Sea level data conventionally refer to a plane located 150 cm below the NANZ.

Figure 3 – Colour-shaded bathymetric maps of LV (from left to right: 1927, 1970; 2002). Dotted red line indicates migration of -1.2 m contour line, showing overall increase in depth (progressively darker blue colour). Emergent areas are indicated in green.

Figure 4 – Distribution of surface areas of specific elevation categories in 1927 (dotted line), 1970 (dashed line) and 2002 (solid line) in whole LV (central plot) and sub-basins A to D.

Figure 5 – Colour shaded sedimentation maps for 1927-1970 (left) and 1970-2002 (centre), and map of continuity/change in sedimentary regime from first to second period (right). Strong erosion means altimetric difference of <-0.5 m, moderate erosion means difference of between −0.5 and −0.1 m, stability means difference within ± 0.1 m, deposition means difference of >0.1 m. Histograms show regimes of four sub-basins in first and second periods. Continuous erosion was seen mainly in tidal and subtidal flats. Continuously stable and depositional areas are mainly surviving or depositional saltmarshes; changes towards erosion (instability) mostly derive from enlargement of permanent erosion area; changes towards deposition derive mostly from channel infilling.

Figure 6 – Sediment budget for whole lagoon (left:1927-70; right: 1970-2002). Riverine input was considered negligible. Unknown portion of dredged material was probably handled more than once. Dashed arrows refer to negative budget (erosion or dredging), solid arrows indicate positive budget (sedimentation). Numbers inside circles are sum of dredged (grey) and eroded (black) material from mudflats and saltmarshes. Net loss is result of balance between eroded and re-sedimented material. During 1970-2002, dredged material was partially re-used for morphological reconstruction (artificial marshes).

Figure 7 – Amount of sediments (Mm^3) dredged and eroded in tidal and subtidal flats for each sub-basin during both periods. Note significance of sub-basin C and differences in processes between two periods.

Figure 8 – Differences between 2000 and 1970 in distribution of sand (>63 µm, left) and clay (<2 µm, right)..

Figure 9 – Grain-size variations from 1970 to 2000 in six sub-areas (areas I, II, V = deposition; II, IV, VI = erosion; see Fig. 5 for colour code). Histograms show combined grain size intervals (<8, 8-63, and >63µm)

Figure 10 – Comparison of area distribution of elevation categories. Above: sub-basins A, B, C and D in 2002; below: whole Lagoon of Venice in 1927, 1970 and 2002 . Note similarities between A, B and D and three historic periods. Evolution of different sub-basins (ontogenesis) reflects historic evolution of whole lagoon (phylogenesis). Sub-basin C may indicate future trend of entire lagoon.

TABLE CAPTIONS

Table 1- Chronology of events recognized as strong drivers able to affect structures and processes in morpho-bathymetry of LV between 1927 and 2002.

Table 2a – Area and area changes by depth range for 1927, 1970 and 2002, entire lagoon.
Table 2b – Area by depth range for 1927, 1970 and 2002 for each sub-basin
Table 2c – Area changes by depth range for 1927, 1970 and 2002 for each sub-basin

Table 3 – Relevant data for whole-lagoon sediment budget calculation in two studied periods. Budgets derive from bathymetric chart comparison. Data on dredged material disposed of on land supplied by MAV, difference indicated as lost though inlets.

Table 4 – Relevant data for calculating sediment budget of each LV sub-basin during two studied periods. Sediment budget is result of bathymetric chart comparison. Data on dredged material disposed of on land supplied by MAV. Rates of sediment loss to sea were averaged for 43 years and 32 years respectively and compared with riverine input. Riverine data for period 1970-2002 are taken from Collavini et al., 2005 and refer to years 1999-2000.

Table 5 – Mean values and ranges (in brackets) of surficial sediment grain-size of mudflats inside each lagoon sub-basin; (after Molinaroli et al., 2009, modified)

Table 6– Relevant data for six zones in figure 9

Figure 1

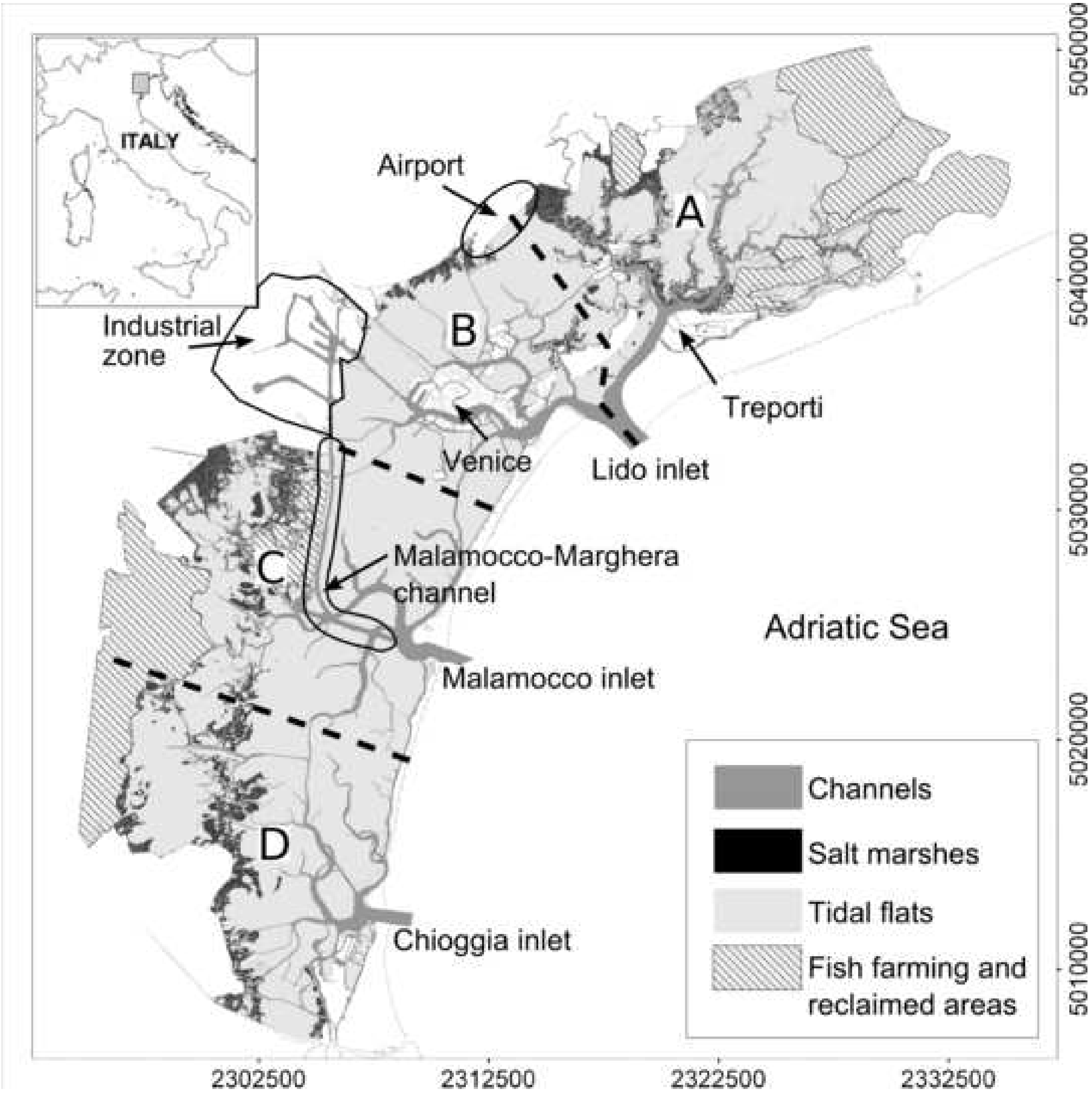
ITALY
Airport
A
B
C
D
Industrial zone
Treporti
Venice
Lido inlet
Malamocco-Marghera channel
Adriatic Sea
Malamocco inlet
Chioggia inlet
Channels
Salt marshes
Tidal flats
Fish farming and reclaimed areas
5050000
5040000
5030000
5020000
5010000
2302500
2312500
2322500
2332500

Figure 2

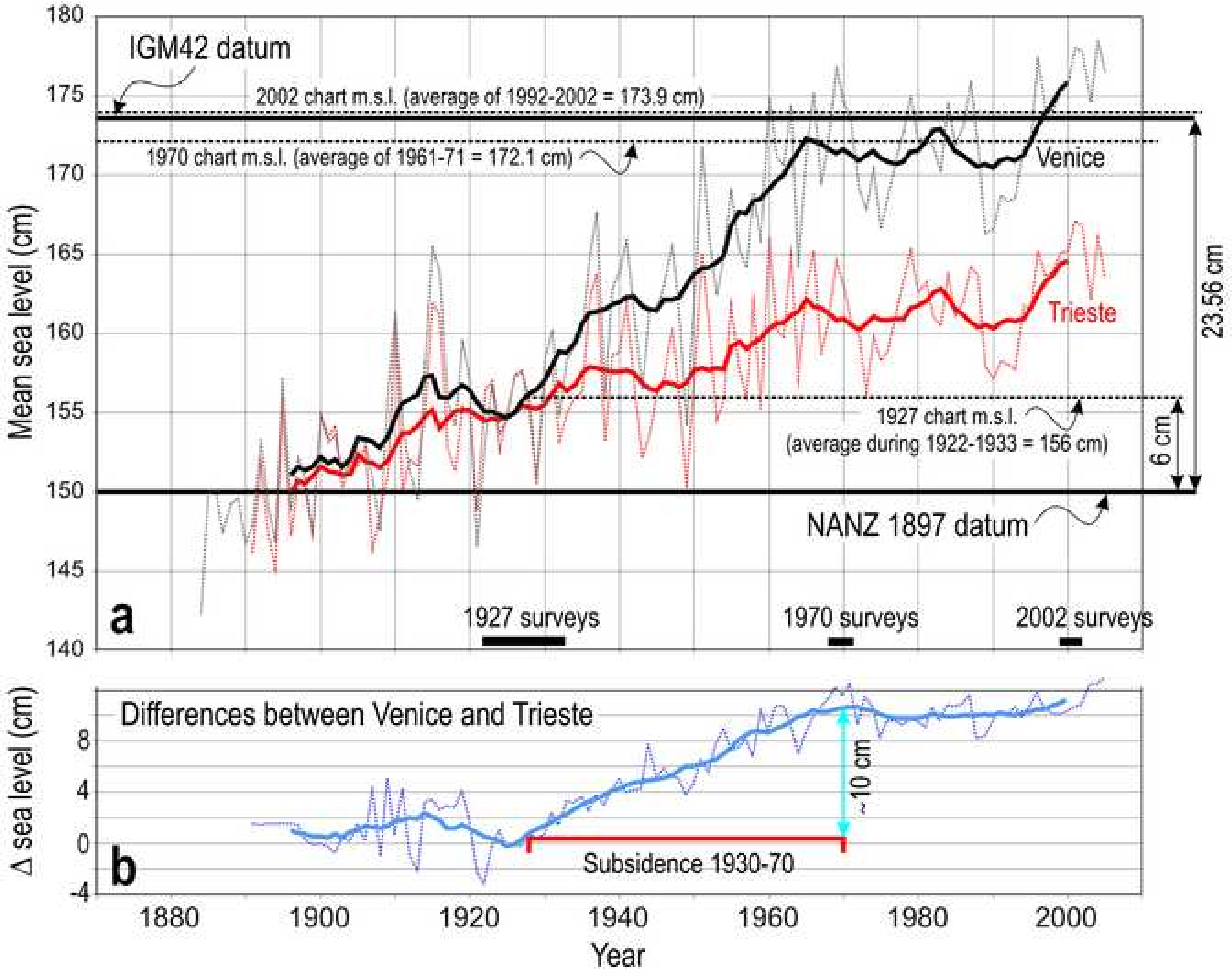
IGM42 datum
2002 chart m.s.l. (average of 1992-2002 = 173.9 cm)
1970 chart m.s.l. (average of 1961-71 = 172.1 cm)
Venice
Trieste
23.56 cm
1927 chart m.s.l.
(average during 1922-1933 = 156 cm)
6 cm
NANZ 1897 datum
a
1927 surveys
1970 surveys
2002 surveys
Mean sea level (cm)
180
175
170
165
160
155
150
145
140
Differences between Venice and Trieste
~10 cm
Subsidence 1930-70
b
Δ sea level (cm)
8
4
0
-4
1880
1900
1920
1940
1960
1980
2000
Year

Figure 3
Click here to download high resolution image

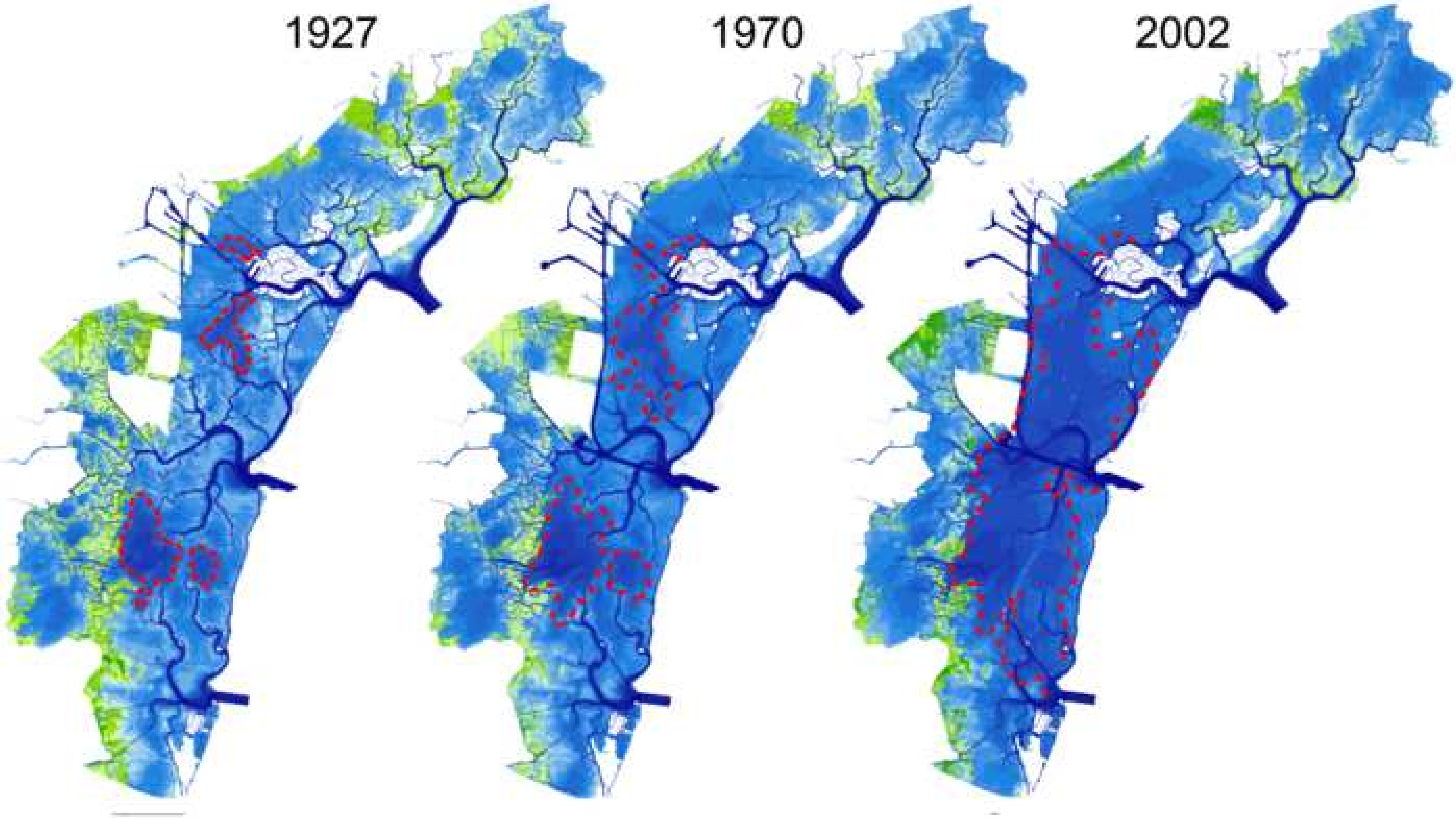

Figure 4

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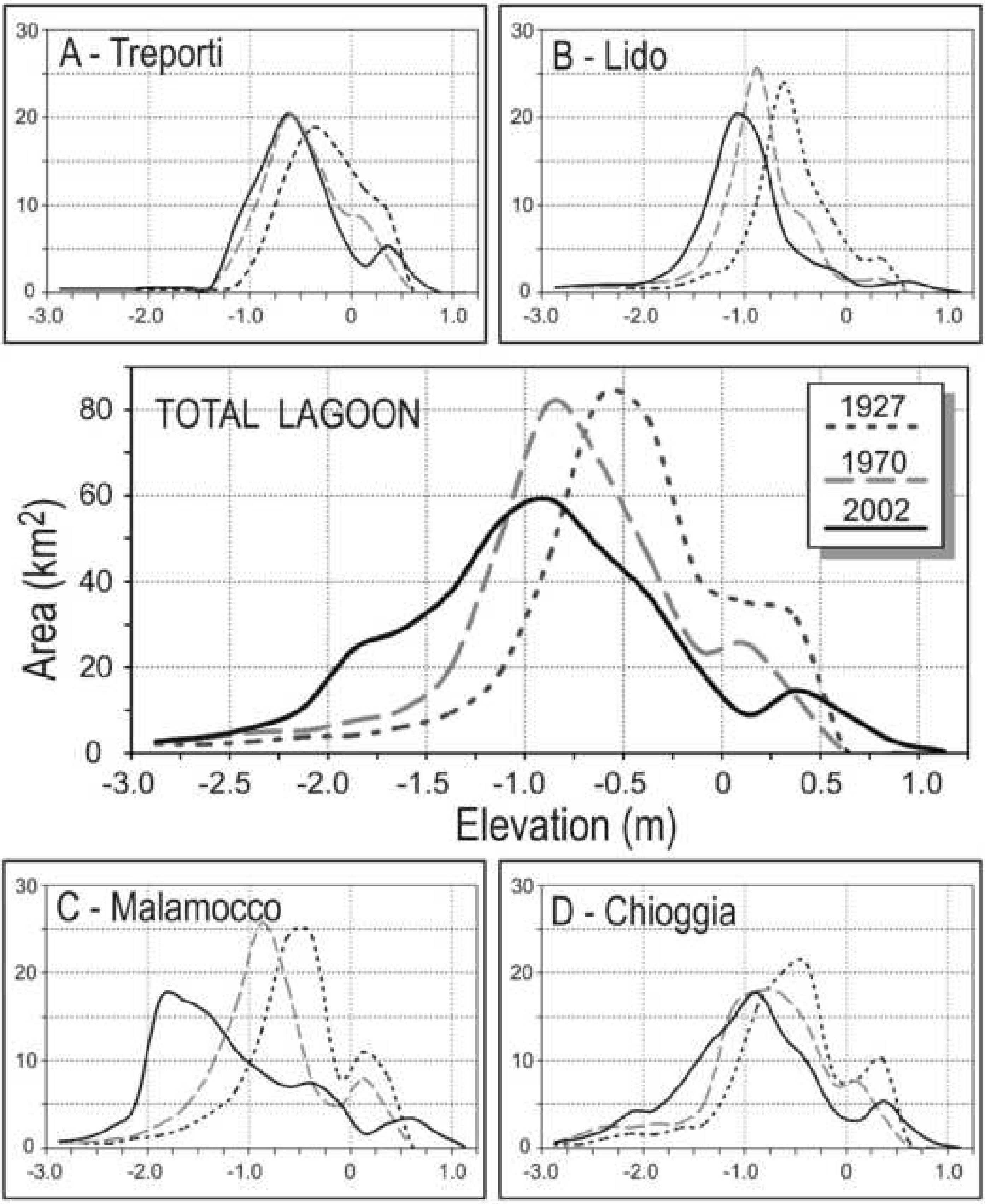

Figure 5

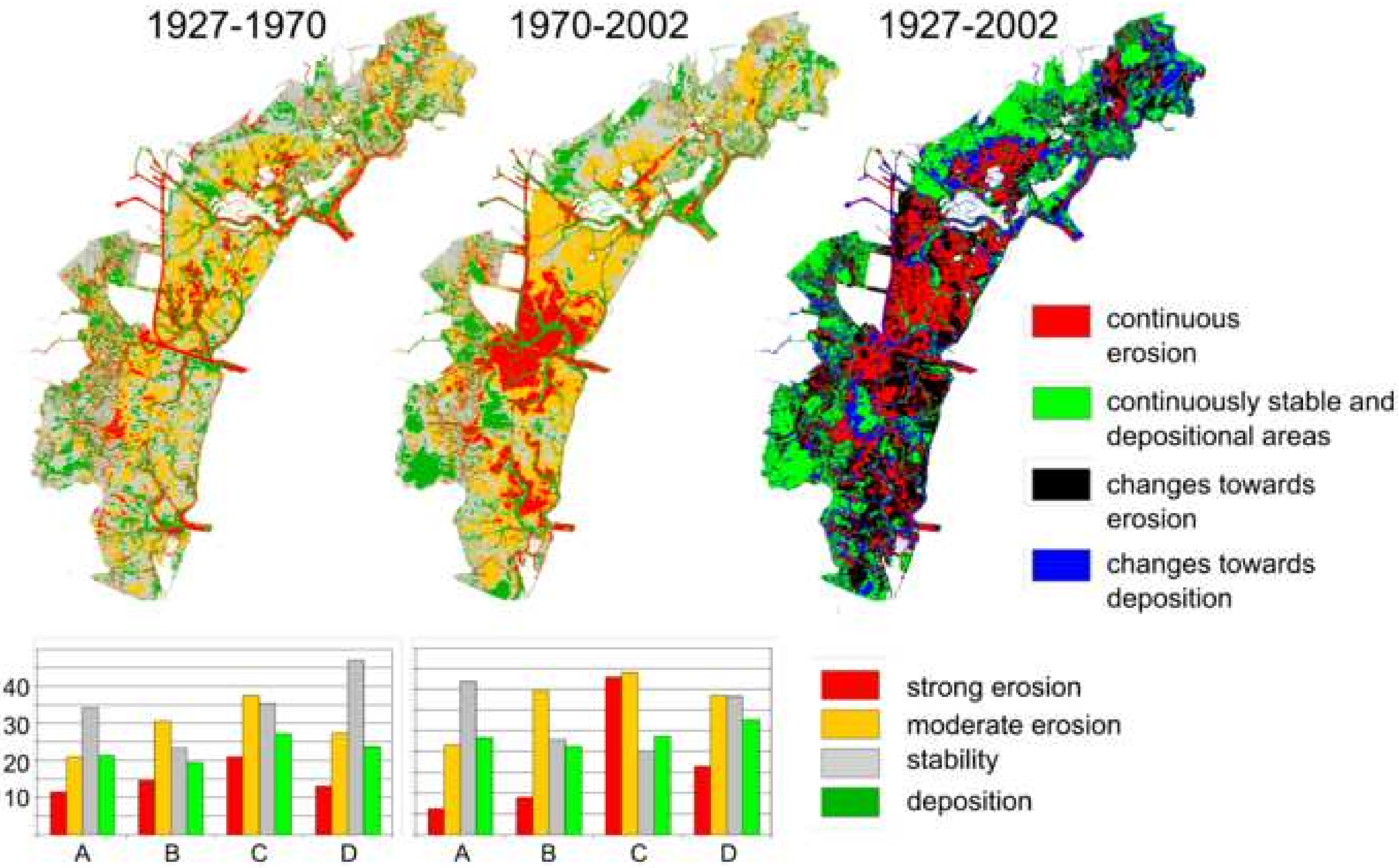
1927-1970
1970-2002
1927-2002
continuous erosion
continuously stable and depositional areas
changes towards erosion
changes towards deposition
40
30
20
10
A
B
C
D
A
B
C
D
strong erosion
moderate erosion
stability
deposition

Figure 6

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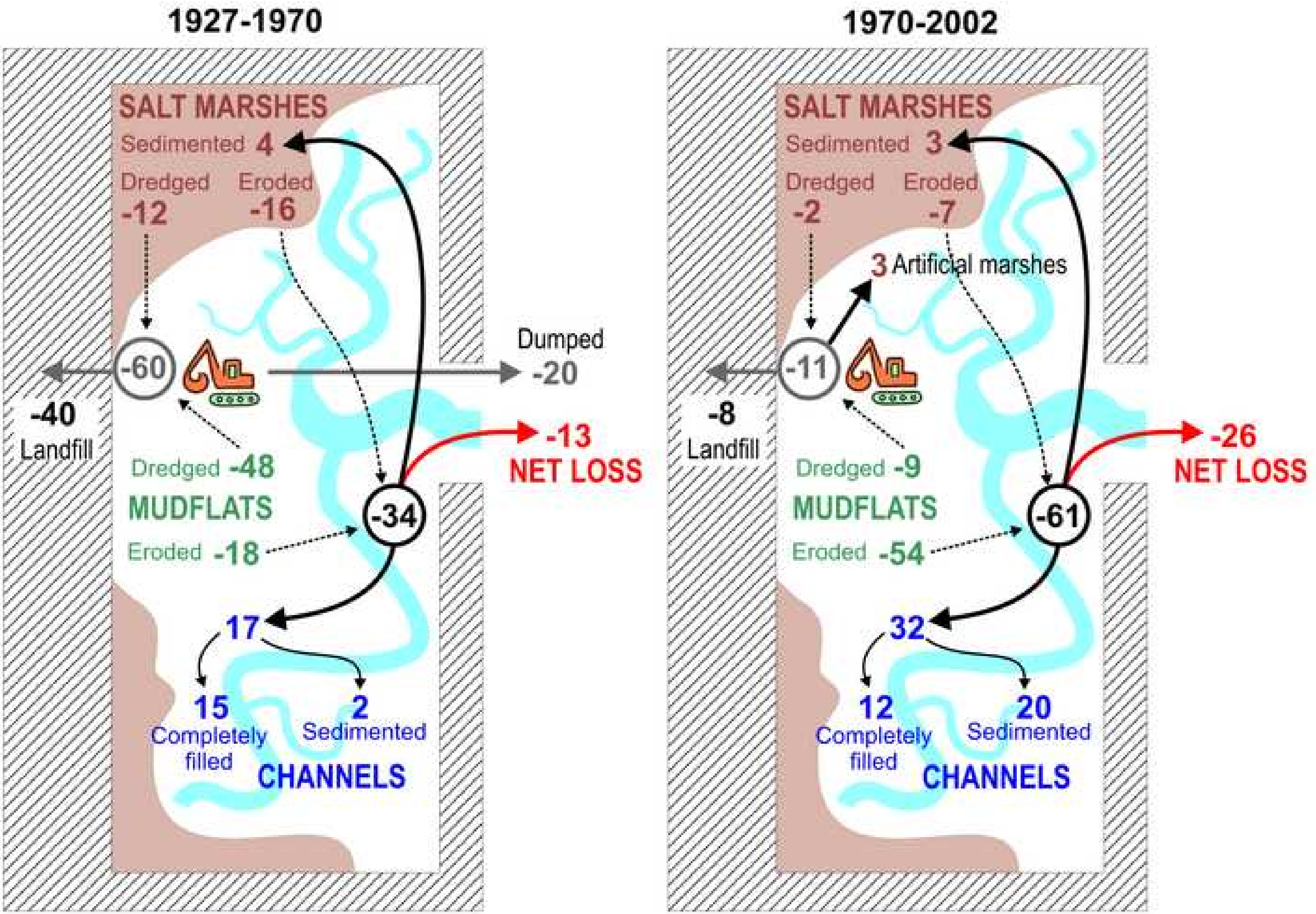

Figure 7

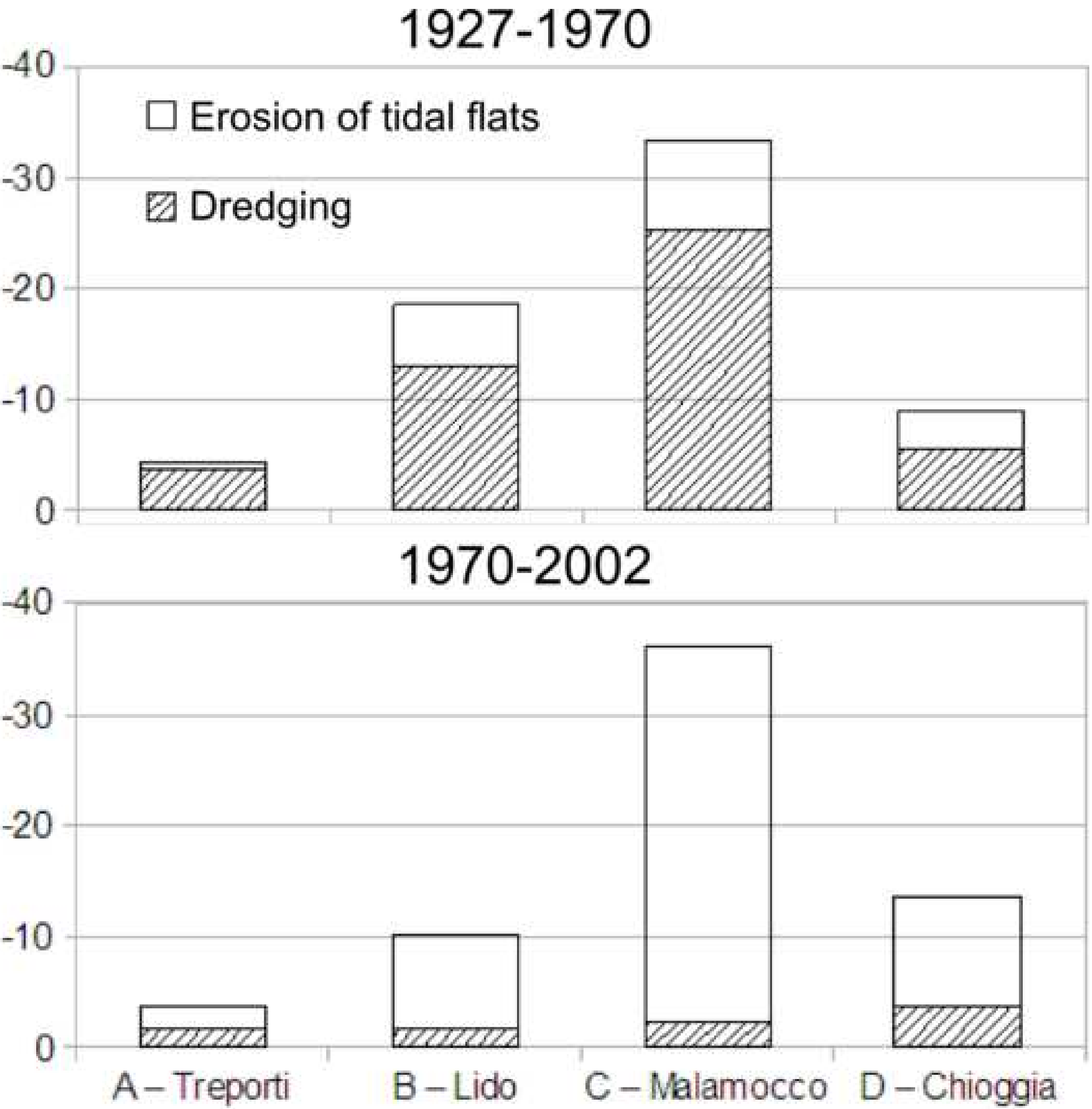
1927-1970
-40
-30
-20
-10
0
☐ Erosion of tidal flats
▨ Dredging
1970-2002
-40
-30
-20
-10
0
A – Treporti
B – Lido
C – Malamocco
D – Chioggia

Figure 8

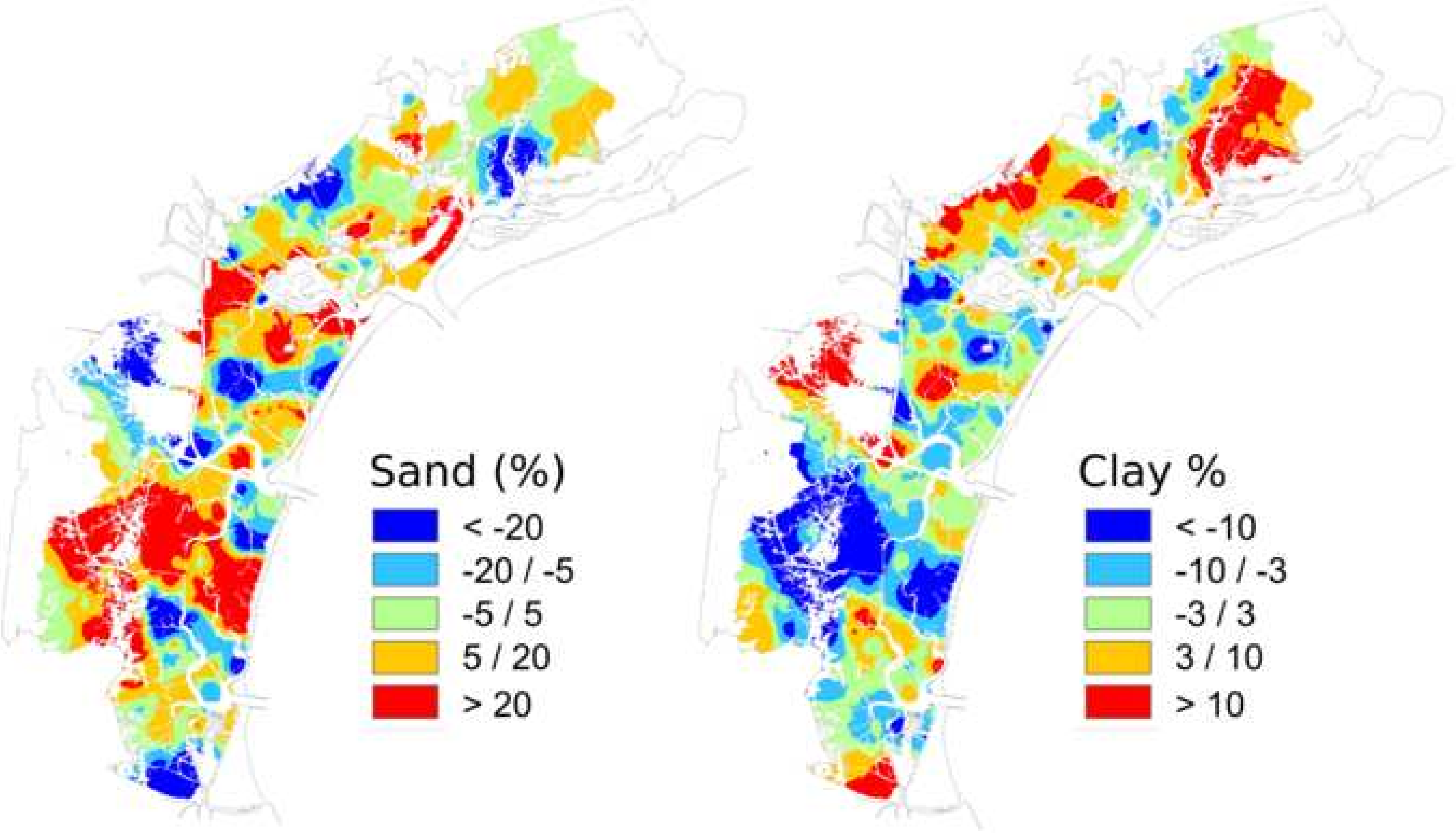

Figure 9

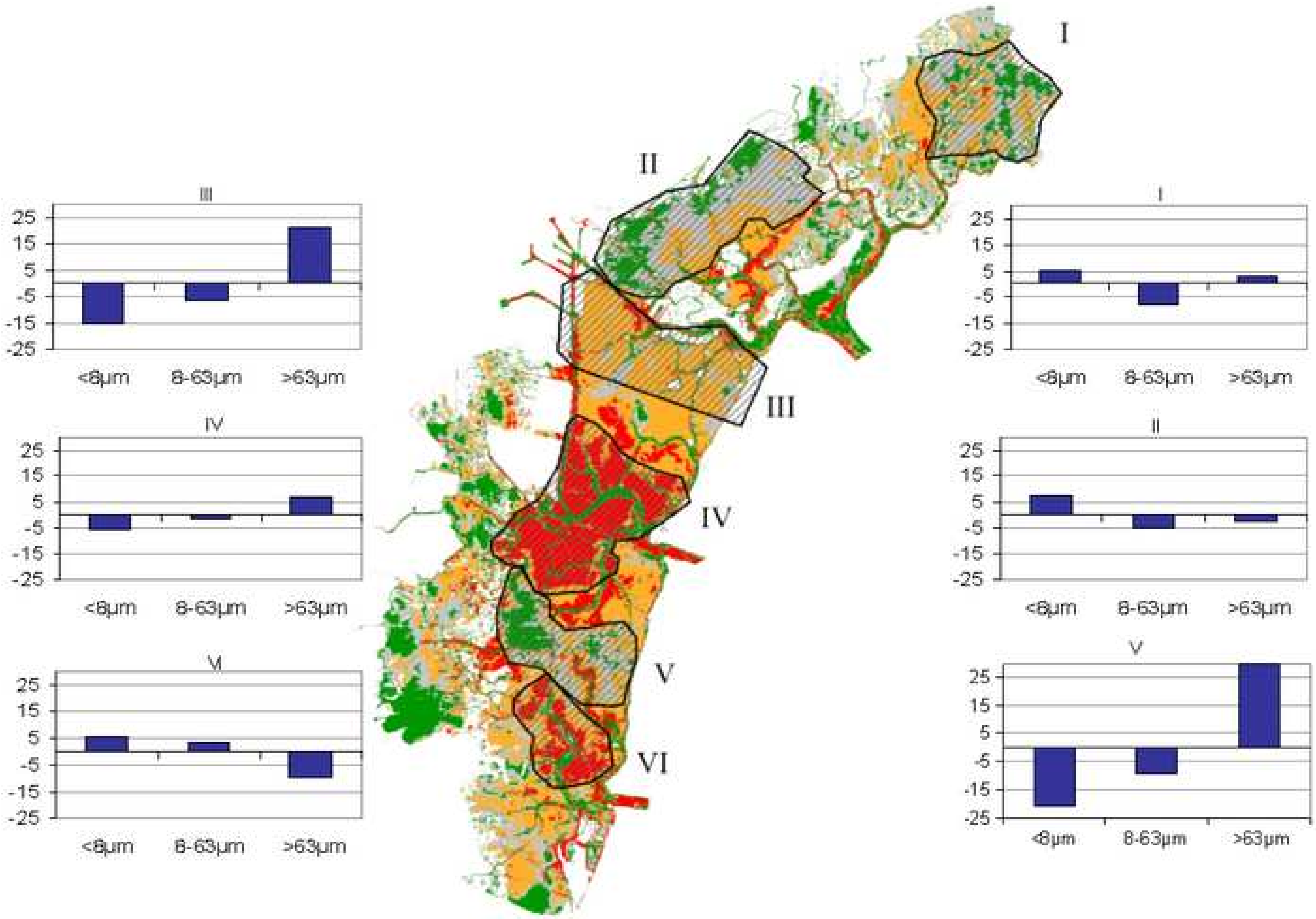

Figure 10

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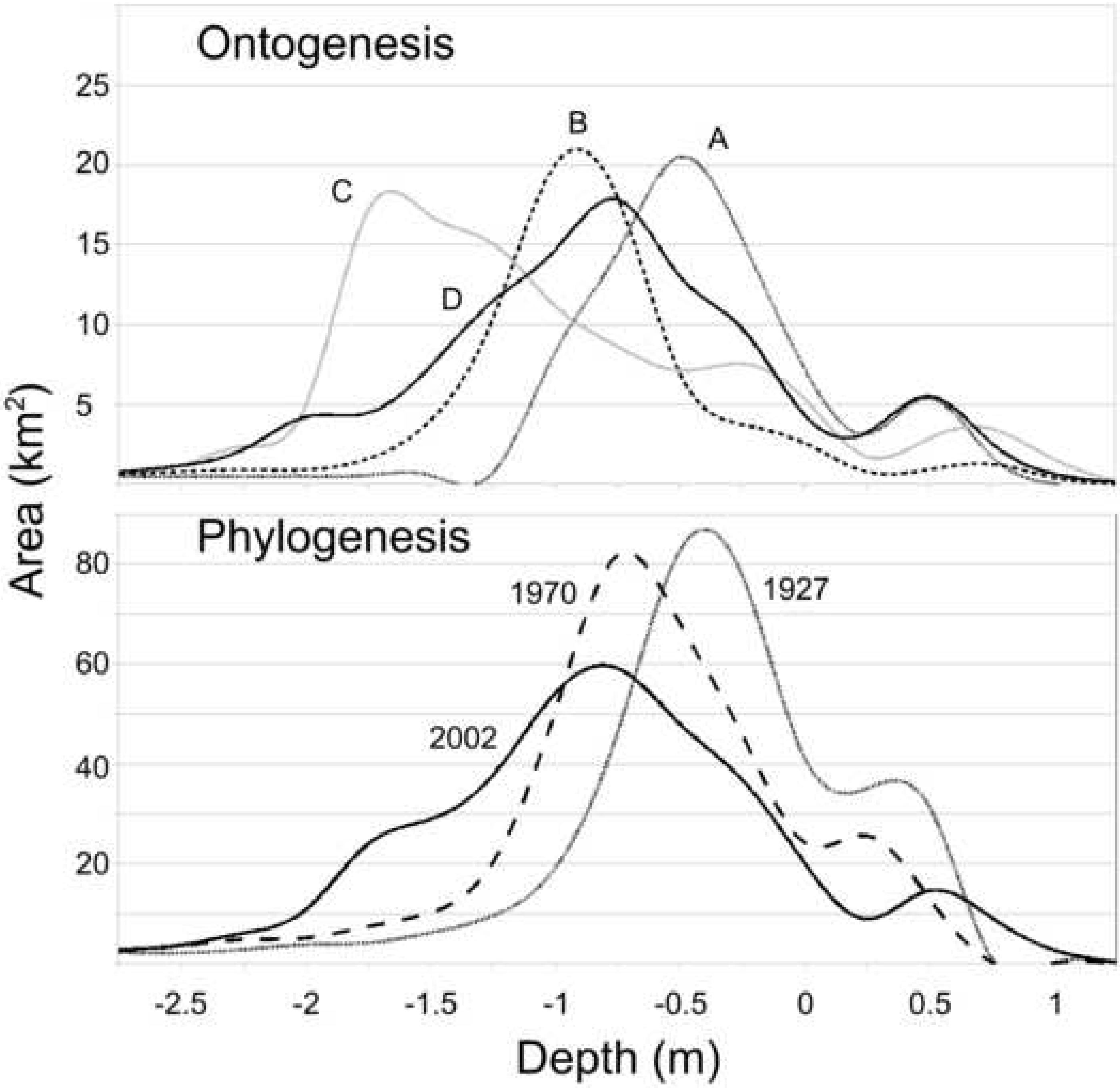

Table 1- Chronology of events recognized as strong drivers able to affect structures and processes in morpho-bathymetry of LV between 1927 and 2002.

FIRST PERIOD	**EVENT**	**NOTES**
1910-1934	new harbour walls at Chioggia inlet	modification of lagoon-sea exchanges
1928	fish farming areas separated from rest of LV	reduction of lagoon surface area (85km^2) / reduction of water residence time
1917-1935	land reclamation for 1st Industrial Zone (IZ)	saltmarsh destruction, (5 km^2, West of City of Venice)
1931-34	construction of trans-lagoon bridge *(Ponte della Libertà*)	modification of tidal current pattern
1950-53	land reclamation for 2nd Industrial Zone	saltmarsh destruction (5 km^2, South of 1st IZ)
1957	land reclamation for housing (*S. Giuliano*, east of Mestre)	saltmarsh destruction (2 km^2, North of trans-lagoon bridge)
1958-1962	airport construction	saltmarsh destruction (~3km$^{2)}$, excavation of new artificial canal from airport to Venice city
1962	land reclamation for 3rd Industrial Zone (never completed), now called "*Casse di Colmata*", i.e. unfinished reclamation islands	saltmarsh destruction (12km^2, South of 2nd IZ)
1966-1969	excavation of Malamocco-Marghera navigation channel ("Oil Canal")	30-50 Mm^3 of sediments disposed of in landfill areas outside the lagoon / modification of hydrodynamic conditions
1930-1970	major development of Industrial activities	from 1932 to 1972, ~12 cm of subsidence were due to water extraction for industrial use
SECOND PERIOD		
from '70s on	dredging of Porto Marghera channels	disposal of 5-15 Mm^3 of polluted sediments, in part outside lagoon
1970-1980	increased discharges from Industrial area (nutrients, metals, POPs)	part of sediments becoming more and more polluted, and thus not suitable for re-use inside lagoon
80s	eutrophication and subsequent macro algae blooms and anoxia	Lagoon bed covered by high quantity of biomass (up to 10-25 kg m^{-2})
middle '80s	introduction of Manila clam for aquaculture purposes	concession of lagoon areas (~14km^2) for clam cultivation and harvesting (seagrass loss, sediment re-suspension and alteration of physical properties)
from 1990	dredging for renovation of Port area	3-5Mm^3 of sediments, partly disposed of outside lagoon
1992	construction of artificial "*Tresse*" island to dispose of polluted industrial waste	saltmarsh destruction (~2 km^2)
90s	"invasion" of LV by *Manila clam*	disturbance of sediments through mechanical clam harvesting
1990-2000	construction of artificial saltmarshes (~4 km^2)	Re-use of non polluted sediments dredged from channels (3-4 Mm^3)

Table 2a,b,c

Tab. 2a – Area and area changes by depth range for 1927, 1970 and 2002, entire lagoon.

Depth interval (m)	Area (km^2)			Area changes (km^2)		
	1927	**1970**	**2002**	**1970-1927**	**2002-1970**	**2002-1927**
<25	0	0	0	0.0	0.0	0.0
-25/-20	0	0	0	0.0	0.1	0.1
-20/-15	1	2	2	1.1	0.0	1.0
-15/-10	5	7	6	2.4	-0.7	1.7
-10/-5	20	20	17	-0.3	-2.6	-2.9
-5/-2	29	32	39	3.4	6.5	9.9
-2/-1.5	10	18	54	7.3	35.7	43.0
-1.5/-1.25	10	21	38	11.5	16.9	28.4
-1.25/-1	20	52	55	32.2	3.4	35.6
-1/-0.75	48	82	59	34.5	-23.2	11.2
-0.75/-0.5	84	67	49	-16.6	-18.5	-35.0
-0.5/-0.25	77	45	37	-31.7	-7.5	-39.2
-0.25/0	39	23	19	-15.9	-3.8	-19.8
>0	68	39	32	-28.8	-6.5	-35.3
Total	**409**	**409**	**408**	**-0.9**	**-0.2**	**-1.1**

Tab. 2b – Area by depth range for 1927, 1970 and 2002 for each sub-basin

Depth interval (m)	1927 Area (km^2)				1970 Area (km^2)				2002 Area (km^2)			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
<25	0	0	0	0	0	0	0	0	0	0	0	0
-25/-20	0	0	0	0	0	0	0	0	0	0	0	0
-20/-15	0	0	0	0	0	0	1	0	0	0	1	0
-15/-10	0	3	2	0	0	4	2	0	0	4	2	0
-10/-5	4	6	6	3	4	6	6	4	4	5	5	4
-5/-2	5	7	8	8	5	6	9	11	5	7	14	12
-2/-1.5	1	1	4	4	1	3	8	6	1	6	34	12
-1.5/-1.25	0	2	4	3	1	5	10	6	1	11	15	12
-1.25/-1	1	4	7	8	5	14	17	16	9	20	11	15
-1/-0.75	6	11	14	16	13	25	26	18	15	18	9	18
-0.75/-0.5	15	24	25	20	20	11	18	18	21	7	8	13
-0.5/-0.25	19	13	24	21	16	8	7	14	15	4	8	10
-0.25/0	16	8	8	8	9	2	5	7	7	3	5	4
>0	21	8	19	19	12	3	12	11	10	3	8	10
Total	**88**	**88**	**121**	**111**	**88**	**87**	**121**	**111**	**88**	**87**	**121**	**111**

Tab. 2c – Area changes by depth range for 1927, 1970 and 2002 for each sub-basin

Depth interval (m)	Area changes 1970-1927 (km^2)				Area changes 2002-1970 (km^2)				Area changes 2002-1927 (km^2)			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
<25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-25/-20	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
-20/-15	0.0	0.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9	0.0
-15/-10	0.2	1.2	0.9	0.1	0.0	-0.2	-0.7	0.1	0.2	1.0	0.3	0.2
-10/-5	-0.2	0.1	-0.7	0.4	-0.5	-0.5	-1.1	-0.4	-0.7	-0.5	-1.7	0.1
-5/-2	0.5	-1.2	0.9	3.1	-0.3	0.6	5.2	1.1	0.2	-0.6	6.1	4.2
-2/-1.5	0.5	1.5	3.6	1.8	-0.1	2.8	26.7	6.2	0.4	4.4	30.3	8.0
-1.5/-1.25	0.5	2.6	5.4	3.0	-0.1	5.9	5.4	5.6	0.4	8.5	10.8	8.6
-1.25/-1	4.2	10.3	9.7	7.9	3.6	6.5	-5.5	-1.2	7.8	16.8	4.2	6.7
-1/-0.75	6.5	14.1	12.2	1.7	2.2	-7.8	-17.7	0.0	8.7	6.3	-5.4	1.6
-0.75/-0.5	5.8	-12.9	-6.6	-2.8	0.2	-4.3	-10.2	-4.2	5.9	-17.2	-16.8	-7.0
-0.5/-0.25	-2.8	-5.5	-16.5	-6.8	-0.8	-4.1	0.9	-3.6	-3.6	-9.6	-15.6	-10.4
-0.25/0	-6.4	-5.5	-3.0	-1.0	-2.1	0.5	0.5	-2.6	-8.6	-5.0	-2.5	-3.6
>0	-8.9	-5.0	-7.2	-7.6	-2.0	0.2	-3.7	-1.0	-10.9	-4.7	-10.9	-8.6

Table 3

Tab. 3 – Relevant data for whole-lagoon sediment budget calculation in two studied periods. Budgets derive from bathymetric chart comparison. Data on dredged material disposed of on land supplied by MAV, difference indicated as lost though inlets.

Entire Lagoon of Venice	**1927-70**			**1970-2002**		
	Km^2	**Depth variation (m)**	**Mm^3**	**km^2**	**Depth variation (m)**	**Mm^3**
sedimentation inside lagoon						
a) within channels	44	0.05	2	50	0.40	20
B completely filled channels	7	2.08	15	14	0.87	12
c) extension of saltmarshes	4	1.08	4	4	0.62	3
dredged sediments	22	-2.78	-60	9	-1.22	-11
sediment eroded						
a) tidal and subtidal flats	269	-0.07	-18	287	-0.19	-54
b) saltmarshes	26	-0.63	-16	10	-0.67	-7
artificial saltmarshes				4	0.91	3
disposed of outside lagoon			60			8
lost through inlets			**-13**			**-26**

Table 4

Tab.4 - Relevant data for calculating sediment budget of each LV sub-basin during two studied periods. Sediment budget is result of bathymetric chart comparison. Data on dredged material disposed of on land supplied by MAV. Rates of sediment loss to sea were averaged for 43 years and 32 years respectively and compared with riverine input. Riverine data for period 1970-2002 are taken from Collavini et al., 2005 and refer to years 1999-2000.

	Sub-basin	Budget (Mm^3)	Disposal outside (Mm^3)	Lost to sea (Mm^3)	Rate of loss in $m^{3*}10^3 yr^{-1}$	Rate of loss in tons^ 10^3 yr^{-1}	River input m^3 10^3 yr^{-1}
1927-1970	**A - Treporti**	-7,0	6	-1,0	-23	-31	
	B - Lido	-20,0	17	-3,0	-70	-92	
	C - Malamocco	-34,2	30	-4,2	-98	-130	
	D - Chioggia	-12,0	7	-5,0	-116	-153	
	Total Lagoon	-73,2	60	-13,2	-307	-406	
1970-2002	**A - Treporti**	1,7	0	1,7	54	71	14
	B - Lido	-4,1	2	-2,1	-65	-85	8
	C - Malamocco	-24,1	3	-21,1	-659	-870	4
	D - Chioggia	-8,0	3	-5,0	-156	-206	7
	Total Lagoon	-34,4	8	-26,4	-826	-1090	33

(^) Volume estimates assume uniform density of 2,650 kgm^{-3} and 50% porosity

Table 5

Tab. 5 - Mean values and ranges (in brackets) of surficial sediment grain-size of mudflats inside each lagoon sub-basin; (after Molinaroli et al., 2009, modified)

Sub-basins	Sand 1970 (%)	Sand 2000 (%)	Silt 1970 (%)	Silt 2000 (%)	Clay 1970 (%)	Clay 2000 (%)
A	8 (0-49)	11 (2-43)	68 (44-84)	61 (45-72)	24 (8-51)	29 (11-43)
B	19 (3-64)	31 (1-91)	60 (25-86)	48 (6-70)	21 (8-35)	22 (3-46)
C	40 (3-96)	42 (6-83)	41 (2-65)	41 (12-73)	19 (1-45)	18 (3-40)
D	39 (0-97)	48 (1-98)	42 (2-73)	36 (1-62)	20 (1-47)	16 (0-45)

Table 6- Relevant data for six zones in figure 9

Sub-zone	Area ID	Erosion/ Deposition regime	km^2	Mean depth variation (m)	Sedimentation/erosion rate (cm yr^{-1})	Volume (Mm^3)
I	A	SD	19	0.12	0.4	2
II	A/B	SD	28	0.08	0.3	2
III	B	ME	24	-0.23	-0.7	-5
IV	C	SE	27	-0.81	-2.5	-22
V	C/D	SD	16	0.11	0.4	2
VI	D	SE	8	-0.60	-1.9	-5

SD: stability + deposition; ME: moderate erosion; SE: strong erosion