HYDRODYNAMICS AND MORPHOLOGY CORILA 3.2

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Sommario.

Il progetto CORILA 3.2 si è occupato dei processi idrodinamici e morfologici che interessano la laguna di Venezia. Questo articolo presenta i temi principali della ricerca e tenta di dare una risposta ad alcune questioni che sorgono quando si studia la laguna di Venezia.

Sono state condotte delle indagini sul ruolo che gioca l'idrodinamica sulle variazioni geo-morfologiche, sulla batimetria, sull'erosione e su trasporto e deposizione di sedimento. Sono stati utilizzati i Foraminiferi come indicatori dei cambiamenti ambientali passati e presenti e sono state utilizzate delle tecniche di telerilevamento per studiare il fenomeno della subsidenza nella laguna di Venezia.

Sono state effettuate delle campagne di misura per studiare l'origine della sabbia in laguna. I risultati sono stati poi riprodotti con l'utilizzo di modelli. È stato adattato un modello idrodinamico per lo studio del trasporto di sedimento, ed è stato applicato ampiamente alla bocca di porto del Lido e al canale di Trerporti.

Abstract.

The CORILA project 3.2 has been dealing with the hydrodynamic and morphological processes ongoing in the Venice lagoon. This article presents the highlights of this research and tries to answer some questions that arise when studying the Venice Lagoon.

Investigations have been carried out on the role of hydrodynamics on geo-morphologic variations, bathymetry, erosion, transport and deposition of sediments. Foraminifera have been used as indicators of past and present environmental changes

and remote sensing techniques have been used to investigate the subsidence in the Venice lagoon.

Field campaigns have been carried out to study the origin of the sand in the lagoon. The findings have then been reproduced with modeling techniques. A hydrodynamic model of the lagoon has been adapted to be used for sediment transport studies, and has been extensively applied to the Lido inlet and the Treporti channel system.

1. Introduction.

Monitoring and managing a coastal ecosystem with a high anthropic influence, like the Venice lagoon, can only be achieved through a multidisciplinary approach. The CORILA project 3.2 *Hydrodynamics and Morphology* has been devised in order to answer the questions that are concerned with the Morphological transformations and its feedback on the Hydrodynamics.. It did this by collecting data and information and developing models and methodology that, hopefully, will also help to set up a management plan for the Venice Lagoon.

The main objectives of this project were:

- to build a state of the art data base of the Venice Lagoon that concerns the geo-morphologic and hydrodynamic characteristics, and of the processes that led to erosion and deposition in the past (time scale of centuries, datation of sediments), the recent past (time scale 10 years, comparison of maps) and the present (time scale 1 year, photo mapping of the lagoon);
- to develop a coupled mathematical model that is capable of describing the changes in the short and medium term and that accounts for the hydrodynamics, transport of sediments and re-suspension due to the wind and wave action on the lagoon.

These objectives have been achieved through:

- the evaluation of short- and medium-term evolutive trends concerning the processes of erosion and sedimentation, both natural and caused by human action;
- the estimate of fluxes of suspended sediments along the major channels;
- the evaluation of the impact of climate changes on the paleodepositional environments in order to obtain input data for the forecasting models;
- the investigation of the role of the hydrodynamics on geo-morphologic variations, bathymetry, erosion, transport and deposition of sediments;
- the increase in forecasting capabilities for the models dealing with hydrodynamics and transport and with the management of coastal ecosystems by collecting new data of physical, chemical, sedimentological and geo-morphological type;
- the indication of tools and methodologies suitable for an efficient management of the Venice Lagoon;
- the implementation and validation of a mathematical model that takes into account the action of tide, wind and waves on the morphological evolution;
- application of the model to different scenarios of the past and the future.

In the following an overwiev of the achievements is given and the results are presented. For more detail the bibliography section should be consulted.

2. Geomorphologic processes and sedimentological characterization of the Venice Lagoon bottom sediments.

2.1. Geomorphologic processes.

Physical and geomorphologic variations that occurred naturally in the lagoon of Venice since its formation have been recognized in the sedimentary layers underlying the Venetian basin.

It is however in recent times that the complex morphology and hydrodynamic of the lagoon have undergone extensive and increasing changes caused by natural processes and by the direct or indirect impact of man activities. The comparison of topographic and bathymetric maps dated 1931, of recent aerial photographs and of all available information on morphology and bathymetry of the lagoon [Bonardi, 1998] has allowed the identification and definition of morphological boundary variations, on a decadal scale, of salt marshes and soft inaccessible mud flats.

A detailed study of the BV (*Barena Vecchia*), BN (*Barena Nuova*) and BNW (*Barena North West*) of the Scanello area, chosen as a representative site of the geomorphologic changes and hydrodynamic processes presently affecting the Venice Lagoon, was carried out in order to better understand the erosion-transportation-sedimentation processes and the hydrodynamics interaction. The study that included detailed topographic and bathymetric surveys has indicated that the medium and short term erosion and deposition trends of the salt marshes under investigations seem to be strongly connected to local hydrodynamics.

Comparing historical topographic maps from 1931 to 1986 and air photos taken in 1961, 1968, 1987 and 1996, it has been possible to evaluate the spatial variations of the salt marshes. In a time span of about 70 years a maximum withdrawing of 58m of the edge lining the Burano Channel of *Barena Vecchia* was observed (Fig. 1), whereas a maximum accretion of 80m of the mud flat facing the north-eastern edge of *Barena Nuova* was calculated.

Furthermore, a series of GPS (Global Positioning System) surveys, conducted for 18 months between 1996 and 1997 and referred to the air photos taken in 1987, has led to the annual quantification of erosional processes (4m/year) occurring along the edges of *Barena Vecchia* and of the area extension of the salt marsh-mud flat limit at *Barena Nuova*. On the basis of textural and mineralogical analyses performed on the sediments from some cores taken in the Scanello area [Bonardi, 1998] we can suppose that the clayey silts eroded at the edge of *Barena Vecchia* settle down at the mud flat facing *Barena Nuova* concurring to expand its surface area.

Recently, in the framework of the morphological recovery activities of salt marshes performed by the Italian Ministry of Public Works, Water Authority of Venice by way of its concessionary Consorzio Venezia Nuova, the edges of the *Barena Vecchia* salt marsh have been marked out with containing piling. During a topographic survey performed in 2000 the reconstructed edges of *Barena Vecchia* were mapped; the restored south-western limits of the salt marsh actually lie approximately along the ones surveyed in 1996. The topographic survey was extended also to *Barena North West*, in order to find out if these restoration activities could interfere with the natural morphological trends of the adjacent mud flats and salt marshes.

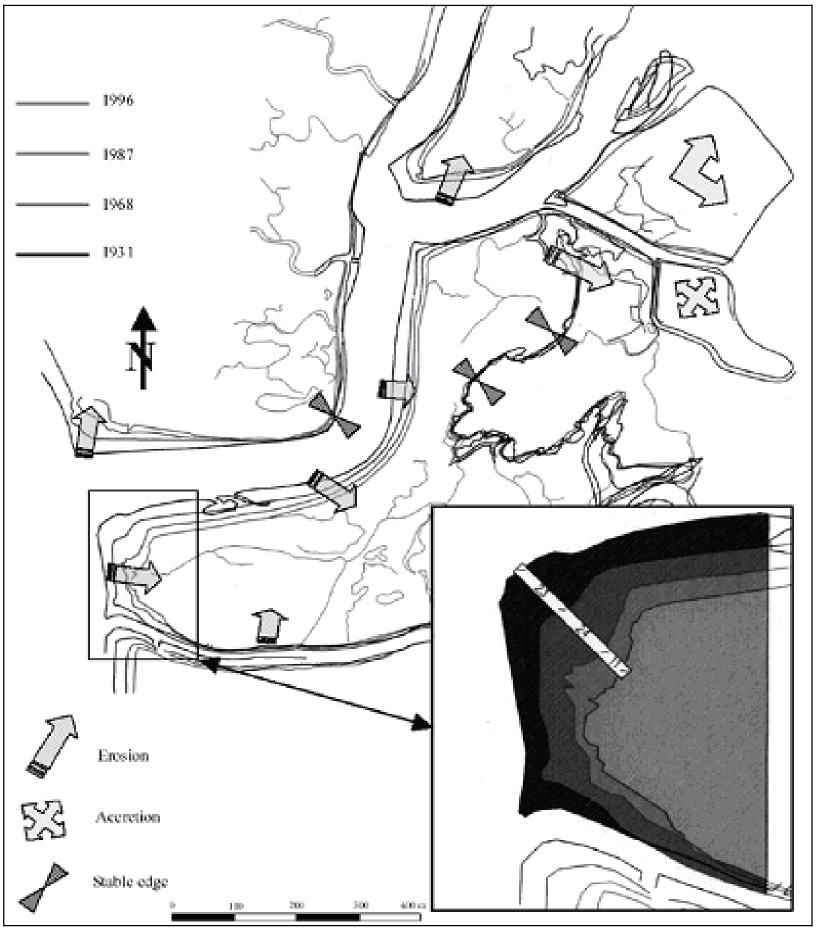

Fig. 1 – Comparison of *Barena Vecchia* (BV), *Barena Nuova* (BN) and *Barena North West* (BNW) edges between 1931 and 1996.

In 2002, a new series of GPS measures was so performed only at *Barena Nuova* and *Barena North West* (Fig. 2). *Barena Nuova* shows a general surface reduction even though it is very limited and meanly quantified in 0.50 m in the two years considered time span. A maximum shifting back of about 2m was observed at the south-western corner and in correspondence of the main tidal creeks. Nevertheless, it is important to note that between 2000 and 2002 at the salt marsh edge retreat there was a contemporaneous increase in its altitude, which varies between a minimum of about 2mm to a maximum of about 2cm, and deepening of the tidal creeks. *Barena North West* also suffers a general surface reduction, but it is greater than the one observed at *Barena Nuova*. In fact it retreated about 3.75m at its south-western corner and more than 7m along Scanello Channel (Fig. 2); however, a slight accretion of about 1m was observed along the north-western edge facing Scanello Channel. Even though altitude measures were not performed in 2000, it appears that a tidal creeks deepening is actually taking place on the edge facing *Barena Nuova* of this salt marsh.

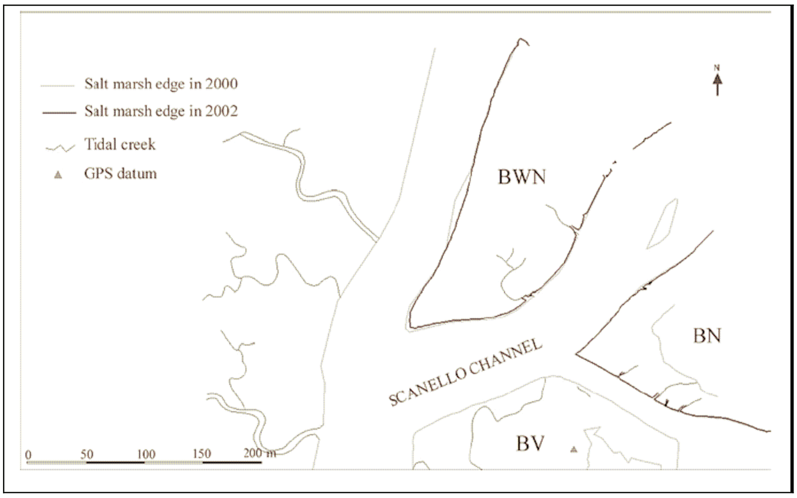

Fig. 2 – Comparison of *Barena Nuova* (BN) and *Barena North West* edges between 2000 and 2002.

2.2. Sedimentological characterization of the surficial sediment.

The geomorphologic study was later complemented with a comprehensive grain size, mineralogical and geochemical investigation of the bottom sediments of the Venetian basin .The characterization of the sediments is an important tool for the evaluation of the hydrodynamic processes. Hence, while the mineralogical composition of the bottom sediments is related to the ancient fluvial supply to the lagoon, which was different in the north and south lagoon areas; anomalous percentages of the mineral content may be considered a consequence of the hydrodynamic reworking processes. Textural characteristics also give important information about processes responsible for sediment erosion, transport and deposition. The study has provided an updated overview of the spatial textural, mineralogical and geochemical variations of the top lagoon sediments. It is based on more than one hundred analyzed samples taken in selected sites, which represent the various morphologies and hydrodynamic conditions of the lagoon system.

As already observed in many previous studies, our investigation indicates an overall similar mineralogical composition with distinct percentage changes from the northern sector of the lagoon, where carbonate-rich sediments prevail (Fig. 3), to the southern silicate-rich sector. This distribution mainly corresponds to the ancient fluvial input of the Piave and the Brenta-Bacchiglione river systems, from the north and the south respectively.

In particular, carbonate content shows dominant dolomite and subordinate calcite, whereas within silicates (quartz, k-feldspar and plagioclase) quartz is dominant. Clayey minerals (mica, chlorite, kaolinite, illite, hastingsite) show higher contents within the Brenta river deposits and in low energy areas, particularly landwards.

Geochemical analysis by ICP-MS (Induced Coupled Plasma Mass Spectrometry) on more than one hundred samples collected in proximity of the sites of the 1983 extensive sampling reported by Albani *et al.* [1995; 1998] and Albani and Serandrei Barbero [2001] was carried out for comparison in order to have some indication of possible heavy metal content variation during the past 20 years.

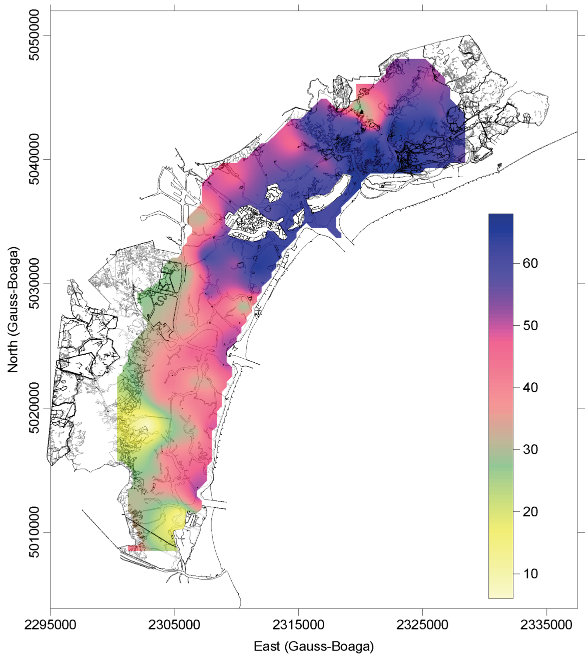

Fig. 3 – Spatial distribution of total carbonates (dolomite+calcite+ankerite+aragonite).

The geochemical data were elaborated [Bonardi and Bonsembiate, 2004] according to the method suggested by Albani *et al.* [1995] The analyzed elements have therefore been divided into two groups: 1) *natural elements* such as Si, Ti, Al, Fe, Mg, Ca, Na, K, Ni, Zr, and Ba of fluvial and coastal origin and *elements of anthropogenic origin* such as Cr, Cu, Zn, As and PB, the concentration of which could be linked mainly to industrial activities in the area of Marghera and Chioggia and to other past and present activities such as hospitals and glass industries (Sr, Y) in the area of Murano.

The analytical data obtained allowed the reconstruction of areal distribution of the heavy metals and gave an indication of restricted areas with abnormal concentration of heavy metals. The locations of these restricted areas and the fine texture of the sediments (clayey-silt and silty-clay) suggest an anthropogenic origin rather than due to transport, areas of provenance or local hydrodynamics. In fact it is the low hydrodynamic characteristic of these restricted areas that allows the concentration rather than the dilution with time of the heavy metals. The only exception to the above consideration is the Industrial Area of Porto Marghera where the concentration of heavy metals is spread over a large area, as indication of the intense environment use of the area during the past decades.

3. Foraminifera as indicators of past and present environmental changes.

Benthic foraminifera (Kingdom Protoctista, Phylum Granuloreticulosa, Class Foraminifera) have been often used to assess the level of environmental stress and pollution in coastal zones. They offer an effective and integrated view of the prevailing environmental conditions. For this purpose the total assemblage is considered, both biocenosis and tanatocenosis, as only the totality of the species present reflect the physical-chemical parameters prevailing, and is capable to recognize subtle but permanent changes in the environmental condition [Albani, 1993; Alve, 1995].

This methodology is of great value in a coastal setting such as the Lagoon where the level and direction of environmental stress can be determined and evaluated.

A complex sampling (733 samples, open dots in Fig. 4) of the Lagoon and the Gulf of Venice during the '80s has provided a baseline study of the distribution of benthic foraminifera (biotopes) [Albani *et al.*, 1984; 1991; 1998; Serandrei Barbero *et al.*, 1989; 1999], recent sediments and their geochemical characteristics [Albani *et al.*, 1995]. In particular foraminiferal biotopes identify, on the basis of the faunal similarities, the areas characterized by similar environmental conditions.

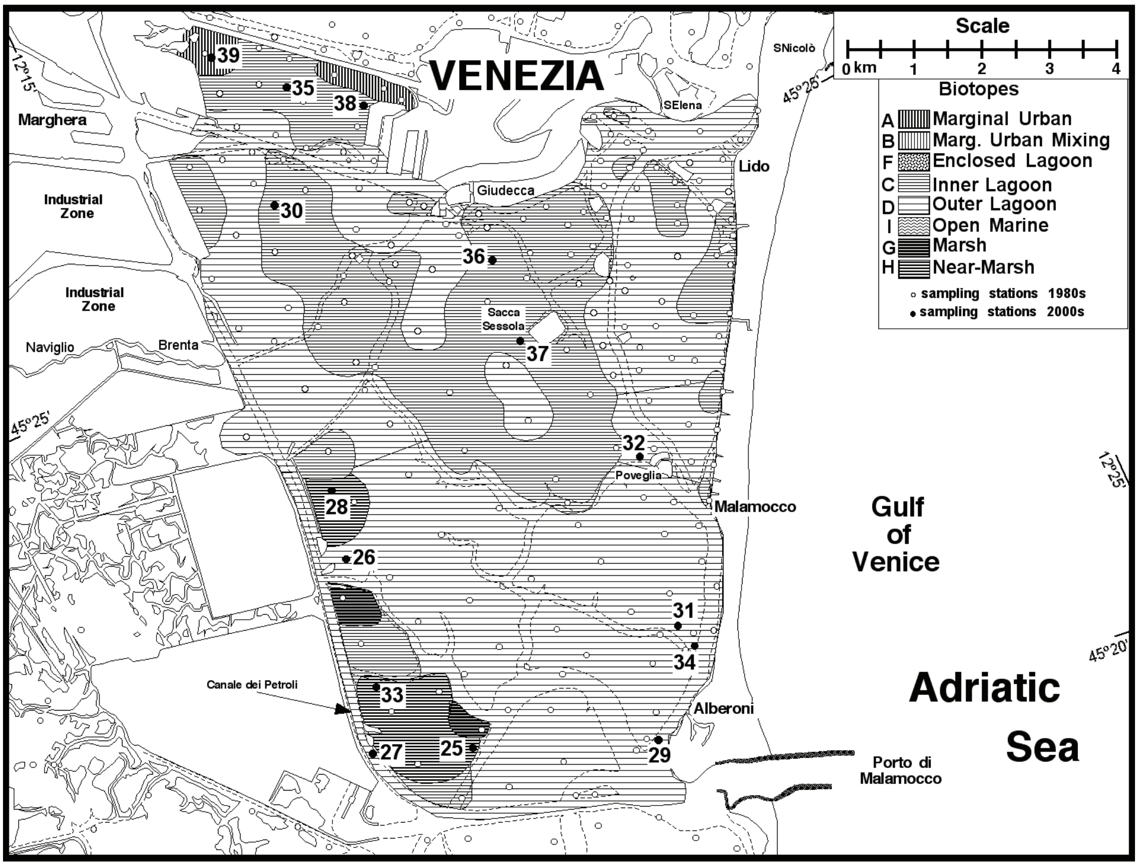

Fig. 4 – Central sector of the Lagoon of Venice with the 1983 biotopes distributions and the locations of the 2001 samples (solid dots).

The distribution of benthic foraminifera is mainly affected by the residence time of the water masses [Guelorget and Parthuisot, 1983]; some taxa reflect a relationship with the water level [Albani *et al.*, 1984; Hayward and Hollis, 1994; Petrucci *et al.*, 1983; Scott and Medioli, 1980] others the presence of fresh water [Donnici and Serandrei Barbero, 2005]. Changes in the level of abundance reflect the morphological evolution of the lagoon, as clearly shown by the study of palaeoenvironments [McClennen *at al.*, 1997; Reinhard *et al.*, 1994; Serandrei Barbero *et al.*, 1997; 2004].

During 2001 a set of 52 sampling sites, selected within the already identified biotopes (Fig. 4), have been analyzed using the same methodology adopted in the 1983 survey; the new quantitative data set was based on at least 300 individuals [Buzas, 1990; Serandrei Barbero *et al.*, 1997] of the fraction >0.125 mm. The 2001 numerical data set was added to the data from the 1983 study and the combined set was analyzed using cluster analysis (Pearson coefficient); this phase of the analytical process allowed the establishment of the level of similarity within the existing biotopes and establish the cluster links.

In addition, to assess the degree of environmental change, the quantitative data have been used for a comparative study between the 2001 and the nearby 1983 samples using the Kolmogorov-Smirnov statistical test, [Sneath and Sokal, 1981]. This non-parametric test compares the cumulative frequency values of two samples and records the value of the level of difference; the smaller the value the smaller is the difference and thus greater is the similarity of the two samples. The combination of the Kolmogorov-Smirnov test, which determines the level of similarity between each pair [Albani *et al.*, 1998], and the cluster links determines not only the degree, but also the direction of the change, if any.

The comparative study between the faunal distributions of the base-line 1983 and the 2001 samples, using the cluster analysis and the Kolmogorov-Smirnov indices, shows areas of environmental stability, although with a slight decrease of the residence times. These are linked to the maintenance dredging of the channel in response to the navigational needs. The purification plant, operating since 1986, has improved the conditions in areas where industrial and urban stress predominated, shown by the decrease of faunas tolerant of such conditions, whereas no improvement is recorded in areas with local pollution sources such as at Tronchetto and off the island of S. Michele (stns 6 and 38). In addition, new areas with high environmental stress are noted in the northern sector of the Lagoon. Along the Canale dei Petroli the collapse of some intertidal morphologies (Fig. 5) appears to be related to the local predominance of more marine conditions.

But the biological description of an environment also consents the interpretation and the measurement of its physical aspects. The quantitative analysis of benthic communities in sedimentary sequences, revealing the presence of *ecological transitions*, shows environmental changes occurred and provides the conventional radiocarbon ages BP through the ^{14}C analyses on shells buried in the sediment during deposition.

Recent researches have shown the variability of lagoon conditions, testimonied by the channel migration, made evident by the ancient buried channel beds [McClennen *et al.*, 1997], the presence of the shoreline in areas lying inside the lagoon [Serandrei Barbero *et al.*, 2001] and evidence of ancient marsh, sometimes with human remains, today buried [Serandrei Barbero *et al.*, 1997; 2004]. Temporal and spatial variability in environmental conditions leads to a wide range in sediment accumulation rates, the importance of which is vital for today's lagoon morphologies to survive.

Within the different sediment areas identified with foraminiferal biotopes were therefore drilled 26 sediment cores about 1 m deep to verify the persistence of biotopes present in the current lagoon system. Rich organogenic deposits, on which 57 radiocarbon datings were performed, allowed verifying previous biofacies and their age, obtaining mean sediment accumulation rate, in the presence of constant biofacies, or the age of the event that changed the deposition environment, in the presence of surface erosion or of evident discontinuities in the sediment sequence. Sediment accumulation rates are considered constant in the sedimentary sequence in which *ecological transitions* are not present.

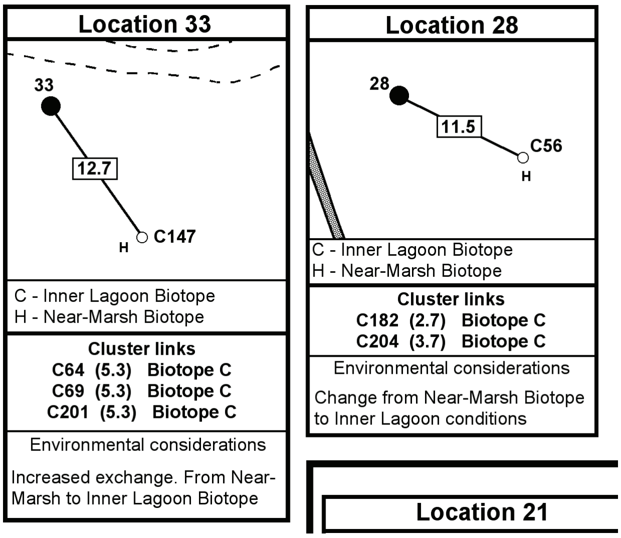

Fig. 5 – Relationships between the 2001 faunas (solid dots) and the 1983 faunas (open dots) for the changed morphologies. The Kolmogorov-Smirnov indices are also shown (smaller the value, smaller the difference or higher the similarity). The cluster links are derived from the combined cluster analysis of the total fauna.

A sediment accumulation rate of 0.5 mm/year was obtained from the 57 radiocarbon datings obtained from organogenic materials in the lagoon sedimentary sequence. Different results are obtained considering two different periods:

- between about 2500 and 1500 years BP the accumulation rate is 1 mm/year.
- between 1500 years BP and present the accumulation rate is 0.4 mm/year.

Cores taken at the continental margin of the lagoon have often reached the continental environment before the lagoon settling: the lagoon: in these marginal areas the age of marine transgression occurred between 2117 and 1620 years BP.

Cores 2, 8 and 14 give no evidence of *ecological transitions* and sediments have been deposited at a constant accumulation rate of 0.5 mm/year. *Ecological transitions* present in cores 39 and 53 show the presence of marsh dating back to 1887 and 820 years BP, respectively. The sedimentation rate is equal to 0.8-0.9 mm/year for marsh and much less (0.2-0.3 mm/year) in the following environment of marsh edge or subtidal zone. The *ecological transition* present in core 29 drilled to a 90-cm depth, allowed dating the ancient coastline back to 3180 years BP, which afterwards migrated to its present position.

4. The application of sar interferometry for ground vertical displacement of small islands in the Venice Lagoon.

Repeat-pass spaceborne Synthetic Aperture Radar (SAR) interferometry is a powerful technique for the observation of land surface deformation at mm resolution, as demonstrated in the Venice area by Tosi *et al.* [2002] and Strozzi *et al.* [2001b].

In order to provide land displacement rates in small islands of the Venice Lagoon not covered by traditional surveys (levelling and differential GPS), SAR-based monitoring techniques, i.e. differential SAR interferometry [Strozzi *et al.*, 2001a] and interferometric point target analysis [IPTA, Werner *et al.*, 2003], were performed.

The validation of the SAR interferometric displacement rates performed in the framework of the ISES and VENEZIA Projects [Carbognin and Tosi, 2003; Carbognin *et al.*, 2004] through levelling and differential GPS surveys in areas where data from all techniques are available demonstrated a mm/year accuracy of the vertical displacement rates.

First, a time series of six interferometric radar images of the European Remote Sensing Satellites ERS-1 and ERS-2 from 1993 to 2000 was considered. In order to generate a displacement map with reduced errors, the six INSAR images were combined [Strozzi *et al.*, 2001b]. The INSAR map shows information over the major urban areas, with a few scattered points in other regions.

Then, IPTA has been applied with 59 ERS-1/2 SAR images between 1992 and 2000. Point targets with valuable information are scattered over villages, suburban areas, and isolated structures. Deformation time series, as indicated for two points in Fig. 6, are available from IPTA.

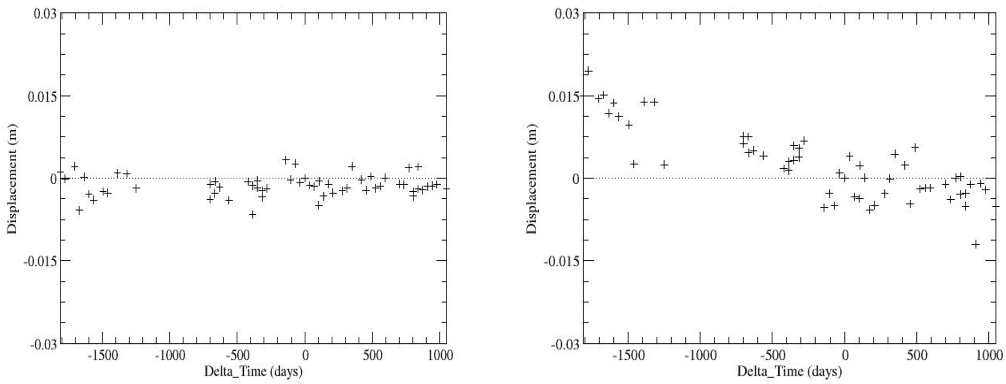

Fig. 6 – Deformation time series from IPTA for two points target located in Murano Island for the time period from 1992 to 2000.

This analysis of ground vertical displacement with SAR interferometry demonstrated a general land stability of Murano Island, with maximum sinking rates of less than 2 mm per year.

In conclusion, the application of SAR-based monitoring techniques appears an important tool capable of providing data for the morphodynamics study of the lagoon setting.

5. The origin of the sand – Field work.

This study comprised a coupled programme of numerical modelling, laboratory experimentation, and field surveying in order simulate the factors leading to the evolution of muddy tidal flats in northern Venice Lagoon for purposes of prediction and management. This study has resulted in 7 scientific publications, 3 Ph.D theses (two completed; one in progress), 1 M.Sc. thesis (completed), 1 Tesi di Laurea (completed), and 4 B.Sc. theses (completed). The most important aspects of the study are the predictive calibrated sediment transport model of Venice Lagoon (SEDTRANS05), the discovery that sand is a vital component to the protection and development of salt marshes in Venice Lagoon as it forms the foundation on which marshes grow, and also provides protection from wave erosion at the margins.

We have collected over 512 line km of bathymetric data and digital sidescan, 258 bottom sediment samples, 6 days of current speed, depth and turbidity data at 6 key sites in the Burano canal system (burst sampled at 4 Hz), 3 days of hourly ADCP profiles (Fig. 7) across Burano, Scanello, Treporti and S. Felice canals from which residual transports of sediment have been estimated, and wave attenuance data across three profiles of submerged beaches. Analyses are still underway and include the updating of the cohesive sub-routine of SEDTRANS05 (and the production of a scientific paper on the model), the application of SEDTRANS05 to the Po delta plume for the 2000 event (and scientific publication), the production of a bathymetric chart based on a compiled data set, the production of a bottom character map based on the sidescan data (and production of review paper) and the application of the O'Brien relationship to the Lido-Treporti-Burano canal system.

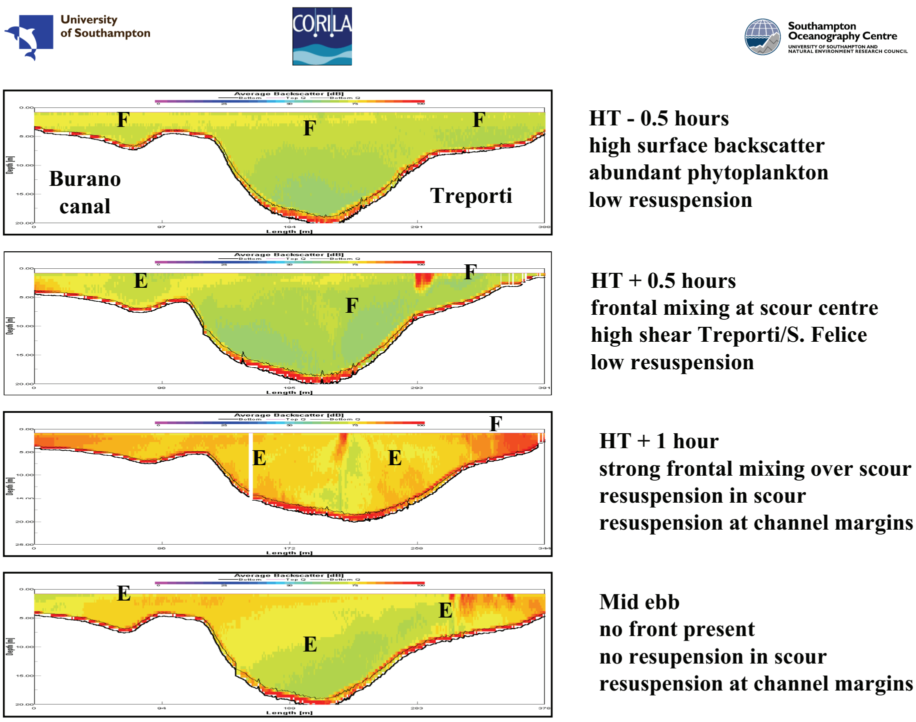

Fig. 7 – ADCP profiles across Treporti canal though the scour hole at the Burano-Treporti-S. Felice triple junction.

Four field surveys were undertaken in this project (two summer and two winter, for a total of about 40 days field surveying) in order to map the Lido-Treporti-Burano canal system and to characterise the dominant morphological features within this system: As well, to provide a data set for numerical model simulation and calibration. SEDTRANS96 has been linked to the hydrodynamic model of Venice Lagoon

[Umgiesser, 2000; Umgiesser *et al.*, 2004] and the sedimentation sub-routines have been advanced on the basis of our field results. The new version, called SEDTRANS05, will be used for both sand and fine-sediment transport in the future. As well, a number of significant discoveries have been made which will help understand the morpho-dynamical evolution of northern Venice Lagoon. These are:

- submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance;
- active scours occur at the triple junctions of canals and are up to 18 m deep. They form through turbulence induced at the fronts between ebbing water masses and are thus a source of mobile material to the system;
- there is strong headward residual transport of suspended sediment in the study region caused largely by the residual circulation of tidal waters. Such residuals do not favour a loss of material from the lagoon and may, in part, explain the local growth of tidal flats; and
- the grain size trends (fining headwards) and the orientation of megaripples within the Lido entrance favour a movement of sand as bedload into the lagoon. This contrasts with initial model results that indicate a net export of sand from the lagoon.

The overall conclusion of this work is that knowledge of the origins, transport pathways and depo-centres of sand is vital to the understanding of the evolution and well-being of the lagoon.

6. The origin of the sand – Modelling.

In this part of the project the model SEDTRANS96 and the model SHYFEM have been applied to the lagoon of Venice to look for the reasons of erosion and deposition and to study the origin of the sand that can be found in the lagoon.

6.1. Exploring the bottom stress variability in the Venice Lagoon.

The Venice Lagoon is a complex system when speaking in terms of hydrodynamic and bio-chemical processes. Narrow channels determine the tidal propagation and the large tidal flats represent a delicate ecosystem that is susceptible to erosion. Moreover, climatic changes seem to have a high impact on the delicate equilibrium that has been formed in the last centuries. The possible global sea level rise will have a higher impact on the Venice Lagoon and the island of Venice than on any other coastal zone in the Mediterranean.

In order to preserve the delicate lagoon ecosystem a modeling approach that combines hydrodynamics, waves and the sediment dynamics of the Venice Lagoon is highly desirable. This model could be used to estimate the actual loss or gain of sediments from the lagoon to the Adriatic Sea and the importance of the various forcing factors that influence these dynamics.

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As a preliminary step towards this direction, a framework of numerical models has been implemented and applied to the Venice Lagoon. The models consist of a state of the art hydrodynamic model for shallow areas and lagoons and a last generation wave model. With these models the bottom stress distribution during typical strong meteorological situations is studied.

Results show a good agreement of the computed bottom stress patterns and the empirical erosion and deposition rates found in the lagoon. The areas where wave action is responsible for sediment re-suspension are identified; they consist basically in the large shallow areas that are spread out all over the lagoon. This makes the wave action the most important erosion mechanism in the lagoon during typical strong winds.

During a tidal cycle the bottom stress distribution due to currents only appears to be non negligible only during maximum flood or ebb tide. (The following pictures refer to the latter situation). Values appear to be higher in correspondence of deeper channels, those hydrodynamically more active. The situation does not change significantly when the wind forcing is switched on, except that now the values at the inlet is increased and some shallow areas are showing some evidence of increased stress. As an example, we present here results of Scirocco wind forced situation (Fig. 8a) where the bottom stress is computed only from currents.

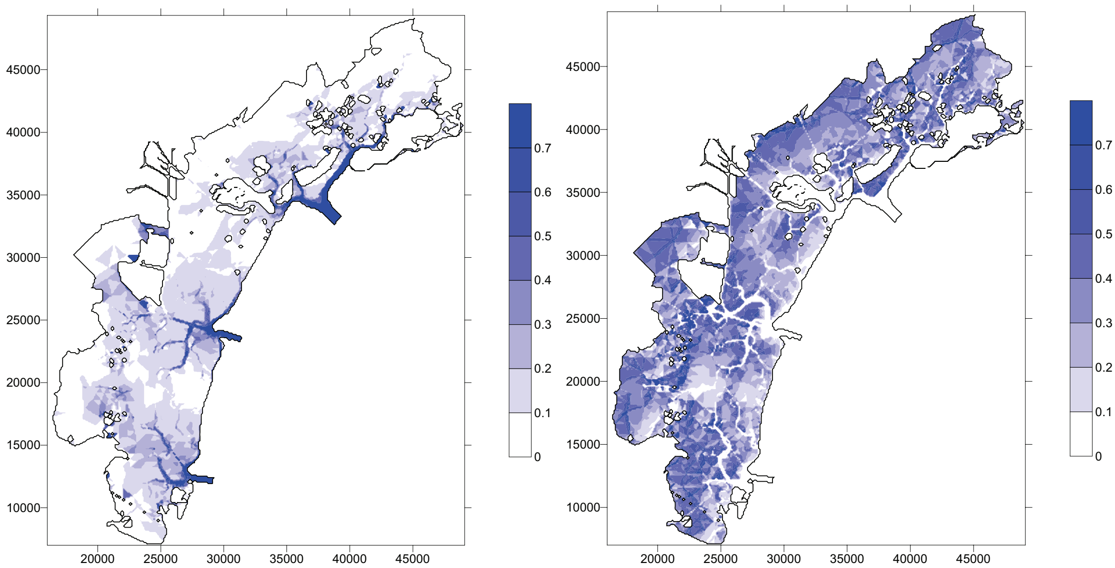

Fig. 8 – Bottom shear stress (N/m^2) induced by currents only (top panel, a) and waves only (bottom panel, b) and during a Scirocco event.

Fig. 8b presents the bottom stress taking into account only the wave contribution. The scale presents a maximum value of 0.7 N/m^2 as this value is considered to be the threshold above which cohesive sediments may be mobilized in the Venice Lagoon [Amos *et al.*, 2004].

Comparing the two figures, the bottom stress induced only by currents is maximum along the deepest channels, i.e., where the hydrodynamics is more active. In the case where only waves have been taken into account, the channels show very low values, reflecting the fact that in deep regions wave effects are negligible. On the other hand, the shallower parts exhibit values higher than 0.7 N/m^2. Therefore, generally speaking, the two pictures are in a way complementary: where wave effects are higher, current effects are weaker.

Three scenarios of future climatic changes are simulated: an increase in the amplitude of the tidal oscillation, a global sea level rise and the combination of both. The results show that the most vulnerable parts of the lagoon are the flat regions close to the deeper channels. The erosion of these channel borders could be the cause of the filling of the deeper channels that then would need artificial dredging.

6.2. Modeling sand transport in the Venice Lagoon inlets.

The lagoons developing along the coast of sedimentary zones are in an unstable situations. If not destroyed by the sea, they tend to be filled up by the sediment flow from the sea or from the rivers ending into the lagoon. Geomorphological variations have been naturally occurring in the Venice Lagoon since its formation. In the past the large sediment discharge from the main lagoon tributaries threatened to transform the lagoon into a marshland. Then the increase in the lagoon depth, due to subsidence and eustatic water level rise, and in recent times the impact of anthropic activities have reversed the lagoon's natural tendency to silt up transforming it slowly into a more sea-like environment.

To understand the sediment dynamics in the Venice Lagoon it is necessary to analyze the hydrodynamic behavior of the three inlets. The aim of this study was to describe the sediment transport in the Venice Lagoon in order to evaluate the sediment exchanges between the sea and the lagoon through the three inlets of Lido, Malamocco and Chioggia.

Up to now numerical models of sediment transport have not been applied extensively in the Venice Lagoon, therefore a lack of knowledge concerning sediment erosion, resuspension, transport and sedimentation remains. This work represents a first attempt to evaluate the role that the hydrodynamics plays in the sediment processes occurring at the three inlets.

A sediment transport model Sedtrans96 coupled to a hydrodynamic model has been applied to the Venice Lagoon in order to evaluate the sediment exchanges between the sea and the lagoon through the three inlets of Lido, Malamocco and Chioggia. At the three inlets the sediments are mostly non-cohesive and therefore the transport model has been applied uniquely to this sandy sediment type.

To evaluate the influence of the wind (in this case consisting of bora and scirocco) the simulations have been carried out both with the tidal forcing only and with the tide-wind combined action. Two different sets of simulations have been setup. In the first the models have been applied for 12 hours time and the basin was forced with idealized wind and tide values; in the second set the simulations have been extended to one year and carried out with a real time series of in-situ wind and tide elevation measurements.

The sediment suspension and transport have been evaluated through two sections per inlet in order to calculate the mass balance and the bottom thickness variation caused by erosion and deposition processes.

From the modeling analysis at the inlets of Malamocco and Chioggia a tendency of erosion has been calculated (Fig. 9) and this situation shows a good agreement with the empirical data collected during the last 20 years. As far as the Lido inlet is concerned, a clear tendency of erosion or deposition is more difficult to see and further work has to be carried out.

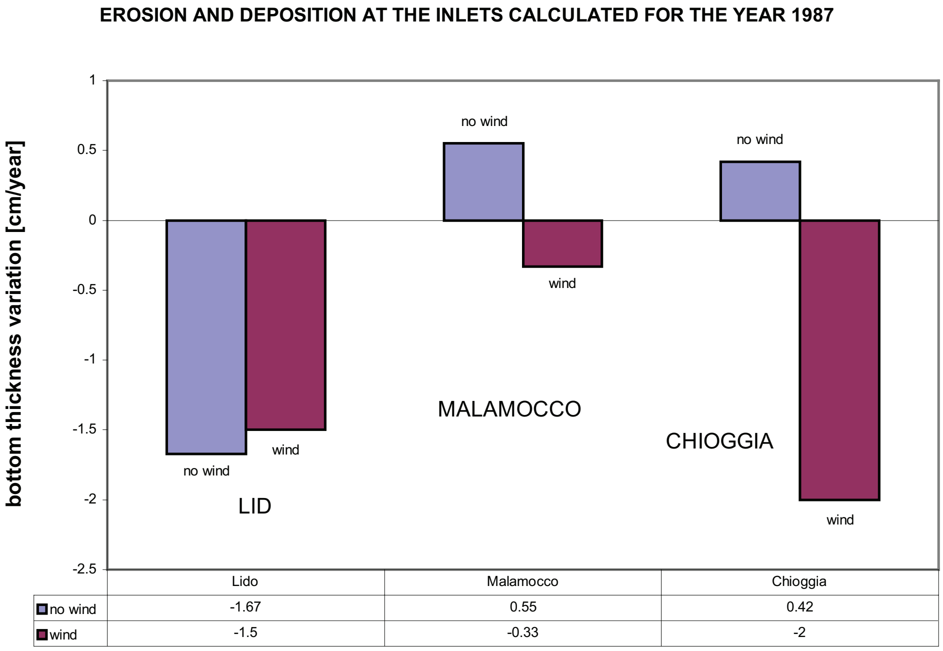

Fig. 9 – Bottom thickness variation rate calculated by the model in the simulations over the whole year 1987 with real forcing data. The positive values represent the deposition and the negative represent the erosion. The rate is in cm/year.

6.3. Modeling sand transport in a canal system, northern Venice lagoon.

The dominant factor governing the long-term evolution of a coastal lagoonal system is the stability and evolution of its barrier island system which is controlled by the availability and supply of sand. The fact that Venice is located within a lagoon immediately illustrates the dominating role of sand in the evolution of this coastal setting. The string of barrier islands and beaches fronting Venice Lagoon attest to the supply and longshore transport of sand from fluvial point sources in the NE, as well as artificial replenishment. Indeed much of the shelf off Venice is composed of sand (sculpted into megaripples) indicative of high-energy events in the past high in sand content.

Submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance.

However, the origin of the sands close to the inlets is still unclear: are they from ancient deposits cropping out in the lagoon and continuously reworked by the tidal action or are they transported into the lagoon from the Adriatic Sea through the inlets.

The origin of the sands in the Venice lagoon has therefore been the subject of extensive field surveying in parallel with numerical modeling. Three transects along Treporti and Burano canals were conducted from which 33 bottom sediment samples were collected. These samples were analysed for grain size and sorting to examine any trends in the granulometry of these sediments that might shed light on transport paths (Fig. 10).

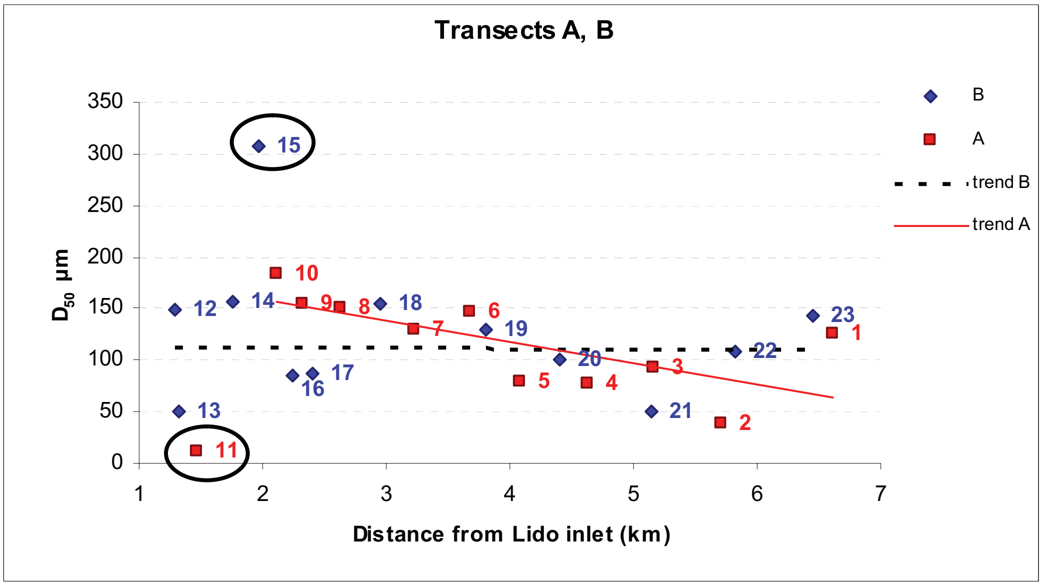

Fig. 10 – Grain size distribution in transect A and B. Two outliers have been eliminated (samples 11 from A and 15 from B).

The modeling study consists of two parts: the sediment transport model SEDTRANS96 was used with a finite–element, hydrodynamic model (SHYFEM) to simulate sand transport in Treporti canal. A type of linked box model was created by combining elements of the main model and subsequently computing water and sediment fluxes for the so-created boxes. Several grain size classes were simulated; the distribution before and after the simulation were examined. A variety of wind regimes were used to force the tidal flows, as well as a full year of measured tidal and wind data. Only a part of the Venice lagoon was covered by the simulation: a major channel running from the Lido inlet north towards the northern lagoon.

The total transport through all of the sections was computed for 1987 (a normal year in Venice lagoon). Sediment mass balance was determined and the resulting trends of erosion and deposition were computed. There were no trends in the median grain diameter and sorting of bottom samples from Treporti canal; all sands were fine (120 microns, one outlier of 300 micron was removed).

The absence of a trend in grain size suggests that there is no significant import of sand to the lagoon through the Lido inlet. The results from the simulations seem therefore to confirm the hypothesis of reworking of sand within the lagoon. The computed erosion is some cm/year diagnostic of channel scouring and enlargement with time. The Treporti canal is subject to strong current velocities of around 1 m/s which hold fine sand in suspension and thus prevent sedimentation.

Conclusions.

The CORILA project 3.2 on Hydrodynamics and Morphology has collected valuable data needed for an insight into the transformations ongoing in the Venice Lagoon. The project was an interdisiplinary approach: geomorphological methods have been used to characterize the sediment characteristics of the lagoon, and Foraminifera have been used as indicators of past and present environmental changes. Remote sensing has been used to investigate the subsidence in the Venice lagoon.

Field campaigns have been carried out to study the origin of the sand in the lagoon. The findings have then been reproduced with modeling techniques. A hydrodynamic model of the lagoon has been adapted to be used for sediment transport studies, and has been extensively applied to the Lido inlet and the Treporti channel system.

Summarizing, the three year project has been a great success, bringing together scientists from different disciplines and working on a common goal: to better understand the morphological and hydrodynamic processes of the Venice Lagoon.

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