Published in Journal of Marine Systems, v. 68, pp. 303-317 (2007). © Elsevier Science Bv.
DOI:10.1016/j.jmarsys.2006.12.003

LINK BETWEEN HYDROLOGY AND SEDIMENTOLOGY IN THE LAGOON OF VENICE, ITALY

Emanuela Molinaroli[a*], Stefano Guerzoni[b], Alessandro Sarretta[b], Andrea Cucco[c], Georg Umgiesser[b]

[a] Università Ca' Foscari, Dipartimento di Scienze Ambientali, Dorsoduro 2137, 30123 Venezia, Italy
[b] CNR - Istituto di Scienze Marine, Riva VII Martiri 1364/A, 30122 Venezia, Italy; e-mail:
[c] CNR - Istituto sull'Ambiente Marino, Loc. Sa Mardini, Torregrande-OR, Italy

* Corresponding author. Tel.: +39-041-2348583; fax +39-041-2348510. *E-mail address:* molinaro@unive.it (Emanuela Molinaroli)

stefano.guerzoni@ismar.cnr. (Stefano Guerzoni)
alessandro.sarretta@ismar.cnr.it (Alessandro Sarretta)
andrea.cucco@ismar.cnr.it (Andrea Cucco)
georg.umgiesser@ismar.cnr.it (Georg Umgiesser)

Abstract

A textural classification of sediments collected in input channels, shallow lagoon beds and navigation channels of the Lagoon of Venice is presented. Some variables describing both the hydrodynamics and the transport time scales of the Lagoon are compared with bottom sediment distribution inside the basin. A high correlation between residence time (REST) and the silt fraction (4-31 µm) was only found for REST values < 20 days. A good correlation was also found between root mean square velocity (RMSV) and the fine sand fraction (63-105 µm) for RSMV > 10 cms^{-1}. The distribution of the various sediment types was explained by the use of PCA applied to both grain-size and hydrological parameters, which extracted two principal factors and formed four groups of clustered samples. Groups 1 (clayey silt) and 2 (very silty slightly sandy mud) comprise samples located mainly in the northern and central lagoon and inshore. The samples of group 3 (very silty sandy mud) seem to show stabilisation, reflected in the reduction of sand and the sedimentation of silt with respect to samples in group 4 (slightly silty sand), some of which were collected on a previous seagrass bed which has now disappeared and/or been reduced in size.

Keywords: Italy, Lagoon of Venice, Residence Time, Root Mean Square Velocity, hydrodynamic model, grain size, Lat. 45°N, Long.12°E

1. Introduction

Estuaries, wetlands and coastal areas worldwide have been affected by habitat loss on a large scale: they are the sites of the largest populations, agricultural systems, infrastructures and industry, each of which requires land (Elliott and Cutts, 2004). The Lagoon of Venice is no exception with respect to these problems. Its complex combination of marshes (*barene*), intertidal mudflats (*paludi*) and navigation channels (*canali*) have been subject to human activities since 900 AD. Over the last century, almost one quarter of the lagoon habitat has been permanently lost (Favero, 1992). In addition to this, temporary habitat loss due to changes in water quality, sediment quality, and turbidity must also be taken into account (Elliott and Cutts, 2004).

Hydrological parameters such as water currents, surface elevation and transport time scales have been assessed by many authors as fundamental parameters for the understanding of the ecological processes that involve lagoonal environments (Monsen et al., 2002). It has been shown that hydrodynamic and sediment transport models can be used in conjunction with integrated models to address potential ecosystem responses to some changes or conditions of interest (Teeter et al., 2001). Bottom stress variability has been explored and compared with erosion and deposition patterns inside the Lagoon (Umgiesser et al., 2004a), and the role of the biota in controlling the stability of tidal flats in a range of different bed/habitat types of the Lagoon of Venice has been highlighted by Amos et al. (2004).

In this work, the renewal capacity of the Lagoon of Venice is investigated with a 2D hydrodynamic model, which has previously been successfully implemented by various authors (Umgiesser, 2000; Umgiesser et al., 2004b; Solidoro et al., 2004; Cucco and Umgiesser, 2005, 2006).

Most of these studies lack a detailed sedimentological description of the spatial distribution and transport of bottom sediments influenced by hydrodynamic energy, e.g., tidal and/or wind-driven currents and waves. For example, residence time is a fundamental concept in estimating transport time scales for both particle-size and biological processes occurring in a lagoonal basin (Monsen et al., 2002), but - although the importance of this parameter for this particular ecosystem is clear - no references or estimates are available in the literature between residence time and grain size in the Lagoon of Venice.

In order to better understand the close link existing between water and bottom sediment compartments, some fundamental variables describing both hydrodynamics and transport time scales in the Lagoon of Venice have been computed by means of a numerical approach and compared with bottom sediment distribution inside the basin. This paper may therefore be considered the first attempt to combine detailed grain-size data with hydrodynamic parameters such as residence time and residual bottom velocities in the Lagoon of Venice. Relationships between vegetated areas and shallow lagoon beds are also discussed.

1.1 Study area

The Lagoon of Venice is the largest lagoon in the Mediterranean and is located in the northern Adriatic Sea (45°N, 12°E). It extends for about 50 km along the coast and has an average width of 15 km (Fig.1). It covers an area of 550 km^2 and has a microtidal regime: the Adriatic tides govern water exchange in the Lagoon and have a mean tidal excursion of 35 cm during neap tides and about 100 cm during spring tides. Particular atmospheric conditions such as strong southerly winds (s*cirocco*) and low atmospheric pressure produce frequent storm surges which can increase the maximum water level (Pirazzoli, 1991; Canestrelli et al., 2001). These *scirocco* winds typically have maximum speeds around of 50-60 km h^{-1} and generally occur in spring and autumn, producing extensive flooding of the historical city centre of Venice (Pirazzoli, 1991). Only 5% of the Lagoon has a depth greater than 5 m, and 75% is less than 2 m deep; the average depth is 1.2 m.

The Lagoon proper forms part of a tripartite ecosystem: catchment basin, lagoon, and adjacent upper Adriatic. It is connected with the Adriatic Sea by three inlets (Lido, Malamocco, Chioggia), permitting water and sediment exchange driven by the tidal cycle (Ghetti, 1974). The average water volume is approximately 390 x $10^6 m^3$, and the amount of salt water that flows in and out during each tidal cycle amounts to around one-third of the total volume of the Lagoon (Gačić et al., 2004).

The Lagoon has a drainage basin of 1850 km^2, which provides a mean yearly freshwater input of 35.5 $m^3 s^{-1}$, of which the main contributors are the rivers Silone (23.1%), Dese (21.1%), Naviglio-Brenta (14.3 %), and Taglio-Nuovissimo (13.2%), the latter two being partially channelised. The most important tributaries are located in the northern basin which, on average, receives more than 50% of the annual total load (Zuliani et al., 2001; Zonta et al., 2001). The associated sediment input was calculated at 33×10^3 tons yr^{-1} for the years 1999/2000. This hydrological pattern creates a typical brackish environment with a salinity gradient that ranges from 10 ‰ near the mainland border to 32‰ at the inlets (Fig. 1).

Numerous sedimentological studies of the Lagoon of Venice have been carried out over the last 15 years (Barillari, 1978, 1981; Barillari and Rosso, 1976; Hieke Merlin et al., 1979; Menegazzo Vitturi and Molinaroli, 1984; M.A.V.-C.V.N., 1999; Albani and Serandrei Barbero, 2001). However, different teams used different criteria for sediment sampling (e.g., depths: 0-6 cm, 8-10 cm or 0-15 cm) as well as different methods of analysis. Few teams collected samples from the whole Lagoon; rather, most studies concentrated on small areas of local interest. Samples were also collected at different times between 1975 and 1997. Recently, Albani and Serandrei Barbero published a paper covering most of the Lagoon, with more than 500 samples collected in the 1980s (Albani and Serandrei Barbero, 2001), describing some interesting sedimentological features. Four sedimentological facies were identified on the basis of grain-size distribution. These authors showed that sediment distribution was related to a large flood delta, and that sedimentological evidence supported the conclusion that, until the 1980s, mass transfer of unconsolidated material from the Lagoon to the Adriatic was negligible.

This paper utilized one of the most comprehensive and recent data-sets provided by the Water Authority (M.A.V.-C.V.N., 1999) which analysed ~100 sediment samples collected between 1997 and 1998 from all over the Lagoon (Fig. 1).

Figure 1

2. Geological and morphological setting

The Lagoon of Venice first formed about 10,000 years ago, at the end of the Würm glaciation, when the sediments of the rivers Adige, Po, Tagliamento, and Piave constructed a littoral bar which isolated a shallow body of water from the Adriatic Sea (Gatto, 1980; Gatto and Carbognin, 1981). Venice Lagoon is the most important survivor of a chain of natural lagoons in the northern Adriatic.

On one hand, tributary rivers (Adige, Bacchiglione, Brenta, Sile, and Piave) discharging into the Lagoon guaranteed the brackish character of the lagoonal water. On the other hand, fluvial sediments deposited in the marshlands threatened to choke the inlets (Ciabatti, 1967; Avanzi et al., 1981). Neither the gradual lowering of the lagoon bottom due to consolidation of late alluvial deposits (up to 2 mm y^{-1}) nor the eustatic rise in sea level could counterbalance this steady tendency which is still in progress. These two processes threatened to turn the Lagoon in to a slowly silting-up marsh flat. Prior to the year 1500, the rivers entering the

Lagoon contributed approximately 700,000 m^3 of fine-grained material, most of which was deposited to form fringing salt marshes and mud flats. An additional 300,000 m^3 of sand entered from the sea to form flood tidal deltas (Suman et al., 2005).

A range of man-made changes has affected the Lagoon from the 15th to the 19th centuries. These anthropogenic activities included diverting river outflows outside the Lagoon, opening and widening the tidal inlets, and creating waterways for navigation towards the inner coastal area. All diversions, which were followed by the construction of breakwaters at the lagoon inlets during the period 1808-1930 and increased dredging of lagoon channels for navigation purposes (up to 20-m-deep channels for shipping were dredged in 1926 and 1970), have had a significant impact on the lagoonal morphology (Avanzi et al., 1981). The last century saw a boom in commercial activities in the Lagoon, leading to exploitation of groundwater resources which generated high subsidence rates (Carbognin and Taroni, 1996).

The average sedimentation rate in the Lagoon is about 0.5 cm yr^{-1}, although erosion is prevalent near Malamocco and Chioggia, as indicated by radionuclide studies (Battiston et al., 1988; Pavoni et al., 1992; Adami et al., 1992; Zoppi et al., 2001). Its morphology is characterised by a network of channels of variable depths, estuaries, tidal marshes, mud flats, and open and closed fish ponds. Today's sediment budget is negative. This evolutionary tendency can be seen in the progressive disappearance of salt marsh (from 90 km^2 in 1901 to the current 47 km^2) (Favero, 1992; Runca et al., 1993) and mud flats, the gradual and constant increase in water depth, and the disappearance of tidal creeks.

Differentiated in time and space, geological subsidence took place in the Venice area throughout the Quaternary. Long-term subsidence, occurring millennia before the origin of the Lagoon, mainly reflects tectonic processes (Kent et al., 2002), while natural consolidation of sediments played a major role in successive periods (late Pleistocene and Holocene), mostly after the Lagoon had begun to form (Donnici et al., 1997; Serandrei Barbero et al., 1997).

During the last century, the relative lowering of Venice has totalled 23 cm, consisting of about 12 cm of land subsidence, both natural (3 cm) and anthropogenic (9 cm), and 11 cm of sea-level rise (Gatto and Carbognin, 1981). The relative sea-level rise of 23 cm has created great concern regarding the fate of the Venice coastlands because it has contributed to increases in (a) flooding, both in frequency and degree, (b) internal hydrodynamics leading to erosion of the lagoon bed, silting-up of channels, and changes in the habitat of flora and fauna, (c) fragility of littoral strips which provide tenuous protection in defending the entire Lagoon against destructive sea storms.

Groundwater pumping and related land sinking began with the first industrial installations in the 1930s, and peaked between 1950 and 1970. This last factor caused subsidence, calculated between 3.8 mm yr^{-1} (Carbognin and Taroni, 1996) and 6 mm yr^{-1} for the period 1930-1970 (Sestini, 1992; Bondesan et al., 1995). Following the end of groundwater pumping in the early 1970s, land subsidence has slowed down (Carbognin and Taroni, 1996; Tosi et al., 2002; Brambati et al., 2003; Carbognin et al., 2004; Teatini et al., 2005).

3. Methods

3.1 Sedimentological data-base

The samples processed in the present study are part of a data-base reported in the M.A.V.-C.V.N. (1999) study. Bottom sediment samples from the Lagoon of Venice were collected at 96 sites during field work in 1997-1998, organised by the *Consorzio Venezia Nuova* (C.V.N.) and sponsored by the *Magistrato alle Acque* (Water Authority) (Fig. 1). Sites from B01 to B76 represent bottom sediments from shallow lagoon beds (average depth ~ 1 m), sites I02 to I14 are channel and river inputs from the catchment area (average depth ~ 2 m), and sites C01 to C19 are samples from lagoon navigation channels (average depth > 2 m) where a dredging project was planned by the C.V.N. At each site, the area (a circle approximately 2 m across, with a central point fixed by geographical co-ordinates) and sample dimensions (6 sediments cores of 15 cm depth) were defined, and a "composite" sample was prepared from cores equally distributed within this area.

Surface samples (0-15 cm) were taken from short cores obtained by various techniques, a 7-cm-diameter Plexiglas corer and a Shelby corer. The first was used in water 0-1.5 m deep and the second in water 1.5-4 m deep. Grain-size analysis of sediments were performed by dry sieving and a settling tube system (aerometer) for sand and mud fractions respectively.

The four major grain-size parameters - mean, standard deviation (sorting), skewness, and kurtosis, were calculated using the well-established method of moments (McBride, 1971; Folk, 1974; Boggs, 2001), i.e., the mathematical expression of four characteristics of a quasi-Gaussian distribution. In this case, the moments were calculated using ϕ values ($\phi=-\log_2 d$, where d is the particle diameter in mm). The descriptive terms of Folk (1974) were used.

Sediments were classified using the textural classification of gravel-free muddy sediments on ternary diagrams proposed by Flemming (2000). The silt-clay boundary was taken at 4 µm.

3.2 Hydrological parameters

The hydrology of the Lagoon of Venice was studied by means of numerical models. In particular, only water circulation induced by tides was considered here, and neither wind nor other meteo-marine forcing agents were taken into account. This approach is explained by the fact that tides are the main forcing factor for water circulation in the Lagoon. Although strong wind events, such as those due to the *bora* and *sirocco* (respectively from south-east and north-east), can affect water circulation, their effects are negligible in the long run when compared with the daily frequency of tidal influences on basin water circulation. This is also confirmed by experimental measurements of water discharges through the Lagoon inlets collected with acoustic doppler current profilers (CADCPs), which reveal that the discharge signal is mainly due to the principal components of the tide. A residual of about 4% of the total amplitude is due to meteorological forcing such as wind and atmospheric pressure (Gačić et al., 2002).

To reproduce the tidal circulation in the Lagoon of Venice, a 2D hydrodynamic model was used. It is based on the finite-element method and resolves the vertically integrated shallow-water equations, with water levels and transports on a numerical domain representing the whole Adriatic and the Lagoon of Venice. Details of the numerical treatment are given in Umgiesser and Bergamasco (1995), Umgiesser et al. (2004b) and Cucco and Umgiesser (2005). The model was calibrated to reproduce tidal propagation in the Adriatic and in the Lagoon. A full description of the calibration procedure and results are given in Umgiesser et al. (2004b), Solidoro et al. (2004) and Cucco and Umgiesser (2005). The importance of winds and waves on bottom stress distribution inside the Lagoon is discussed in Umgiesser et al. (2004a) and their results were taken into account in order to corroborate the hypothesis of the dominance of tidal forcing on long-term lagoon water circulation patterns. Therefore, not only tides but also wind and wave effects were considered, in order to reproduce water circulation in the Lagoon to a higher degree of accuracy.

The following section presents variables describing the water circulation and the water transport time scale when the tide is the only forcing mechanism in the basin, together with the methods adopted to compute them.

3.2.1 Water circulation

Sediment dynamics in environments such as the Lagoon of Venice are mainly dependent on water circulation induced by meteo-marine forcings. Many hydrological variables, such as sea surface elevation, tidal amplification and delay, and bottom shear stress (WBSS) may be considered to describe the spatial variability of the water circulation in the Lagoon. In particular, its sediment distribution is characterised by a temporal scale of variability which is much larger than the typical time scales of tidal forcing (semidiurnal and diurnal cycles). Therefore, in order to describe the spatial variability of sediment distribution, a time-integrated hydrological variable able to capture the average features of water circulation in the Venice Lagoon had to be considered. In addition, sediment erosion and transport processes which govern the spatial variability of bottom sediments are mainly influenced by current velocity and circulation patterns. Therefore, with the aim of correlating bottom sediment distribution with water circulation variability across the Lagoon, the depth-integrated root mean square current velocity (RMSV) was computed for each element of the grid domain when only the tide forces the basin. RMSV(x,y) was computed for each element of the grid domain through the formula:

$$RMSV(x,y) = \sqrt{\overline{vel^2(x,y)}}$$

where $vel(x,y)$ is the depth-integrated horizontal velocity at point (x,y), the bar meaning a suitable time average. The RMSV was computed over a whole lunar cycle of simulation (about 30 days) in order to capture the variability of the tidal signal and to give a good estimate of hydrodynamic activity in various areas of the Lagoon.

Since temporal variations of tidal current intensity are given by a sinusoidal curve, the peak tidal current velocity (VMAX) for each element can be computed from the RMSV values through the formula:

$$VMAX = \sqrt{2} * RMSV$$

Therefore, due to the linear relationship between RMSV and maximum velocity VMAX, RMSV, alone, may be used as a variable to be correlated with sediment distribution. This means that it is possible to analyse both relationships between sedimentological variables and mean hydrodynamic activity as expressed by RMSV, and, indirectly, relationships between sedimentological variables and peak hydrodynamic activity as described by VMAX. However, this analysis is subject to uncertainty, as sediment resuspension processes are highly non-linear and can be completely studied only by means of a model of sediment transport and erosion (which is beyond the scope of the present study).

The choice of RMSV as the variable to be compared with grain size data is also justified by the fact that it is a scalar, describing the characteristic features of a fixed area in the domain. In this case, the correlation between sedimentological data and hydrodynamic features can be studied in a static manner without considering the real dynamics of sediment transport processes which, in order to be investigated by means of numerical modelling, need a sediment transport model. Nevertheless, even considering other hydrodynamic variables (such as residual currents, which give information about long-term water circulation) they cannot be used to describe the sediment transport processes. Indeed, such processes occur only over current velocity thresholds, which are not taken into account in the computation of the hydrological variables.

3.2.2 Residence times

In the literature, transport time is defined by many different concepts: age, flushing time, residence time, transit time, and turn-over time. Of these, residence time (REST) may be considered as a first-order description of the transport process (Monsen et al., 2002) and is generally defined as the time required for the total mass of a conservative tracer originally within the whole or a segment of the water body to be reduced to a factor of 1/e (Takeoka, 1984a, 1984b; Sanford et al., 1992; Luketina, 1998; Wang et al., 2004). The REST, thus defined, represents a property of a specific location within the water body which describes the proper transport time scale for the physical process in question.

The water REST of the Lagoon was estimated following a numerical approach and the finite-element hydrodynamic model. To compute it, we refer to the mathematical expression of Takeoka (1984a, 1984b) known as the remnant function. The water REST was computed for each element of the grid domain when only tide forces the basin and tidal return flow effects are prevented. A detailed description of this approach and results are reported in Cucco and Umgiesser (2006).

3.4 Statistical analysis

The following steps summarise the strategy employed in this study: 1) a correlation coefficient between variables was obtained; 2) a log-ratio transformation was applied to the data to obtain a comparable unit of the variables for representation of outliers, and because the data were “closed”; 3) cluster analysis in *r-mode* was investigated by eigenvector methods within principal component analysis. This statistical strategy allowed us to proceed gradually from simple data analysis to more sophisticated pattern recognition. All calculations were based only on log-ratio data.

Aitchison (1986) provides an extensive treatment of closure and offers a number of transformations which convert compositional variables into forms which can be analysed by conventional statistical techniques. Methods involving eigenvector extraction such as principal components, factor and canonical analyses, require a set of covariances in which all variables are directly expressed. For these applications, Aitchison proposes the use of log-ratio covariance, in which the divisors of the log-ratio are the geometric means of the original compositional variables. A geometric mean was computed for each of the *n* rows of the data matrix.

4. Results and discussion

4.1 Sediment classification

The bottom sediments of the lagoon consist mainly of clayey silt (mean mud content ~80% of dry weight). The silt fraction dominates, being 44-61 % on average (Tab. 1). Some differences are evident for the three sets of data. Input channel samples (I) have the lowest silt/clay ratios (mean 1.7) due to relatively lower silt contents (<50%) and relatively higher clay contents (>25%). These samples also have the highest residence time (REST = 18 days) and the lowest mean RMSV velocities (~ 4 cm s^{-1}). Shallow lagoon beds (B) and navigation channels (C) have similar grain-size compositions and hydrological characteristics, with average typical silt/clay ratios of ~ 3, silt contents of 60-70%, REST values of 15 days, and RMSV velocities of 7-8 cm s^{-1}.

Table 1

The textural trend of the Lagoon sediment samples are represented on a ternary diagram on the basis of sand/silt/clay ratios (Fig. 2a). This shows that the three ratios plot in two bands reflecting an intermediate energy gradient (Flemming, 2000) commonly found in intertidal sediments. The sediment composition defines diagonal bands which gradually widen towards the silt-clay axis. However, in the case of I (channel) samples, the textural gradient shows a progressive shift towards higher clay contents, indicating a more rapidly decreasing energy gradient in the samples. Considering B (shallow lagoon beds) sediments, samples with sand contents of up to 30% correspond to locations in the southern part of the Lagoon and those near the three sea inlets. Taking into account the hydrodynamic models of Pejrup (1988) and Flemming (2000), the location of data within the ternary diagram reflects specific hydrodynamic energy conditions. With respect to the relative proportions of silt and clay, the closer a set is located to the silt end-member, the higher is the energy level.

Figure 2b shows data from Flemming (2000), the three data-sets representing back-barrier tidal flats (Danish Wadden Sea, band 2), bay (Minas Basin, Bay of Fundy, Canada, band 4), and lagoonal (Mugu Lagoon, band 5) sedimentary environments. A comparison between the Lagoon of Venice and Mugu Lagoon sediments shows that the two occupies different areas in the plot, which implies different depositional conditions. The finer sediment in the Mugu Lagoon reflects a lower-energy hydrodynamic system. The Venice Lagoon sediments are more similar to the Minas Basin and the Danish Wadden Sea, both signifying higher-energy environments.

These data seem to confirm the findings of various authors regarding the consequences of man-made interventions over the last few centuries, i.e., increasing mean depth of the Lagoon and erosion due to reduced silting-up - no longer compensated by the subsidence rate - have caused a flattening of the lagoonal bottom and evolution toward a marine bay environment (Ravera, 2000).

Figure 2

The results highlighted by the Flemming classification are better described by mapping the distribution of the mud fraction (Fig. 3). A clear-cut north-south pattern is revealed, with very high mud contents (75% to > 90%) in the north-central area; a lower one in the southern lagoon (70% to < 50%); and very similar values (<50%) at the three inlets. This suggests that the tendency of the Lagoon of Venice to evolve into a marine bay environment is less evident in its northern part than in the rest of the Lagoon. In fact, the northern area is dominated by river influences, and receives the largest part of the total load (Zonta et al., 2001) whereas in the rest of the Lagoon fluvial inputs are very low and marine influences dominate. Therefore, considering the sedimentological and hydrodynamic features of the northern basin, we may classify it as a lagoonal environment.

Figure 3

4.2 Hydrological parameters

The RMSV distribution is shown in Figure 4. It clearly identifies channels because of their overall high values. The channels may be considered as the main driving force of the hydrodynamics in the Lagoon. The highest values, about 0.60 m s^{-1}, occur in the inlets where peak velocities of up to 1 m s^{-1} are measured. Hydrodynamic activity decreases from the inlets towards the inner regions where low RMSV values are calculated. Also note that the areas between the inlets and others located north of the island of Sant Erasmo are characterised by low hydrodynamic activity.

Figure 4

These areas correspond to the watershed zones and divide the Lagoon into four sub-basins (Solidoro et al., 2004). A detailed description of tide–induced water circulation is given in Umgiesser (2000). Figure 5 shows the distribution of water residence times in the Lagoon. Computations were carried out when the basin circulation was forced by the tide only, and return flow effects from the Adriatic were absent. Residence times range between less than 1 day close to the inlets, to over 30 days in the inner lagoon. As in the previous case, the distribution mainly depends on the relative distance from the three inlets and on the presence of channels. Nevertheless, contrary to the RMSV distribution, low residence times occur in the inlets and channels where tidal flushing is more efficient, whereas higher values are measured in the inner areas and along the two lagoonal watersheds where almost no water is replaced by tidal action. A full description of these results can be found in Cucco and Umgiesser (2006).

Figure 5

4.3 Hydro-sedimentological correlation

As we have seen, both sedimentological and hydrological characteristics are quite different between the deeper input channels and the inner lagoon (shallow channels and mud flats). Among all the variables, the combination of hydrological parameters and grain-size data shows the best correlation coefficients between the grain-size fraction of 4-31 µm (fine silt) and REST (cor. coef.: 0.57; p <0.010), as well as between RMSV and the very fine sand fraction (63-105 µm) (cor. coef.: 0.42; p<0.010). The relationship between these hydrological parameters and the grain-size fractions is shown in greater detail in two bivariant plots. Figure 6 shows a box-plot graph between the grain-size fraction of 4-31 µm and REST, in which the two parameters are positively correlated for REST values of up to 15-20 days. At higher REST values the trend reverses, i.e. when mean residence times are higher than 20 days, no further increase in this grain-size fraction is evident in any part of the Lagoon. It seem plausible that the finest grain fraction accumulates increasingly for longer RESTs, which indicate lower forcing conditions. After periods of more then 10-15 days a rather constant part of the material has settled at the seabed leading to a maximum silt fraction around 40-50%.

Figure 6

Similarly, figure 7 illustrates the relationship between the very fine sand fraction (63-105 µm) and RMSV. In this case, a clear positive correlation is evident only for velocities above 10 cm s^{-1}, when the very fine sand fraction start to increase from <5% to ~30%. When mean RMSVs are lower than 8-10 cm s^{-1}, sediments have low contents of very fine sand (0-10%), which are poorly correlated with RMSV. The above velocity corresponds to the threshold for non-cohesive sediment movement, i.e., the critical current velocity required to move grains of different sizes on a plane bed (Miller et al., 1977). The lower influence of RMSV on very fine sand is seem observed at an RMSV value of 3 m s^{-1}, at which correlation cannot be made because the sediment no longer reacts. This means that the sand fraction increases to the point at which mean forcing exceeds the threshold for grain movement. The finer grains are assumed to be resuspended and removed.

Data scatter is not only caused by the rather low number of samples in each subclass, but also by the fact that both REST and RMSV are derived quantities which characterise the forcing conditions on the sediments only indirectly.

In order to further confirm the thesis of the dominance of tidal forcing on long-term water circulation patterns, and the validity of the results, a further analysis was carried out. In particular, grain size data were compared with the results of Umgiesser et al. (2004a) on the WBSS induced by the combined effect of wind, wave and tidal forcing. As expected, low correlation coefficients (< 0.2; p <0.010) between WBSS and grain size data were found, revealing that the effect of low-frequency strong meteorological events on long-term sediment distribution in the Lagoon is less significant, or totally negligible, with respect to regular forcing by tides.

This issue has also confirmed by the results of Umgiesser et al. (2006), in which a sediment transport model was applied to the Lido inlet. Comparing results from three idealised simulations (tide only, tide with s*cirocco,* tide with *bora* winds) with a simulation using real forcings over one year, it was found that the long-term results were closest to the simulation when only tidal forcing was taken into account. This shows that intermittent forcing events due to strong winds have less impact on long-term evolution than regular tides acting continuously on lagoon dynamics.

Figure 7

4.4 Multivariate statistics

Principal components analysis (PCA) may be regarded as an ordering technique which reduces large data-sets into a small number of groups of statistically related samples. PCA is suitable for reducing the directions of maximum variance of data, using them to order data in one or more dimensions and interpret them as factors influencing data distribution. The method is well described in Le Maitre (1982) and Swan & Sandilands (1995).

In the present study, PCA was applied to the grain-size and hydrodynamic parameters of shallow lagoon beds (B in Fig. 1). Two components were extracted, explaining ~ 75% of variance, and which were sufficient to separate sediments from different areas of the Lagoon. Factor 1 (F1) is characterised by the mud fraction (2-2.8 to 31-44 µm), residence times in the negative sense, sand, skewness, kurtosis in the positive sense, accounting for ~ 65% of the variance. Factor 2 (F2) is influenced by the coarser fraction (63-105 μm) and RMSV, and represents 10% of the total variance. All samples were then plotted in the space of the new variables (factors). Figure 8 shows the samples ordered in two dimensions (F1, F2): all the coarser sediment samples and higher values of RMSV plot on the right side of the graph (group 4, slightly silty sand). The samples on the left side of the plot have long residence times and consist of finer fractions which increase upward along the axis of factor 2, indicating decreasing bottom energy. Fine samples are divided into three groups with different clay contents and silt composition.

Figure 8

Groups 1 (clayey silt) and 2 (very silty slightly sandy mud) comprise samples located mainly in the northern and central basin of the Lagoon and inshore with clay contents of ~ 25% and fine and coarse silt contents of ~ 26% and ~ 44%, respectively (Fig. 9). In group 3 (very silty sandy mud), the clay content decreases to ~ 15%, and the silt fraction becomes increasingly coarser (Fig. 9). The sedimentological pattern reflects the main sources of sediments: clay and silt from the rivers, occurring mainly in the northern basin, and sand from the sea through the three lagoon inlets.

Figure 9

Half the samples of groups 3 and 4 come from seagrass beds (see Fig. 1). The role of seagrass in affecting the stability of tidal flats and thus in modifying bottom characteristics in the Lagoon of Venice was studied by Amos et al. (2004), who examined various bed types including bare mudflats, and regions colonised by seagrasses, filamentous cyanobacteria and patches of macrophytes. They demonstrate that, especially in the northern lagoon during summer, biostabilisation on average strengthens the bed by a factor of 1.5-2 times the level due solely to cohesion. During winter, some sites in the northern lagoon still indicate biostabilisation, but bed strength is now due only to cohesion, whereas values below 100% in the southern lagoon reflect disturbance. Unfortunately, a relation between sediment texture and organic matter was not investigated due to the lack of reliable data.

The samples of group 3 in our PCA show signs of stabilisation, reflected in the reduction of sand and the accumulation of more silt with respect to group 4, some samples of which were collected from previous seagrass beds which have in the meantime disappeared and/or have been reduced in area (Curiel and Rismondo, 2005). This effect may be due to seagrass which modifies waves and therefore affects relationships among the non-dimensional scaling parameters commonly used in wave analysis. Seagrass shelters the bed, often causing aggradation and changes in grain size while increasing total resistance to flow (Teeter et al., 2001).

5. Conclusions

1. The bottom sediments of the Lagoon of Venice mainly consist of clayey silt (mean mud content ~80% of dry weight) and the silt fraction which, on average contributes 44-61 % to the sediment. Some differences are clear-cut between samples from input channels [lowest silt contents (<50%) and highest clay contents (>25%)], shallow lagoon beds and navigation channels.

2. Sedimentological processes in the Lagoon of Venice are more similar to those characteristic of a bay environment than a lagoonal environment, but it seems that the tendency of the Lagoon to evolve into a marine bay is less evident in the northern part than in the rest.

3. Residence times (REST) range from values of less than 1 day close to the inlets, to over 30 days in the inner areas.

4. The highest root mean square velocities (RMSV), i.e. ~ 60 cm s^{-1}, occur in the inlets, and RMSV distribution shows that hydrodynamic activity decreases from the inlets towards the inner regions where RMSV values are low (< 2 cm s^{-1}).

5. A high correlation between REST and the silt fraction (4-31 µm) was found only for REST values <20 days. A good correlation was also found between RMSV and the fine sand fraction (63-105 µm) where RSMV were >10 cm s^{-1}.

6. Principal Component Analysis applied to grain size and hydrodynamic parameters separated shallow lagoon beds (type B in Fig. 1) into four groups. Groups 1 (clayey silt) and 2 (very silty slightly sandy mud) comprise samples located mainly in the northern and central areas of the Lagoon and inshore. Groups 3 (very silty sandy mud) and 4 (slightly silty sand),

mostly collected on seagrass beds, show distinct differences in sand and silt contents, which are perhaps due to stabilisation effects by seagrasses.

Acknowledgments

This is ISMAR–CNR scientific contribution No. xxxx. Ms. Gabriel Walton revised the English text. We thank the two reviewers for their valuable comments.

References

Adami, A., Cecchi G. and Degetto, S., 1992. Bathymetric survey and radiodating for evaluating the erosion of shallows. 23rd International Conference on Costal Engineering. Venice, Italy, pp. 47-48.

Aitchison, J., 1986. The statistical analysis of compositional data. Chapman & Hall, London.

Albani, A.D. and Serandrei Barbero, R., 2001. The distribution of surface sediments in the lagoon of Venice (Italy) in the 1980s. Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, 159:363-378.

Amos, C.L., Bergamasco, A., Umgiesser, G., Cappucci, S., Cloutier, D., DeNat, L., Flindt, M., Bonari, M., Cristante, S., 2004. The stability of tidal flats in Venice Lagoon—the results of in-situ measurements using two benthic, annular flumes. J. Marine Syst., 51, 211– 241.

Avanzi, C., Fossato, V., Gatto, P., Rabagliati, R., Rosa, Salva P. and Zitelli, A., 1981. Ripristino, conservazione ed uso dell'ecosistema lagunare Veneziano. Comune di Venezia, Italy.

Barillari, A., 1978. Prime notizie sulla distribuzione dei sedimenti superfciali del bacino centrale della laguna di Venezia. Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 136:125-134.

Barillari, A., 1981. Prime notizie sulla distribuzione dei sedimenti superfciali del bacino meridionale della laguna di Venezia. Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 139: 87-109

Barillari, A., and Rosso, A., 1976. Prime notizie sulla distribuzione dei sedimenti superfciali del bacino settentrionale della laguna veneta. Mem. Biogeogr. Adriat. suppl. 9:13-32

Battiston, G.A., Degetto, S., Gerbasi, R., Sbrignadello, G., and Tositti, L., 1988. The use of ^{210}Pb and ^{137}Cs in the study of sediment pollution in the Lagoon of Venice. Sci. Tot. Environ. 77:15-23.

Boggs, S., Jr. 2001. Principles of Sedimentology and Stratigraphy. 3rd ed., Prentice Hall, New Jersey.

Bondesan, M., Castiglioni, G., Elmi, C., Gabbianelli, G., Marocco, R., Pirazzoli, P., Tomasin, A., 1995. Coastal areas at risk from storm surges and sea-level rise in north-eastern Italy. J. Coastal. Res., 11:1354-1379

Brambati, A., Carbognin, L., Quaia, T., Teatini, P. and Tosi, L., 2003. The Lagoon of Venice: Geological setting, evolution and land subsidence. Episodes, 26:264–268

Canestrelli, P., Mandich, M., Pirazzoli, P.A., Tomasin, A., 2001. Wind, depression and seiches: tidal perturbations in Venice (1951-2000). Technical report, Comune di Venezia, Centro Previsioni e Segnalazioni Maree, Venice, Italy.

Carbognin, L. and Taroni, G., 1996. Eustatismo a Venezia e Trieste nell'ultimo secolo (Eustasy at Venice and Trieste in the last century). Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 156:33–52.

Carbognin, L., Teatini, P. and Tosi, L., 2004. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium. J. Marine Syst., 51:345– 353.

Ciabatti, M., 1967. Ricerche sull'evoluzione del Delta Padano. G. Geol. 2, 34, 2:26.

Cucco, A., Umgiesser, G., 2005. Modeling the tide induced water exchanges between the Venice Lagoon and the Adriatic Sea. In: Campostrini, P. (Ed.), Scientific Research and Safeguarding of Venice. Proceedings of the Annual Meeting of the Corila Research Program, 2003 Results, 3:385-402.

Cucco, A., Umgiesser, G., 2006. Modeling the Venice Lagoon Water Residence Time. Ecol. Model., 193:34-51.

Curiel, D. and Rismondo, A., 2005. Seagrass distribution: comparisons 1990-2002, Table 60. In: Guerzoni, S. and Tagliapietra, D., (Eds.), Atlante della Laguna. Venezia tra Terra e Mare, Marsilio, Venice, pp.130-131.

Donnici, S.; Serandrei Barbero, R. and Taroni, G., 1997. Living benthic foraminifera in the lagoon of Venice (Italy): population dynamics and its significance. Micropaleontology, 43:440-454.

Elliott, M. and Cutts, N. D., 2004. Marine habitats: loss and gain, mitigation and compensation. Mar. Pollut. Bull., 49:671–674.

Favero, V., 1992. Evoluzione morfologica e trasformazioni ambientali dalla conterminazione lagunare al nostro secolo. Con terminazione lagunare: storia, ingegneria, politica e diritto nella Laguna di Venezia. Proceeding of the Conference "Convegno di studi bicentenario della con terminazione lagunare", Venice, Italy.

Flemming, B. W., 2000. A revised textural classification of gravel-free muddy sediments on the basis of ternary diagrams. Cont. Shelf Res., 20:1125-1137.

Folk, R.L., 1974, The Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, Texas.

Friedman, G.M., 1979. Differences in size distributions of populations of particles among sands of various origins. Sedimentology, 26:3–32

Gačić, M., Kovacevic, V., Mazzoldi, A., Paduan, J., Arena, F., Mosquera, I. M., Gelsi, G. and Arcari, G., 2002. Measuring water exchange between the Venetian Lagoon and the open sea. EOS, Transactions, AGU 83, (20), 217:221 222.

Gačić, M., Mazzoldi, A., Kovacevic, V., Mancero Mosquera, I., Cardin, V., Arena, F. and Gelsi, G., 2004. Temporal variations of water flow between the Venetian lagoon and the open sea. J. Marine Syst., 1:33– 47.

Gatto, P., 1980. Il sottosuolo del littorale veneziano. Technical report, CNR-Istituto Studio Dinamico Grandi Masse, Venice.

Gatto, P. and Carbognin, L., 1981. The lagoon of Venice: natural environmental trend and man-induced modification. Hydrol. Sci. B., 26 (4):379– 391.

Ghetti., A., 1974. Problemi idraulici della Laguna di Venezia. Giornale Economico, Camera di Commercio di Venezia, 3-48.

Hieke Merlin, O., Menegazzo Pitturi, L. and Semenzato, G., 1979. Contributo alla conoscenza dei sedimenti superficiali della laguna veneta. Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 137:36-51.

Kent, V.D., Rio, D., Massari, F., Kukla, G. and Lanci, L., 2002. Emergence of Venice during the Pleistocene. Quat. Sci. Rev., 21:1719–1727.

Le Maitre, R.W., 1982. Numerical Petrology: Statistical Interpretation of Geochemical Data. Elsevier, Amsterdam.

Luketina, D., 1998. Simple tidal prism models revisited. Estuar. Coast. Shelf Sci., 46:77–84.

M.A.V.-C.V.N., 1999. Mappatura dell'inquinamento dei fondali lagunari. Studi ed indagini, relazione finale luglio 1999. Consorzio Venezia Nuova.

McBride, E.F., 1971. Mathematical treatment of size distribution data. In: Carver, R.E. (Ed.) Procedures in Sedimentary Petrology. Wiley Interscience, New York, pp. 109–207.

McLaren, P. and Bowles, D., 1985. The effects of sediment transport on grain-size distributions. J. Sediment. Petrol., 55:457-470.

Menegazzo Vitturi L. and Molinaroli, E., 1984. Il ruolo della caratteristiche mineralogiche e fsiche dei sedimenti nei processi di inquinamento di un'area tipo della laguna veneta. Atti Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 9:353-367.

Miller, M. C., McCave, I. N. and Komar, P. D., 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24:507–527.

Monsen, N. E., Cloern, J. E. and Lucas, L. V., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnol. Oceanogr, 47:1545–1553.

Pavoni, B., Marcomini, A., Sfriso, A., Donazzolo, R. and Orio, A., 1992. Changes in an estuary ecosystem. The Lagoon of Venice as a case study. In: Dunnette, D.A. and O'Brien, R.J., (Eds.), The Sciences of Global Change. ACS Symposium Series N. 483, pp.288-305.

Pejrup, M., 1988. The triangular diagram used for classification of estuarine sediments: a new approach. In: de Boer, P.L., van Gelder, A. and Nio, S.D., (Eds.), Tide-Influenced Sedimentary Environments and Facies. Reidel, Dordrecht, pp. 289–300.

Pirazzoli, P.A., 1991. Possible defences against a sea level rise in the Venice area, Italy. J. Coastal Res., 7:231-248.

Ravera, O., 2000. The Lagoon of Venice: the result of both natural factors and human influence. J. Limnol., 59(1): 9-30.

Runca, E., Bernstein, A., Postma, L. and Di Silvio, G., 1993. Control of macroalgae blooms in the Lagoon of Venice. Proc. MEDCOAST, 93 Conference, Antalya, Turkey.

Sanford, L., Boicourt, W., and Rives, S., 1992. Model for estimating tidal flushing of small embayments. Journal of Waterway, Port, Coastal and Ocean Engeneering, 118 (6):913–935.

Serandrei Barbero, R., Albani, A.D. and Zecchetto, S., 1997. Paleoenvironmental significance of a benthic foraminiferal fauna from an ecological excavation in the lagoon of Venice, Italy. Palaeogeogr. Palaeocol., 136:41-52.

Sestini, G., 1992. Implications of climatic changes for the Po Delta and the Venice Lagoon. In: Jeftic, L., Milliman, J. and Sestini, G., (Eds.), Climate change and the Mediterranean, Arnold, London, UK, pp. 429-495.

Solidoro, C., Melaku Canu, D., Cucco, A. and Umgiesser, G., 2004. A partition of the Venice Lagoon based on physical properties and analysis of general circulation. J. Marine Syst., 51:147-160.

Suman, D., Guerzoni, S. and Molinaroli, E., 2005. Integrated coastal management in the Venice lagoon and its watershed. Hydrobiologia, 550:251–269.

Swan, A.R.H. and Sandilands, M., 1995. Introduction to Geological Data Analysis. Science, Oxford.

Takeoka, H., 1984a. Exchange and transport time scales in the Seto Inland Sea. Cont. Shelf Res., 3 (4):327 341.

Takeoka, H., 1984b. Fundamental concepts of exchange and transport time scales in a coastal sea. Cont. Shelf Res., 3 (3):311 326.

Teatini, P., Tosi, L., Strozzi, T., Carbognin, L., Wegmüller, U. and Pizzetto, F., 2005. Mapping regional land displacements in the Venice coastland by an integrated monitoring system. Remote Sens. of Environ., 98:403 – 413.

Teeter, A.M., Johnson, B. H., Berger, C., Stelling, G., Scheffner, N.W., Garcia, M.H. and Parchure, T.M., 2001. Hydrodynamic and sediment transport modeling with emphasis on shallow-water, vegetated areas (lakes, reservoirs, estuaries and lagoons). In: Best, E.P.H. and Barko, J.W., (Eds.), Modelling Sediment Resuspension, Water Quality and Submerged Aquatic Vegetation. Hydrobiologia, 444:1–23.

Tosi, L., Carbognin, L., Teatini, P., Strozzi, T. and Wegmüller, U., 2002. Evidences of the present relative land stability of Venice, Italy, from land, sea, and space observations. Geophys. Res. Lett., 29(12):10.1029/2001GL013211.

Umgiesser, G., 2000. Modeling residual currents in the Venice Lagoon. In: Yanagi, T. (Ed.), Interactions between Estuaries, Coastal Seas and Shelf Seas. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 107–124.

Umgiesser, G. and Bergamasco, A., 1995. Outline of a primitive equation finite element model. Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy, 12:291-320.

Umgiesser, G., Sclavo, M., Carniel, S. and Bergamasco, A., 2004a. Exploring the bottom stress variability in the Venice Lagoon. J. Marine Syst., 51:161-178.

Umgiesser, G., Melaku Canu, D., Cucco, A. and Solidoro, C., 2004b. A finite element model for the lagoon of Venice, Italy. Development and calibration. J. Marine Syst., 51:123-145.

Umgiesser, G., De Pascalis, F., Ferrarin, C and Amos, C., 2006. A model of sand transport in Treporti channel: northern Venice lagoon. Ocean Dynamics, 56:339-351

Wang, C., Hsu, M. And Kuo, A., 2004. Residence time of the Danshueij river estuary, Taiwan. Estuar. Coast. Shelf S., 60:381 393.

Zonta, R., Bettiol, C., Collavini, F., Fagarazzi, O.E., Zaggia, L. and Zuliani, A., 2001. DRAIN project fresh water and pollutant transfer from the drainage basin to the Venice Lagoon, Project Report, No. 15B.

Zoppi, U., Albani, A., Ammerman, A.J., Hua, Q., Lawson, E.M. and Serandrei Barbero, R., 2001. Preliminary estimate of the reservoir age in the Lagoon of Venice. Radiocarbon, 43:489-494.

Zuliani, A., Zonta, R., Zaggia, L. and Fagarazzi, O.E., 2001. Fresh water transfer from the drainage basin to the Venice Lagoon. In: Drain Project Workshop: discussion and presentation of the methods and the main results of the Drain Project, Thetis S.p.a., Venice, Italy, pp. 31-36.

FIGURE CAPTIONS

Fig. 1. Location of sediment sampling sites in Lagoon of Venice. [● = shallow lagoon beds (B); ☐ = channel and river inputs (I); ✳ = lagoon navigation channel (C)]. Dashed areas: clam cultivation and harvesting; dotted areas: seagrass beds.

Fig. 2. (**a**) Ternary diagram of surface sediments based on sand/silt/clay ratios. Boundaries in the diagram define different sediment types, after Flemming (2000). [● = shallow lagoon beds (B); ☐ = channel and river inputs (I); ✳ = lagoon navigation channels (C)]. (**b**) Three sedimentary environments, Danish Wadden Sea (band 2); Minas Basin, Bay of Fundy, Canada (band 4) and Mugu Lagoon (band 5), from Fig. 5 in Flemming, 2000.

Fig.3. Distribution of the mud fraction (weight - %).

Fig. 4. Distribution of root mean square velocities: RMSV (m s^1).

Fig. 5. Distribution of water residence time: REST (days).

Fig. 6. Box-plot of the grain-size fraction 4-31 µm vs. REST for B samples.

Fig. 7. Box-plot of the grain-size fraction 63-105 µm vs. RMSV for B samples.

Figure 8. Plot of factor 1 vs. factor 2 of B samples derived from PCA, of grain-size parameters and hydrodynamic variables. In parenthesis the number of samples belong to each group. Histograms represent mean grain sizes of samples for each group identified by PCA.

Fig. 9. Location of the groups derived from the PCA. The four groups together are the sediment shallow lagoon beds (B) in Fig. 1.

Table captions

Table 1. Mean and range (in brackets) values of sedimentary and hydrological variables of three sets of sediment samples. B=shallow lagoon beds; I= channel and river inputs; C= lagoon navigation channels.

	N° samples	Depth (m)	Sand (%)	Silt (%)	Clay (%)	Silt/Clay
B	70	1.0	19.2	60.7	20.1	3.2
		(0.2 - 2.9)	(0.8 - 90.2)	(6.3 - 83.0)	(3.3 - 38.4)	(1.9 - 5.2)
I	11	2.0	28.9	44.0	27.1	1.7
		(0.3 - 3.1)	(0.3 - 67.2)	(20.8 - 69.2)	(11.8 - 48.4)	(1.1 - 1.4)
C	15	2.2	21.4	58.8	19.8	3.0
		(0.2 - 6)	(1.5 - 71.9)	(23.5 - 78.5)	(4.5 - 29.7)	(5.2 - 2.6)

	REST (days)	RMSV (cm s^{-1})	Mean (µm)	Sorting (Φ)	Skewness (Φ)	Kurtosis (Φ)
B	15.6	7.3	25.1	2.1	1.0	3.3
	(0.1 - 26.3)	(0.1 - 24.5)	(4.4 - 118.6)	(1.5 - 2.7)	(-0.2 - 3.3)	(1.5 - 13.6)
I	17.9	4.3	19.4	2.3	0.4	2.2
	(7.9 - 31.2)	(1.7 - 7.6)	(5.7 - 46.5)	(1.6 - 2.8)	(-0.5 - 1.3)	(1.6 - 3.5)
C	15.0	8.1	21.1	2.1	0.8	2.6
	(4.6 - 27.3)	(0.1 - 14.6)	(9.8 - 80.7)	(1.7 - 2.7)	(0.3 - 1.7)	(1.6 - 5.2)

Figure1

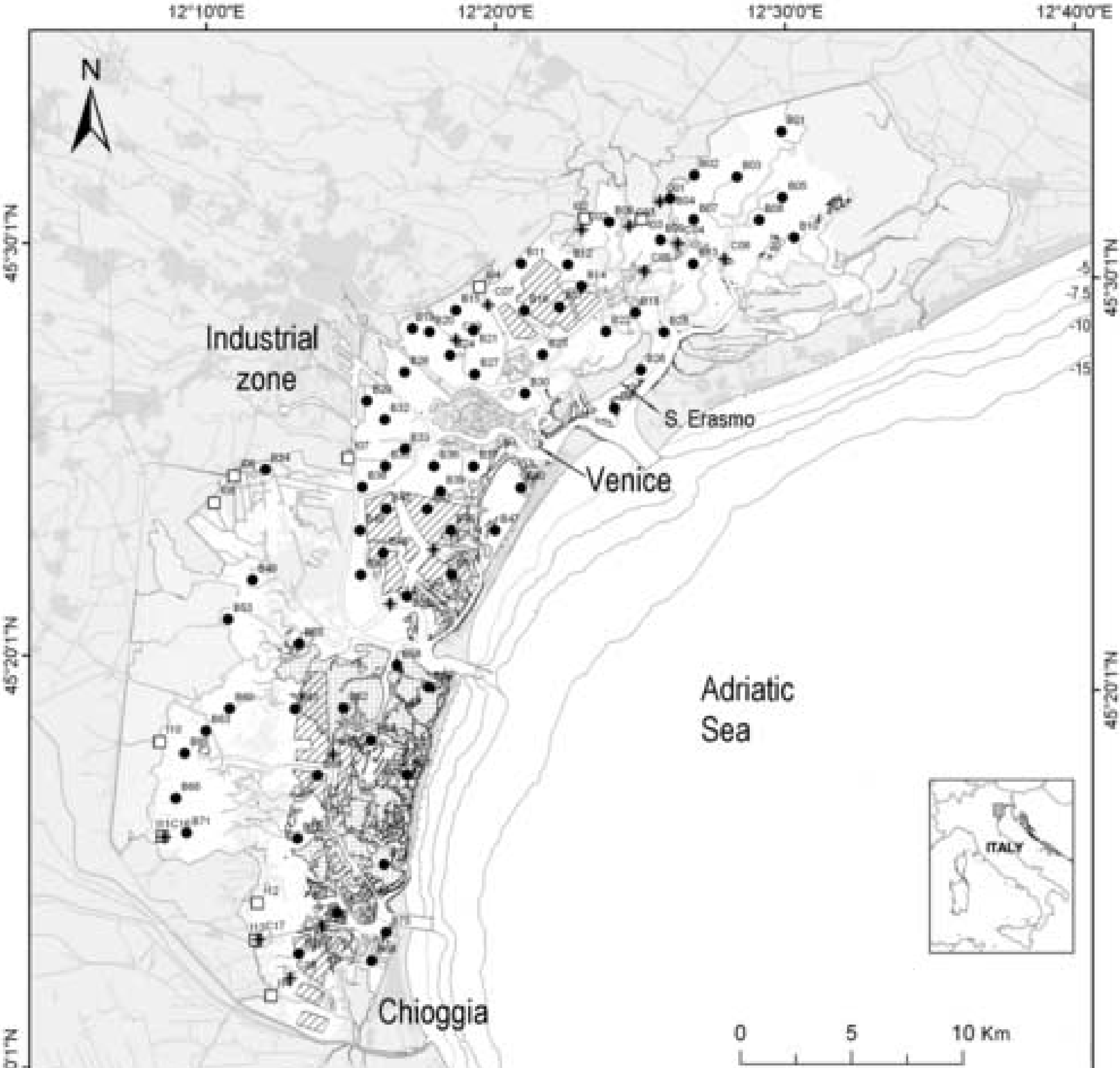

12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E
45°30'1"N
45°20'1"N
45°10'1"N
N
Industrial zone
Venice
S. Erasmo
Adriatic Sea
Chioggia
-5
-7.5
-10
-15
0
5
10 Km
ITALY

Figure 2

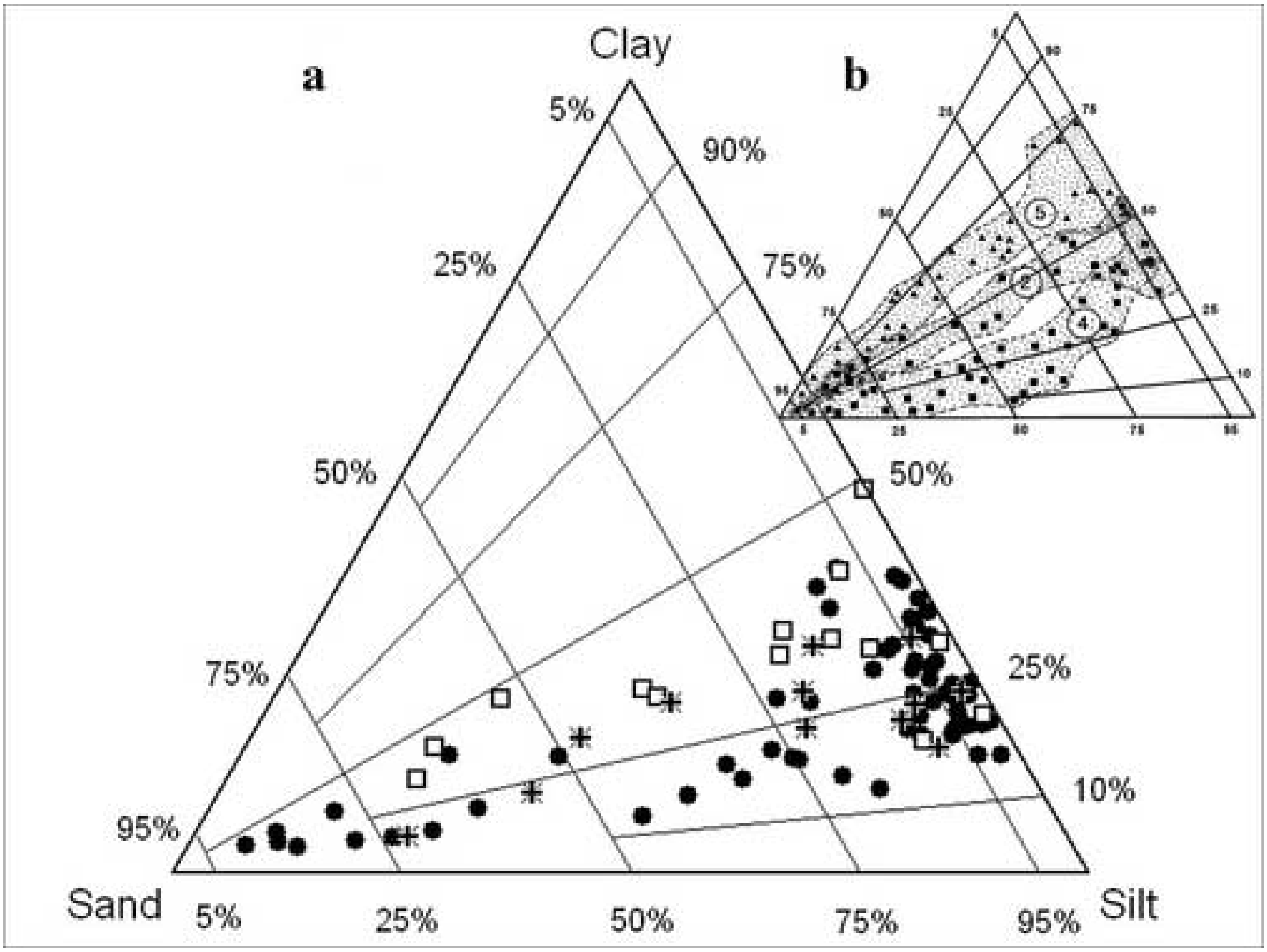

a
Clay
5%
90%
25%
75%
50%
50%
75%
25%
95%
10%
Sand
5%
25%
50%
75%
95%
Silt
b
5
90
25
75
50
50
75
25
95
10
5
25
50
75
95
5
2
4

Figure 3

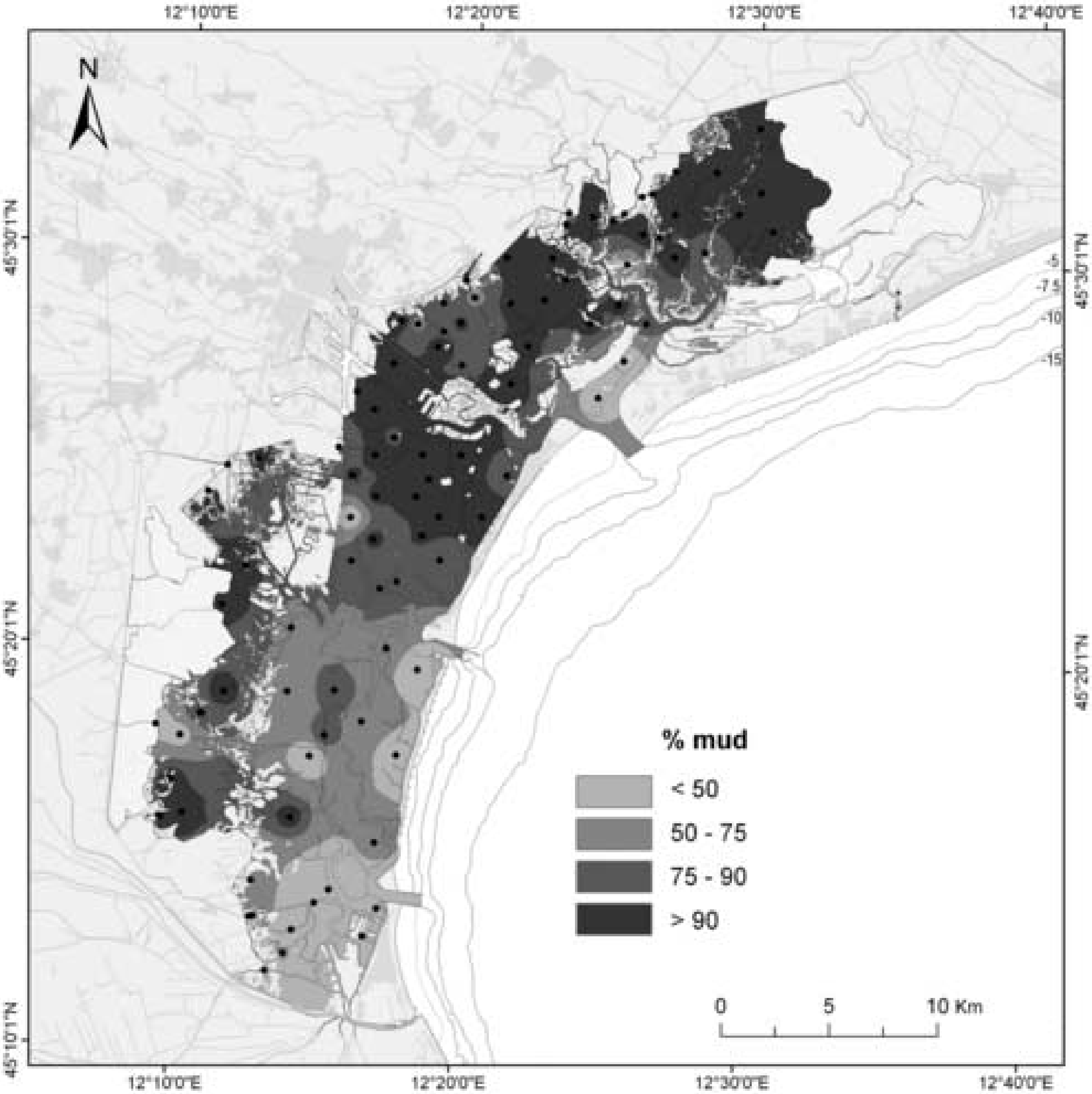

12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E
N
45°30'1"N
45°20'1"N
45°10'1"N
45°30'1"N
45°20'1"N
-5
-7.5
-10
-15
% mud
< 50
50 - 75
75 - 90
> 90
0
5
10 Km
12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E

Figure 4

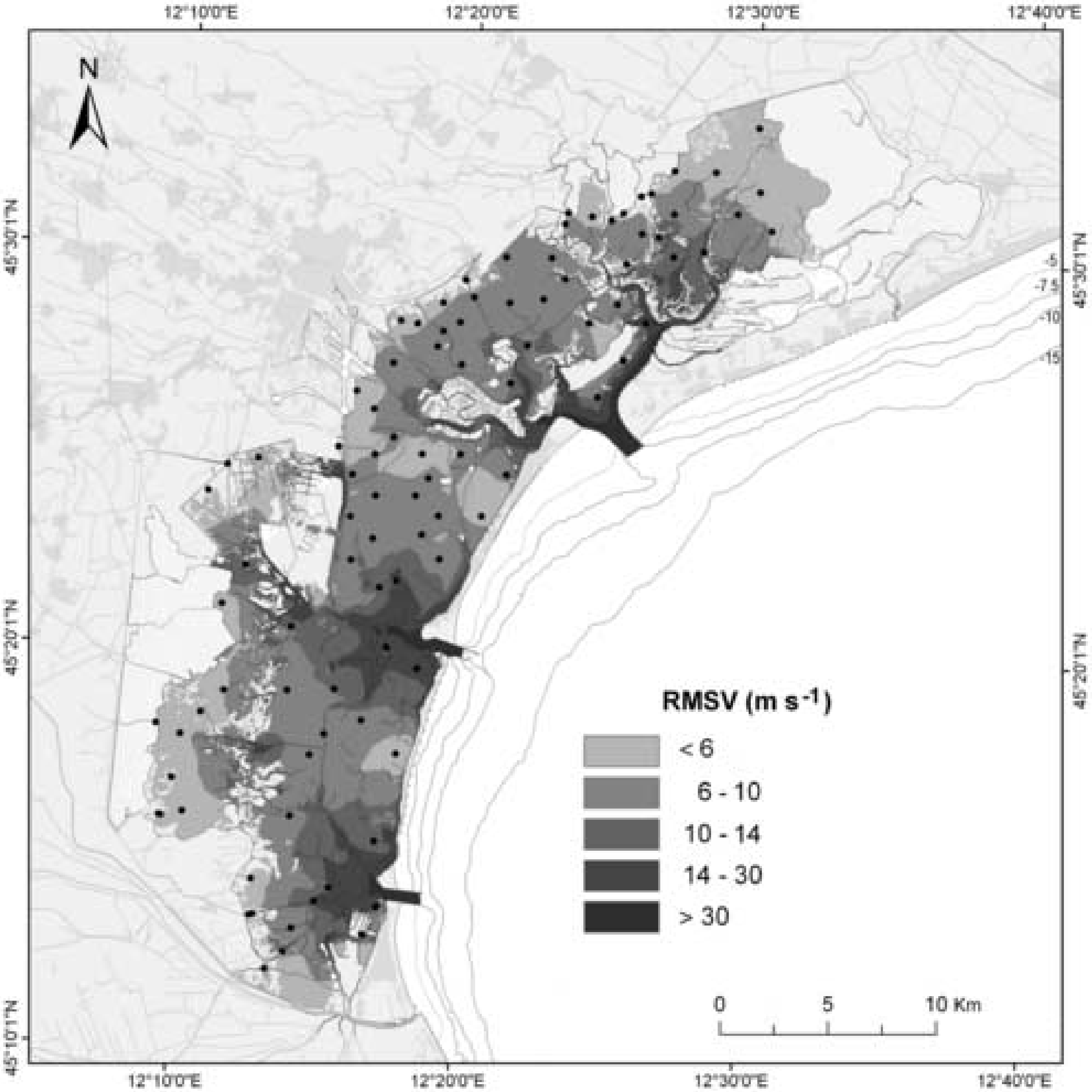
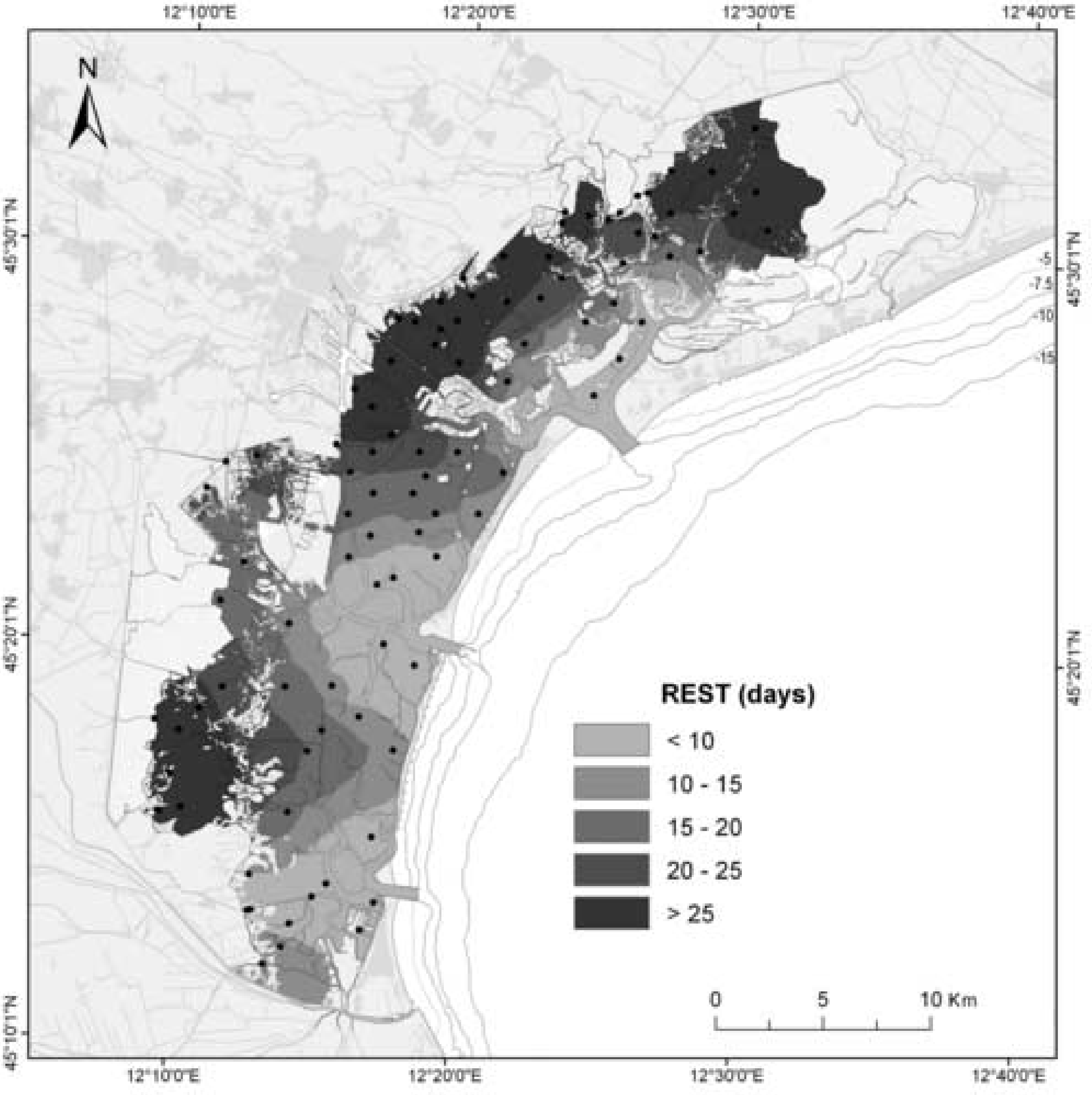
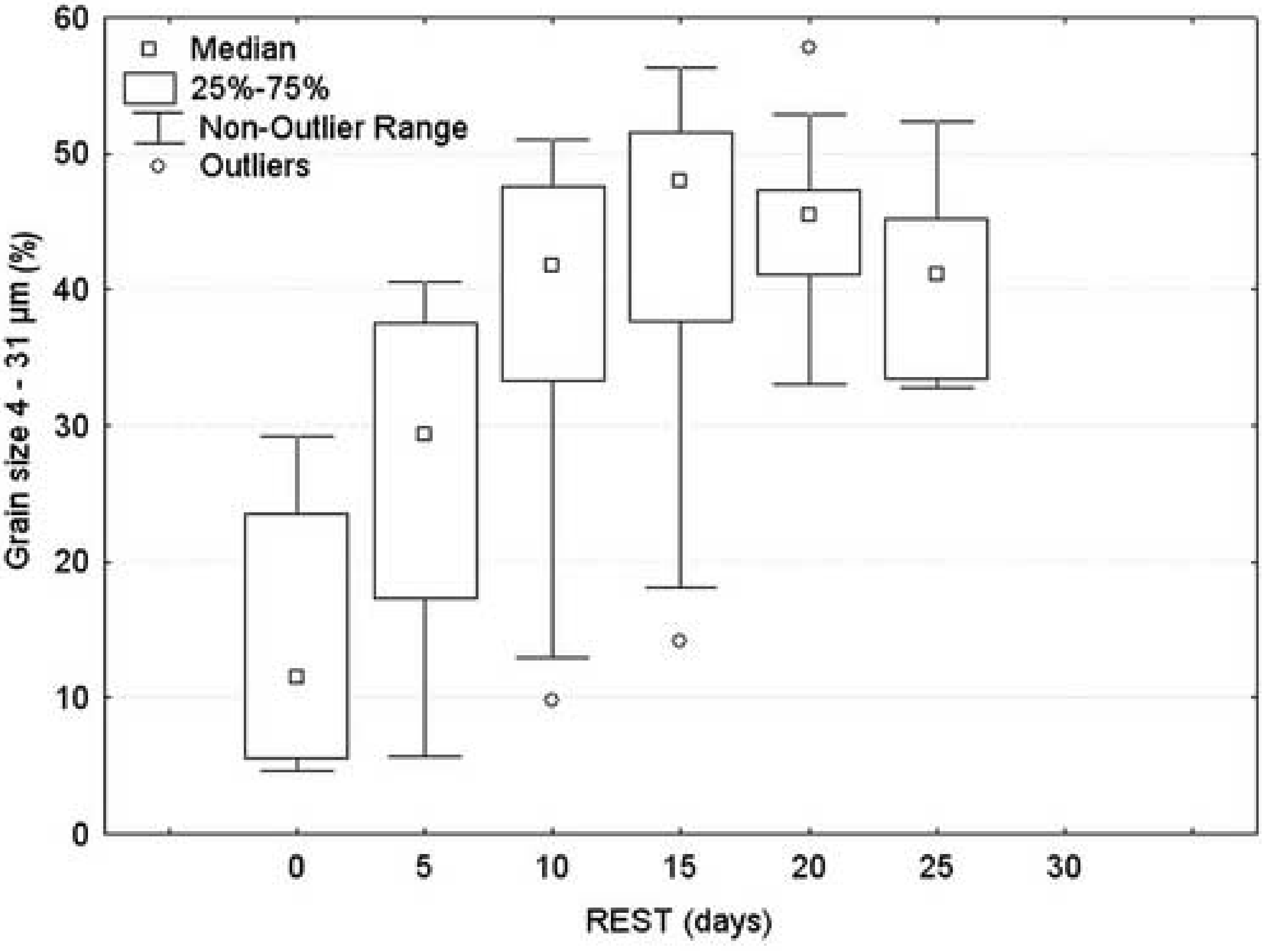

N
12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E
45°30'1"N
45°20'1"N
45°10'1"N
-5
-7.5
-10
-15
RMSV (m s-1)
< 6
6 - 10
10 - 14
14 - 30
> 30
0
5
10 Km

Figure 5



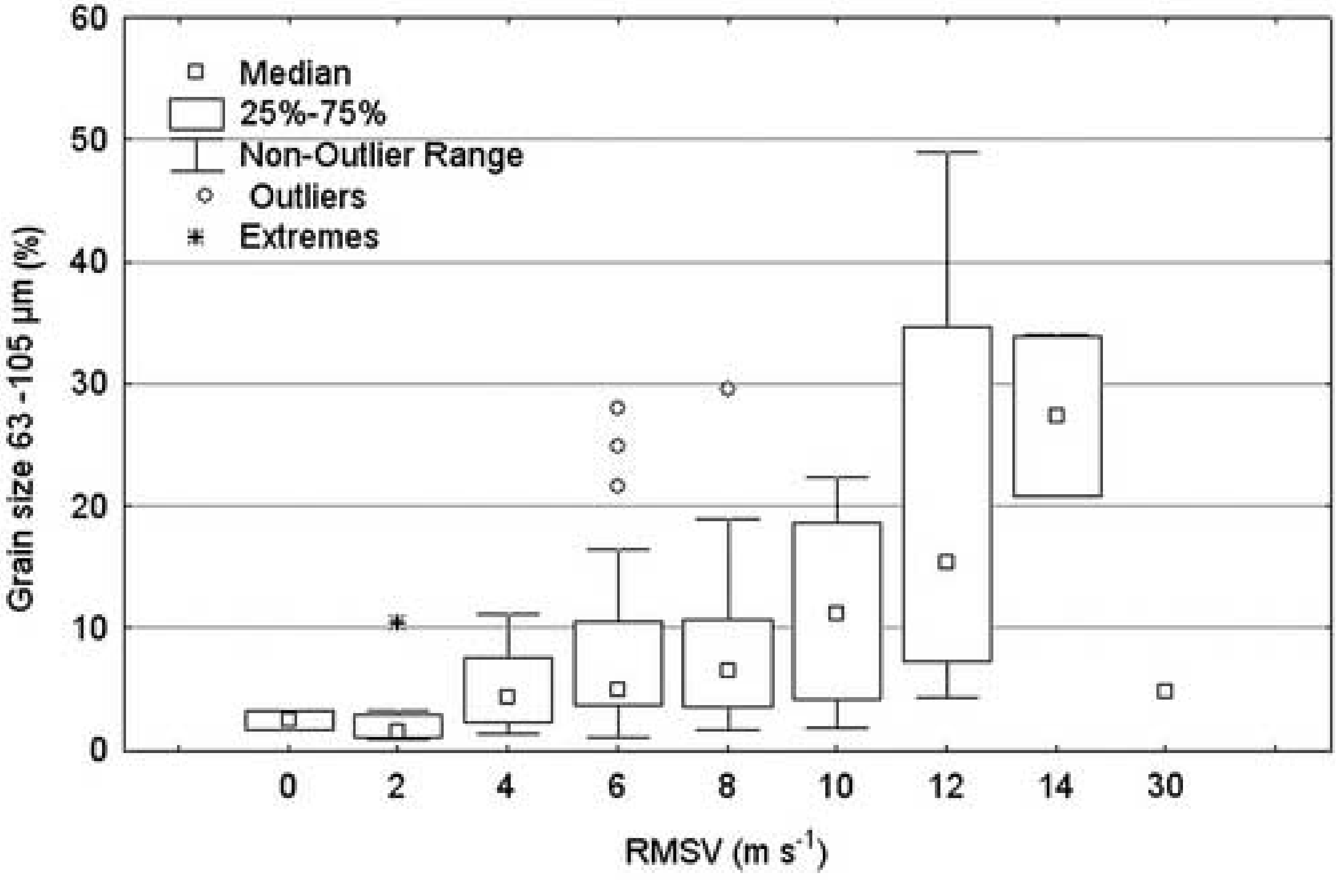
12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E
N
45°30'1"N
45°20'1"N
45°10'1"N
-5
-7.5
-10
-15
REST (days)
< 10
10 - 15
15 - 20
20 - 25
> 25
0
5
10 Km

Figure 6



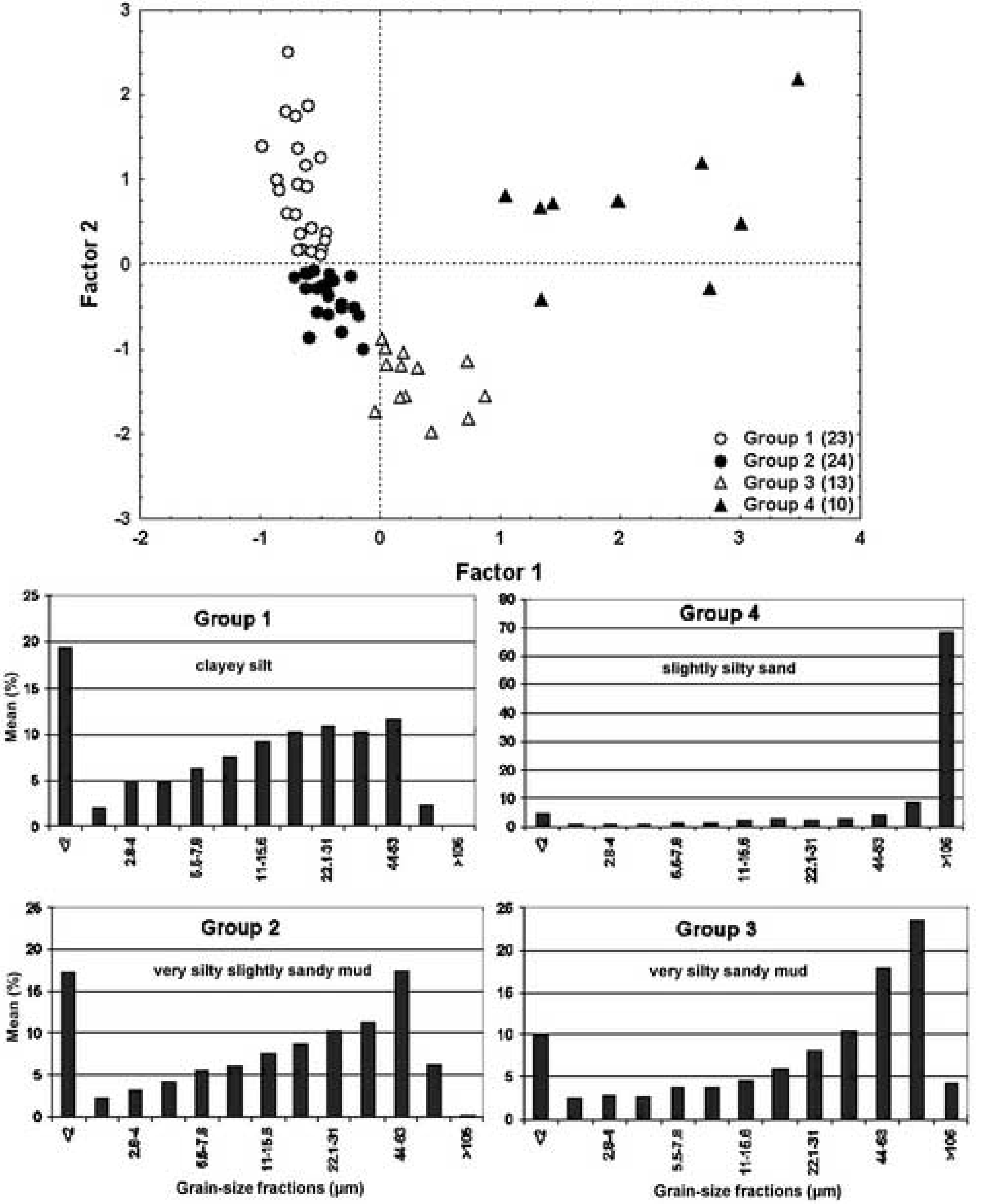
Median
25%-75%
Non-Outlier Range
Outliers
60
50
40
30
20
10
0
Grain size 4 - 31 µm (%)
0
5
10
15
20
25
30
REST (days)

Figure 7



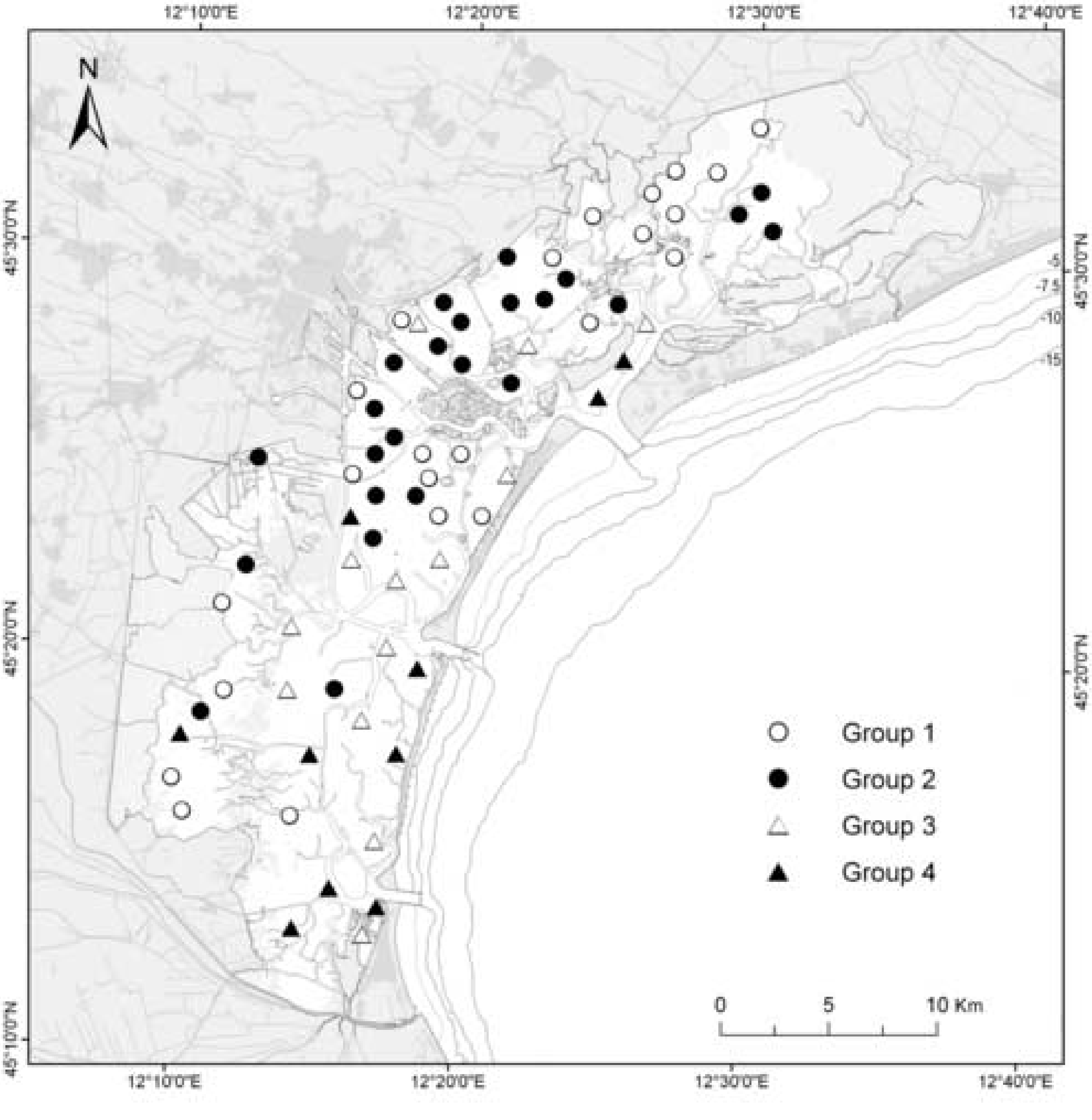
Median
25%-75%
Non-Outlier Range
Outliers
Extremes
Grain size 63 -105 µm (%)
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
30
RMSV (m s-1)

Figure 8



Factor 2
Factor 1
3
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
4
○ Group 1 (23)
● Group 2 (24)
△ Group 3 (13)
▲ Group 4 (10)
Group 1
clayey silt
Mean (%)
Group 4
slightly silty sand
Group 2
very silty slightly sandy mud
Mean (%)
Grain-size fractions (µm)
Group 3
very silty sandy mud
Grain-size fractions (µm)
<2
2.8-4
5.5-7.8
11-15.6
22.1-31
44-63
>106

Figure 9



12°10'0"E
12°20'0"E
12°30'0"E
12°40'0"E
45°30'0"N
45°20'0"N
45°10'0"N
N
-5
-7.5
-10
-15
○ Group 1
● Group 2
△ Group 3
▲ Group 4
0
5
10 Km

Table 1

Table captions

Table 1. Mean and range (in brackets) values of sedimentary and hydrological variables of three sets of sediment samples. B=shallow lagoon beds; I= channel and river inputs; C= lagoon navigation channels.

	N° samples	Depth (m)	Sand (%)	Silt (%)	Clay (%)	Silt/Clay
B	70	1.0	19.2	60.7	20.1	3.2
		(0.2 - 2.9)	(0.8 - 90.2)	(6.3 - 83.0)	(3.3 - 38.4)	(1.9 - 5.2)
I	11	2.0	28.9	44.0	27.1	1.7
		(0.3 - 3.1)	(0.3 - 67.2)	(20.8 - 69.2)	(11.8 - 48.4)	(1.1 - 1.4)
C	15	2.2	21.4	58.8	19.8	3.0
		(0.2 - 6)	(1.5 - 71.9)	(23.5 - 78.5)	(4.5 - 29.7)	(5.2 - 2.6)

	REST (days)	RMSV (cm s^{-1})	Mean (µm)	Sorting (Φ)	Skewness (Φ)	Kurtosis (Φ)
B	15.6	7.3	25.1	2.1	1.0	3.3
	(0.1 - 26.3)	(0.1 - 24.5)	(4.4 - 118.6)	(1.5 - 2.7)	(-0.2 - 3.3)	(1.5 - 13.6)
I	17.9	4.3	19.4	2.3	0.4	2.2
	(7.9 - 31.2)	(1.7 - 7.6)	(5.7 - 46.5)	(1.6 - 2.8)	(-0.5 - 1.3)	(1.6 - 3.5)
C	15.0	8.1	21.1	2.1	0.8	2.6
	(4.6 - 27.3)	(0.1 - 14.6)	(9.8 - 80.7)	(1.7 - 2.7)	(0.3 - 1.7)	(1.6 - 5.2)