Morphological evolution of the Venice lagoon: Evidence from the past and trend for the future

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1. Introduction

[2] The unchanneled portion of a shallow tidal basin usually consists of salt marshes, relatively elevated areas colonized by halophytic vegetation, and tidal flats, unvegetated areas characterized by lower elevations [e.g., Allen, 2000; Friedrichs and Perry, 2001; Marani et al., 2006]. Herein the term “tidal flat” is used in its broadest sense to include shallow subtidal flats, i.e., muddy platforms that do not emerge during ordinary low tide. This intertidal landscape is organized into a bimodal distribution of bottom elevations, with the two peaks corresponding to salt marshes and tidal flats, and few areas lying at intermediate elevations [Fagherazzi et al., 2006; Defina et al., 2007].

[3] Recently, a conceptual stability model has been developed [Fagherazzi et al., 2006] which explains the occurrence of such a bimodality. The model, which is here briefly summarized, is based on the analysis of wind-wave shear stress, which is the main factor responsible for sediment resuspension in the unchanneled portion of a shallow tidal basin [Anderson, 1972; Ward et al., 1984; Schoellhamer, 1995; Möller et al., 1999; Umgiesser et al., 2004; Carniello et al., 2005].

[4] Fagherazzi et al. [2006] assume, as a first approximation, that the fetch unlimited wave height for a prescribed wind speed can be evaluated by imposing the local equilibrium between wave energy input due to wind acting on the free surface, and wave energy dissipation due to bottom friction, breaking, and whitecapping. The energy balance condition allows one to compute the orbital velocity at the bottom, according to the linear theory, and thus the bed shear stress ($\tau_b$) due to waves. The relationship between bed shear stress and water depth, for any prescribed wind speed, is represented by a curve peaking at some intermediate water depth (Figure 1; explained further below). Fagherazzi et al. [2006] showed that wind speed weakly affects the depth at which the shear stress maximum occurs.

[5] The conceptual stability model (hereinafter referred to as the stability model) then describes the time evolution of bottom elevation, $Z_b$, referred to the mean sea level, using the Exner equation:

$$\frac{\partial Z_b}{\partial t} = (1-n)(D_S - E_S) - (1-n)R$$

(1)

where $n$ is porosity, $R$ is the rate of relative sea level rise, $D_S$ and $E_S$ are the local deposition and erosion rates.

[6] The stability model assumes that $(1-n)R \ll D_s - E_s$, thus neglecting, as a first approximation, the rate of relative sea level rise. The model further assumes that the rate of sediment erosion, $E_S$, is proportional to the difference between bottom shear stress ($\tau_b$) and the critical shear stress for sediment erosion ($\tau_{cr}$) [e.g., Mehta, 1984; Sanford and Mau, 2001]. Under such an assumption, the curve of Figure 1 is a proxy for bed erosion rate. The sediment deposition rate, $D_S$, includes the redeposition of the locally eroded sediments and the deposition of sediments advected from nearby areas (Figure 2).

[7] We define $E_{S\text{max}}$ as the maximum rate of erosion corresponding to the peak of the curve ($\tau_b = \tau_{\text{max}}$) in Figure 1. If the deposition rate $D_S$ exceeds the maximum erosion rate (i.e., $D_S > E_{S\text{max}}$) no equilibrium is possible and tidal flats shoal and eventually experience the transition to salt marshes.
Figure 1. The stability model arising from the wind-wave bed shear stress distribution as a function of bottom elevation $Z_b$ (referred to the mean sea level).

If $D_s < E_{s \text{max}}$ an equilibrium bed shear stress $\tau_{eq}$ exists such that deposition and erosion balances each other (i.e., points U and S in Figure 1). When $\tau_b > \tau_{eq}$ deposition exceeds erosion and, according to equation (1), the bottom evolves toward higher elevations. On the contrary, when $\tau_b < \tau_{eq}$ erosion exceeds deposition and the bottom elevation decreases (see arrows in Figure 1). Therefore, any point S along the right branch of the curve is a potential stable point while any point U on the left branch of the curve is an unstable point. The stable branch of the curve, characteristic of tidal flats, extends from the bottom elevation $Z_b = Z_{c2}$ (in fact, if $Z_b < Z_{c2}$ wave induced bottom shear stress becomes ineffective and any, even very small deposition causes the bottom to fill up), to $Z_b = Z_{\text{max}}$ corresponding to the peak of the curve. A stable equilibrium is also possible for $Z_b > Z_{c1}$, i.e., when the wave-induced bottom shear stress is again smaller than the critical shear stress. The latter range of elevations corresponds to salt marshes. It is worth noting that the stability model cannot explain this stable configuration as in very shallow water or partially dry areas the accretion dynamics are not significantly affected by waves. The main factors determining the final salt marsh elevation are sediment supply, organic production driven by vegetation encroachment and sediment compaction [e.g., Silvestri et al., 2005; Paarlberg et al., 2005; D’Alpaos et al., 2007]. Most of these factors are not included in the stability model which in fact focuses on the morphodynamic equilibrium of unvegetated tidal flats.

Figure 2. Schematic of the local sediment budget. $O$ and $I$ are the convective and diffusive sediment fluxes toward and from the neighborhood; $E_s$ and $D_s$ are the erosion and deposition rates, respectively.
sediments the adjacent tidal flats which, therefore, are able to maintain their original elevation (Figure 3). In the following phase (phase 2), because marshes have largely reduced their extension, the amount of sediment they can supply to tidal flats is no longer sufficient to balance the erosion affecting tidal flats. As a consequence, the average tidal flat elevation decreases (Figure 3).

The long-term evolution model agrees with bottom elevation density functions extracted from the 1901 and the present bathymetries of the central southern part of the Venice lagoon [Defina et al., 2007]. However, the time evolution of the lagoon morphology predicted by the model is nonlinear, and a further testing of the model strictly requires more than two data sets. In this work, the reliability of the long-term evolution model is tested through the analysis of the four available bathymetries of the Venice lagoon surveyed during the last century and provided by the Venice Water Authority (Figure 4).

At this point, it is of crucial importance to recall that (1) The stability model [Fagherazzi et al., 2006] focuses on the potential morphological equilibrium configurations within shallow microtidal basins and analyzes the equilibrium stability; (2) Defina et al. [2007] tested the stability model through the use of a numerical model and considered both the present and the 1901 bathymetries of the Venice lagoon; (3) Defina et al. [2007] also proposed a new long-term evolution model which describes the different phases experienced by a tidal basin toward a stable equilibrium both in aggradational and erosional conditions; and (4) the present study aims at testing the latter, long-term evolution model through the analysis of the available bathymetric data of the Venice lagoon.

The paper is organized as follows. Section 2 reports on data (the available bathymetries and their accuracy) and methods. Section 3 compares the results of the data analyses with the prediction of the long-term evolution model. On the basis of the present evolutionary trend, section 4 reports on a simple exercise aimed at inferring a reliable future configuration of the Venice lagoon. A set of conclusions closes the paper.

2. Methods and Data

The Venice lagoon, Italy, which is the subject of the current study, is a shallow microtidal basin characterized by...
a tidal range of about 1.0 m. Within the lagoon tidal currents produce shear stresses large enough to carry sediments into suspension only in the large channels in proximity of the three inlets, while sediment resuspension on tidal flats is mainly caused by shear stresses induced by wind waves [Carnielo et al., 2005]. Scirocco wind, from the southeast, provides the most frequent meteorological forcing. However, the geomorphologically dominant meteorological condition is provided by Bora wind, which blows from the northeast at a speed up to 30–40 m/s.

[17] In order to test the long-term evolution model the present work considers the available bathymetric data. The analyses of such data sets allowed us to build the bottom elevation density function for the entire lagoon of Venice, thus including the fetch limited areas. The deep channels, where bed shear stress is mainly due to tidal currents rather than waves, are removed from the analysis. The present data analysis actually includes all factors causing erosion, such as ship and boat wakes which, in the last few decades, have had as much impact as wind waves on the lagoon deterioration process [Consorzio Venezia Nuova-Technital, 2004, and references therein].

[18] From a morphological point of view, the Venice lagoon can be divided into two different parts. In the central southern lagoon, salt marshes are mainly distributed along the landward boundary (see Figure 4) and the Bora wind (i.e., the geomorphically dominant meteorological condition) is free to generate fetch unlimited wavefields. On the contrary, in the northern lagoon, because of the presence of salt marshes and islands distributed throughout the basin, the fetch is continuously interrupted and fetch unlimited conditions are rare. In addition, in the northern lagoon the path that suspended sediments must follow to reach the Lido inlet is, on average, much longer than paths to the Chioggia and the Malamocco inlets in the central southern lagoon; as a consequence, sediment loss through the inlets to the sea per unit basin area is comparably smaller. For these reasons we prefer to separately study the two parts of the lagoon.

[19] The first map of the lagoon reporting bottom elevation data dates back to 1809–1811 [Déniaux, 1811]. In this map the planimetric relief of the lagoon, i.e., the location and extent of salt marshes, tidal flats and the channel network, is rather precise but no elevation data are provided apart from the depth of the main channels, which were surveyed and recorded for navigation purposes. The 1811 map is then used, through a comparison with more recent bathymetries, only to assess the variation of salt marsh and tidal flat extent.

[20] The 1901 bathymetry (Figure 4a) is actually the first set of data we can use to determine the bed elevation density curve. Unfortunately such an analysis is accurate only for the central southern part of the lagoon. In fact, in 1901, wide embanked salt pits were present in the northern part of the lagoon which prevent a strict comparison with the succeeding configurations and only a rough estimation of average tidal flat bottom elevation is thus possible. The probability distribution of bottom elevations is then analyzed with reference to the bathymetries of the Venice lagoon surveyed in 1932, 1970, and 2003 (Figures 4b–4d), provided by the Venice Water Authority.

[21] Detailed information about data accuracy are available for the most recent bathymetry (2003): the standard error in bottom elevation data is ±5 cm for salt marshes, ±5 cm for subtidal flats and, ±10 cm for tidal channels [Consorzio Venezia Nuova-Technital, 2007]. The bathymetric survey was carried out using different techniques (multibeam, single beam, GPS, orthophoto restitution, direct topographic survey) in order to obtain precise results for each range of elevation. Such a methodology warrants that the minimum around mean sea level in the bimodal distribution of bottom elevation of shallow microtidal basins (also observed by Fagherazzi et al. [2006] and Defina et al. [2007]) is not biased by data collection techniques.

[22] The 1970 bathymetry was gathered by Theodolite on land and stadia rod on shallow flats and, in particular, the Venice Water Authority asserts that the 1970 subtidal flat elevations have an error of ±10 cm [Consorzio Venezia Nuova-Technital, 2007]. No error estimate is available for the 1901 and 1932 bathymetries. Nevertheless subtidal flats, especially at the beginning of the last century, were very shallow (with an average bottom elevation $Z_b \approx -0.5$ m asml) so that we can reasonably assume that subtidal flat elevations have an error smaller than about ±10 cm.

[23] The aforementioned bathymetric errors and the non-homogeneity of the surveys do not allow for a reliable point by point comparison of bottom elevations to evaluate the local bathymetric evolution. However, the present analysis averages data over wide areas (the central southern and northern part of the lagoon, respectively) thus smoothing out the local uncertainties and highlighting the global evolutionary trend.

[24] The comparison of the four available bathymetries must consider that during such a long period of time not only has the lagoon morphology changed, but the boundaries of the lagoon have changed as well. These changes include (1) areas filled up with sediments due to the temporary reintroduction of the Brenta river inside the lagoon during the second half of the 19th century. Such areas, belonging to the lagoon in the 1901 configuration, have been later classified as land (see Figure 4); (2) pond fisheries, uniformly distributed along the landward boundary of the lagoon, progressively embanked and thus isolated from the free propagation of the tide; (3) salt pits, located inside the lagoon at the beginning of the century, which became part of the lagoon as they fell into disuse and their embankments were removed at the beginning of 20th century; (4) restoration activities, which included salt marsh stabilization up to the construction of artificial salt marshes, promoted by the Venice Water Authority since the early 1990s. Therefore, for consistency, our analysis considers a single, common domain extent, which is the one corresponding to the 2003 lagoon and which is included in all previous configurations.

[25] The impact of relative sea level rise is here implicitly considered because all the bathymetries are referred to the mean Adriatic Sea level recorded when each survey was performed.

3. Results and Discussion

[26] The computed bottom elevation density functions of the central southern lagoon of Venice are shown in Figure 5a. The curve for the central southern lagoon in 1901 displays a peak in the frequency of tidal flat elevation approximately at $Z_b = -0.5 \, \text{m}$. During the 19th century (see Figures 4 and 5a)
large areas of the southern lagoon were encroached by salt marshes and, in accordance with the long-term evolution scheme, we deduce that (1) the tidal flat erosion phase (phase 2) had not started yet and (2) the bottom elevation $Z_b = -0.5$ m approximately corresponds to the critical tidal flat elevation $Z_{\text{max}}$.

However, at the beginning of the 20th century the construction of the jetties at the three inlets was completed; as a consequence, the flux of sediment out of the lagoon dramatically increased, enhancing the erosive trend [D’Alpaos and Martini, 2005; Tambroni and Seminara, 2006]. In the period 1901–1932, because of salt marsh deterioration, the first peak, which represents salt marsh areas, is reduced in amplitude, whereas the tidal flat peak is increased. In spite of their amplitude variation, the two peaks maintain the previous bottom elevations thus suggesting that sediments from the salt marsh deterioration process fed the adjoining tidal flats and counteracted their erosion.

The 1970 curve displays a further slight reduction of the salt marsh peak while the tidal flat peak shifts toward deeper bottom elevations. In the years between 1932 and 1970, the salt marsh regression reached a stage such that the amount of sediments provided by their deterioration was not sufficient to counteract the erosion of tidal flats which, in fact, deepened. The same trend, consisting of salt marsh reduction and tidal flat erosion, is displayed by the bathymetric changes during the period 1970–2003, consistently with the results of a recent study by Molinaroli et al. [2009].

The tidal flat peak, while shifting toward deeper bottom elevations, changes its amplitude suggesting that the erosion process was not uniform over the domain (see also Figure 4).

On the whole, the behavior of the four bottom elevation density curves for the central southern lagoon are similar to those predicted by the long-term evolution model.

We then extend the analysis to the northern part of the Venice lagoon (i.e., north of the city of Venice). Figure 5b shows the three bottom elevation density curves evaluated considering the 1932, 1970, and 2003 bathymetries. Similar to the central southern lagoon and consistent with the conceptual model, the bottom elevations are characterized by a bimodal distribution.

The comparison between Figures 5a and 5b shows that for the northern basin the range of unstable bottom elevations is smaller and the average tidal flat elevation in 1932 is slightly higher than the corresponding elevation for the central southern lagoon. This is due to the reduced fetch characterizing the northern lagoon, which shifts toward shallower depths the peak of the theoretical curve in the stability model (see Figure 1, inset). Moreover, the bottom elevation corresponding to the tidal flat peaks in 1970 and 2003 shows that the rate of deepening of tidal flats in the northern lagoon is slower compared to that in the central southern lagoon.

On the whole, it seems that both the northern and the central southern lagoon are still experiencing the tidal flat erosion phase (phase 2) but with two different speeds, and that, as a consequence of the ongoing loss of sediment, tidal flats will move toward a deeper stable equilibrium configuration.

Reasons for the differences between the two parts of the lagoon are manifold: (1) in fetch limited configurations the amplitude of the theoretical stability curve reduces (see Figure 1, inset), therefore, on average, the wave erosive capacity decreases; (2) the sediment supply from the watershed to the lagoon, even if small, on average mainly feeds the northern part of the lagoon; (3) in the northern lagoon the path that suspended sediments must follow to reach the Lido inlet is, on average, much longer than paths to the Chioggia and Malamocco inlets in the central southern lagoon. Therefore, the impact of the jetties at the Lido inlet, completed in 1892, only slightly affected sediment dynamics in the remote northern part of the lagoon.

All these factors suggest that, because in the northern lagoon the average sediment supply is greater and the global erosion rate is smaller than in the central southern lagoon, a tidal flat equilibrium may be achieved that is characterized by a depth smaller than 2 m–2.5 m, which is the depth predicted for the central southern lagoon by the stability model [Defina et al., 2007]. Such an observation agrees.
with the results obtained by Marani et al. [2007], who showed that an enhancement in the local deposition rate (i.e., in the local sediment concentration) leads to shallower tidal flat equilibrium.

The separate analysis of the northern and central southern lagoon enables us to appreciate the different evolutionary trend experienced by the two parts of the lagoon. We conventionally considered the city of Venice as the limit between the two parts. Close inspection of the maps in Figure 4 shows that the more intense erosive trend characterizing the central southern part of the lagoon seems to be “spreading” to the northern part by propagating in the area landward the city of Venice. This erosive trend can be ascribed partly to the boat traffic along the Tessera channel, connecting the city of Venice to the Marco Polo international airport, which dramatically increased in the last few decades.

We can conclude that the reconstructed bottom elevation density curves extending over one century, strongly suggest that the long-term evolution model is appropriate for both the central southern and northern lagoon of Venice.

The long-term evolution model is also confirmed by Figure 6. Figure 6 (top) shows the variation of salt marsh extent during the last two centuries both for the northern and the central southern lagoon; note that in the plot we included salt marsh extent obtained from the 1811 Déniaix map.

We distinguish a slow salt marsh regression during the 19th century, which can possibly be ascribed to the reduction in sediment supply due to the diversion process of the Brenta river started by the Venetians in 1457 and completed in 1896 (see Figure 4). A speed up of the regression process emerges during the beginning of the last century, just after the construction of the jetties at the three inlets (Malamocco was completed in 1872, Lido in 1892, Chioggia in 1934).

At present, some salt marshes still survive, covering approximately 5 ~ 10% of the total lagoon. In the central southern basin, the residual marshes are located along the landward boundary of the lagoon sheltered from wind and boat waves. The moderate increase in salt marsh area computed for the northern lagoon in the last few decades (Figure 6) can be ascribed partly to the inaccuracy of bathymetric data, and partly to the restoration activities (i.e., salt marsh stabilization and reconstruction carried out by the Venice Water Authority since the 1990s).

Figure 6 (bottom) shows the spatially averaged bottom elevation of tidal flats as a function of time, computed separately for the central southern part and the northern part of the lagoon. On one hand, it gives a further evidence of the different evolution behavior characterizing the two parts of the tidal basin as discussed above: the different slope of the curves from 1932 to present confirms that the still ongoing tidal flat erosion is more intense in the central southern lagoon than in the northern part.

On the other hand, the comparison between Figures 6 (top) and 6 (bottom) shows that the salt marsh erosion process develops before the tidal flat deepening and, in accordance with the long-term evolution model, the tidal flat erosion phase (phase 2) develops rapidly only after the salt marsh degradation phase (phase 1) is nearly completed.

Both Defina et al. [2007] and Marani et al. [2007] showed that a moderate sea level rise, which does not overtake deposition, will merely adjust the tidal flat attracting point (S point in Figure 1) toward positions characterized by a smaller bed shear stress. However, at present, the sediment supplied to the lagoon of Venice is rather small and the impact of sea level rise on the lagoon evolution is not negligible.

On averaging equation (1) over a wide portion of the lagoon, Ω (e.g., over the central southern or northern lagoon, or over the whole lagoon), we obtain (see Figure 2)

\[
\frac{\partial \langle Z_0 \rangle}{\partial t} (1 - n) = \frac{I - O}{\Omega} - (1 - n)R
\]

where \(\langle Z_0 \rangle\) is the spatially averaged bottom elevation, \(I\) and \(O\) are total sediment input (organic and inorganic) and total sediment output, respectively.

The current sediment supply from the watershed draining into the central southern lagoon is negligibly small (i.e., \(I \approx 0\)), organic sediment production, averaged over the basin, is approximately 0.2 mm/year [Day et al., 1999], and the rate of relative sea level rise (averaged over the last century) is about \(R \approx 3.5\) mm/year [IPCC, 2001; Carbognin
The average elevations of salt marshes and tidal flats in 1901, 1932, 1970, and 2003, are also shown in Figure 7. [49] The rate of relative sea level rise experienced by the Venice lagoon during the last century is rather constant until the beginning of the 1950s. A speed up is observed during the 1950s and 1960s as a result of the subsidence caused by the increased groundwater extraction. Finally, during the last 30 years, the rate of relative sea level rise sensibly reduces tending toward the rate which characterizes the beginning of the century. Figure 7 distinguishes the elevation of salt marshes and tidal flats in the northern and in the central southern part of the lagoon. It emerges that salt marshes are able to keep pace with the relative sea level rise largely because of the organic production and the sediment trapping due to the presence of vegetation [Mudd et al., 2004; D’Alpaos et al., 2006; Marani et al., 2007]. Incidentally, we also observe that the salt marsh elevation in the northern lagoon is lower than the salt marsh elevation in the central southern lagoon by few centimeters. It is also interesting to observe that the average salt marsh elevation in 1970 is the lowest among the four configurations: this can be due to the speed up in the rate of relative sea level rise occurred during the 1950s and the 1960s and to the need of an adaptation time for salt marshes to follow the mean sea level variation.

[50] On the contrary, tidal flats are not able to keep pace with the relative sea level rise as the amount of sediment supplied to tidal flats, mainly coming from the salt marsh deterioration process, is not sufficient. In fact, Figure 7 shows that tidal flats in the northern lagoon have kept approximately a constant (or weakly decreasing) absolute elevation (i.e., \( I - \Omega \approx 0 \)) but, due to sea level rise, their relative depth has slowly increased.

[51] In the central southern lagoon, the absolute elevation of tidal flats weakly decreases until the early 1970s (the average rate of deepening is approximately 1.0 mm/year), while a sharp increase in the rate of deepening occurs during the last thirty years. Such an increase is related to the excavation of the Malamocco-Marghera navigable channel, completed in 1969, which highly modified the hydrodynamics of the central part of the lagoon, increasing the advection of the suspended sediments toward the sea through the Malamocco inlet. In addition, the very intensive ship traffic (mainly oil tanker) along the Malamocco-Marghera Channel, and the daily ship maneuvers in the nearby of S. Leonardo harbor trigger heavy erosion processes. The comparison of the bottom elevations close to S. Leonardo harbor in Figures 4c and 4d confirms such a localized erosion which is superimposed upon to the general deepening trend. As such, we conclude that, at present, the Venice lagoon is not at equilibrium and it is experiencing an erosive trend.

[52] Analysis of the bottom elevation trend, as recorded in the last century, further suggests an improvement to the long-term evolution model for strongly erosive conditions (i.e., when \( I - \Omega < \Omega(1 - n)R \)). The model by Defina et al. [2007] implicitly assumes that \( I - \Omega > \Omega(1 - n)R \); in this case the tidal flats can reach an equilibrium depth which, in the worst conditions, (i.e., \( I - \Omega = \Omega(1 - n)R \)) corresponds to the limiting depth \( Z_{2} \).

[53] In strongly erosive conditions, because the erosion process is not uniform over the entire basin, phase 2 (i.e.,

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**Figure 7.** Absolute average elevation of salt marshes and tidal flats in northern (white bars) and central southern (gray bars) lagoon in 1901, 1932, 1970, and 2003. Also plotted is the mean sea level in the Venice lagoon starting from 1900 recorded at the “Punta della Salute” (PS) gauge, and the variation of the datum occurred in the 1942 (IGM datum). From equation (2) we have that, even if we stop the output of sediment (i.e., we set \( O = 0 \)), the central southern lagoon will keep on deepening relative to the mean sea level. Few salt marshes and tidal flats will survive where local morphodynamic conditions promote a reduction of the erosion rate and an enhancement of the deposition rate but, on the whole, the bottom of the lagoon will inexorably sink.

[46] On the contrary, in the northern lagoon, the sediment supply from the watershed and the organic sediment production overtake the sediment output through the Lido inlet. In this case (i.e., \( I \geq O \)) the sediment budget given by the right hand side of equation (2) suggests that a morphodynamic equilibrium can be reached under the current rate of relative sea level rise.

[47] The bathymetric evolution can be analyzed also in terms of the absolute elevations referred to a fixed datum thus providing a different point of view to consider the issues at hand.

[48] Figure 7 shows the variation of the relative mean sea level in the Venice lagoon starting from the beginning of the last century as recorded at the “Punta della Salute” tide gauge [Ferla et al., 2006; Battistin and Canestrelli, 2006].
present, most of the lagoon is experiencing the erosive process and inexorably evolve toward a bay. Figure 4 suggests that, at formally at the rate given by (2) (phase 2c), and the lagoon flats is no longer available), tidal flats start to deepen uni-

sion of the deepest areas. An example of this behavior is given because of the sediment supplied from the neighboring tidal flat erosion phase) can be split into three subsequent steps. We can distinguish an initial erosion of tidal flats toward the limiting depth \( Z_{c2} \) (phase 2a). When the deepest tidal flats locally reach this limiting depth, the erosion process, with respect to the mean sea level, temporary stops (phase 2b). This temporary equilibrium condition is maintained because of the sediment supplied from the neighboring shallower tidal flats which are eroding. During this phase we have, locally, \( I - O = f(t - n) R \) and the erosion process develops horizontally through a progressive expansion of the deepest areas. An example of this behavior is given by the evolutionary trend of the “Fondi dei Sette Morti” area in the middle of the central southern lagoon (Figure 4). Once the limiting depth has extended over most of the basin (i.e., sediment from the neighboring tidal flats is no longer available), tidal flats start to deepen uniformly at the rate given by (2) (phase 2c), and the lagoon inexorably evolve toward a bay. Figure 4 suggests that, at present, most of the lagoon is experiencing the erosive phase 2a. However, in some areas (e.g., Fondi dei Sette Morti) phase 2b has been developing since the early 1900s.

4. Prediction for the Future of the Venice Lagoon

[54] Prediction of the long-term evolution of a morphologically irregular tidal basin such as the Venice lagoon is an extremely demanding task: besides the lack of accuracy which still affects present morphodynamic models in predicting both vertical and planimetric changes, a reliable description of the morphological evolution requires very refined computational grids and very detailed models for sediment transport processes which, at present, require an unacceptable computational effort. In the context at hand we carry out an exercise aimed at depicting a possible reliable future configuration of the Venice lagoon.

[55] It should be emphasized that such an exercise is not aimed at addressing in detail all the processes and activities responsible for the morphological evolution of the lagoon but rather to infer a reliable future configuration on the basis of the observed present evolutionary trend.

[56] On the basis of the more recent bathymetric data, we evaluate the local rate of bottom elevation change within the lagoon. The analysis is carried out considering bottom elevations relative to the mean sea level, \( Z_{b} \), to simultaneously account for the effects of both erosion and relative sea level rise. Moreover we focus on tidal flat areas and exclude from the analysis salt marshes and tidal channels.

[57] In order to smooth out the bathymetric inaccuracies related to the survey techniques the local rate of change of bottom elevation for tidal flats, \( dZ_{b}/dt \), is averaged over a triangular grid of 1225 elements having an average side of approximately 900m (see Figure 8a). Figure 8a shows the computed rate of bottom elevation change, which spans from \(-3\) cm/year (erosion) to 1 cm/year (deposition). It is worth observing that tidal flats with a bottom elevation close to the deepest depth predicted by the stability model \((-2 m \sim -2.5 \text{ m amsl})\), i.e., Fondi dei Sette Morti, have a negligible \( dZ_{b}/dt \) thus confirming the temporary equilibrium of these areas (phase 2b).

[58] The northern lagoon displays, on average, a very low erosion rate. The same condition applies to the areas adjacent to the landward boundary of the central southern lagoon, sheltered from wave action by the salt marshes aligned parallel to the land. At these locations, a moderate deposition rate is also observed.

[59] High erosion rates are instead observed in the central southern part of the lagoon and close to the city of Venice: in particular very high erosion rates affect the area located in the proximity of the S. Leonardo harbor (Figure 8a). As previously discussed, this occurrence is mainly caused by the heavy ship traffic which is not accounted for by the stability model.

[60] Assuming that the computed rate of change of bottom elevation will continue unchanged in the next few decades, we construct the configuration of the Venice lagoon in 2050 (Figure 8c), starting from the 2003 bathymetry (Figure 8b). A temporal horizon of a few decades is here considered in order to ensure that the linear extrapolation, based on the computed rate of change of bottom elevation, is reasonably acceptable.
Wake energy. The analysis confirmed (1) the existence of two stable configurations in shallow tidal basins: vegetated salt marshes and submerged tidal flats; (2) that the long-term degradation of the lagoon morphology consists of two steps: an initial salt marsh deterioration phase (phase 1) followed by a tidal flat erosion phase (phase 2); (3) that phase 2 can be further split into three sequential steps. In particular one can distinguish an initial tidal flat erosion toward the limiting depth $Z_{c}$ predicted by the stability model (phase 2a); a temporary equilibrium condition characterized by tidal flats, with bottom elevation equal to the limiting depth, which progressively expands horizontally (phase 2b); a final uniform tidal flat deepening (phase 2b) which inexorably drives the lagoon to evolve into a bay.

The separate analysis of the northern and central southern lagoon enables us to appreciate the different evolutionary trends experienced by the two parts of the lagoon. The erosive trend experienced by the central southern lagoon is faster compared to that in the northern lagoon. Such a difference is confirmed not only by the analysis of bottom elevation density curves, but also by the inspection of the temporal evolution of the spatially averaged elevation of tidal flats and the variation of salt marsh extent.

The northern part of the lagoon has been experiencing a slower erosive trend compared to the central southern lagoon for the following reasons: (1) reduced erosion capacity because of the fetch limited conditions characterizing this part of the lagoon; (2) much longer path that suspended sediments must follow to reach the sea (i.e., greater probability of redeposition); (3) slightly greater sediment supply from the watershed.

Finally, under the assumption that the present rate of evolution will not vary in the next few decades, we estimate a possible reliable configuration of the Venice lagoon in 2050 by linear extrapolation of present bottom elevations and we show that this extrapolation agrees with the behavior predicted by the long-term evolution model.

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References


Consorzio Venezia Nuova-Technital (2004), Studio C.2.10:III: Attività di aggiornamento del piano degli interventi per il recupero morfologico in applicazione della delibera del Consiglio dei Ministri del 15.03.01, Studi di base, linee guida e proposte di intervento del piano morfologico: Parte A – Analisi del Sistema 127 pp., technical report, Magistrato alle Acque di Venezia, Venice, Italy.

Consorzio Venezia Nuova-Technital (2007), Studio C.2.10:III: Attività di aggiornamento del piano degli interventi per il recupero morfologico in...
application della delibera del Consiglio dei Ministri del 15.03.01, Studi integrative, Rapporto finale—Modello morfologico a maglia curvilinea: Relazione di sintesi, 129 pp., technical report, Magistrato alle Acque di Venezia, Venezia, Italy.


Déniaux, A. (1811), Carta Topografica Idrografica Militare della Laguna di Venezia e del Litorale compreso tra l’Adige e la Piave eseguita sotto i Ministri de’ Signori Generali Divisionari Conti Caiffarelli e Fontanelli negli anni 1809–10 e 11, Map, 36 sheets, scale 1:15,000, Biblioteca Querini Stampalia - Castello 5252, 30122 Venice, Italy.


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