Sediment dynamics in shallow tidal basins: In situ observations, satellite retrievals, and numerical modeling in the Venice Lagoon

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Abstract The morphological evolution of shallow tidal systems strongly depends on gradients in transport that control sediment erosion and deposition. A spatially refined quantitative description of suspended sediment patterns and dynamics is therefore a key requirement to address issues connected with dynamical trends, responses, and conservation of these systems. Here we use a combination of numerical models of sediment transport dynamics, high temporal resolution point observations, and high spatial resolution remote sensing data to overcome the intrinsic limitations of traditional monitoring approaches and to establish the robustness of numerical models in reproducing space-time suspended sediment concentration (SSC) patterns. The comparison of SSC distributions in the Venice Lagoon (Italy) computed with a numerical model with SSC retrievals from remote sensing data allows us to define the ability of the model to properly describe spatial patterns and gradients in the SSC fields. The use of point observations similarly allows us to constrain the model temporally, thus leading to a complete space-time evaluation of model abilities. Our results highlight the fundamental control exerted on sediment transport intensity and patterns by the sheltering effect associated with artificial and natural intertidal landforms. Furthermore, we show how the stabilizing effect of benthic vegetation is a main control of sediment dynamics at the system scale, confirming a notion previously established in the laboratory or at small field scales.

1. Introduction

Shallow water coastal environments worldwide are subject to increased human pressure and are experiencing dramatic morphological and ecological degradation. Widespread issues are increased pollution of water and sediments, decreasing sediment supply, and increasing rates of relative sea level rise related to climatic change [e.g., Schneider, 1997; Day et al., 2007; Perillo et al., 2009; Kennish and Paerl, 2010]. In spite of these alarming trends, methods for monitoring and predicting water quality and morphology in these environments at the proper scale are still lacking.

Suspended sediment transport is one of the key processes driving the morphological evolution of lagoons and estuaries and is strongly influenced by interactions between physical and biological processes [Morris et al., 2002; Kirwan and Murray, 2007; D’Alpaos et al., 2007; Marani et al., 2007, 2013; Mudd et al., 2009; Perillo et al., 2009; D’Alpaos, 2011; Temmerman et al., 2012]. The fate of such environments, never in static equilibrium, is crucially dependent on a subtle balance between sediment inflow and outflow, sediment resuspension and reworking driven by wind waves and tidal currents, organic soil production and relative sea level rise [Carniello et al., 2009; Kirwan et al., 2010; Marani et al., 2007, 2010; D’Alpaos et al., 2011]. The distribution of suspended sediment concentration (SSC) in space and time plays a major role in determining erosion and deposition patterns and is thus a key factor in the monitoring and management of the morphodynamic evolution of intertidal systems.

SSC monitoring is typically based on in situ point measurements [e.g., Wren et al., 2000], providing either a single value of SSC at one instant (e.g., by water sampling) or a series of SSC measurements (e.g., by acoustic or optical backscatter sensors). Spatially distributed surveys at a limited scale (few tens of meters) can be obtained using, e.g., Acoustic Doppler Current Profilers (ADCPs) which measure velocity profiles within the water column using the Doppler shift principle. In addition, ADCPs can also be used to measure bed load velocity and estimate SSC [Reichel and Nachtnebel, 1994; Gartner, 2004; Kostaschuk et al., 2005; Wall et al., 2006].
These types of data can be used directly to investigate key morphological processes and are commonly used to calibrate and test sediment transport models [e.g., Umgiesser et al., 2006; Neumeier et al., 2008; Defendi et al., 2010; Carniello et al., 2012].

Sediment erosion and deposition, and the related morphological evolution of coastal areas and intertidal systems, depend on gradients in transport. A spatially refined description of SSC patterns is therefore essential in investigating the evolutionary trend of a tidal basin. However, usual point observations are entirely inadequate to evaluate our ability to accurately model spatial SSC gradients and, hence, the associated deposition/erosion patterns, particularly in highly heterogeneous environments such as lagoons and estuaries.

Remote sensing techniques can be used to obtain information about several water quality parameters, including SSC, and may provide the much-needed access to a wide range of spatial scales. The estimation of SSC values from remote sensing is quite developed in the case of deep waters, particularly in the open ocean or deep coastal areas, where contributions of the bottom topography to the remote sensing signal are low [Ruhl et al., 2001; Durand et al., 2002; Babin et al., 2003a; Ouillon et al., 2004; Binding et al., 2005]. Remote sensing estimates of SSC in shallow lagoons is not trivial because the reflected signal from suspended sediments largely overlaps with that generated by the bottom and also because the variability of SSC patterns and bottom features occurs on spatial scales which are much smaller than the resolution of the sensors currently available for ocean color retrieval (e.g., Sea-viewing Wide Field-of-view Sensor, Moderate Resolution Imaging Spectroradiometer-Aqua, Medium-Resolution Imaging Spectrometer, etc.). Finally, these sensors have been designed to monitor the optical properties of marine oligotrophic waters, rather than the more complex case of waters in intertidal environments [Qin et al., 2007; Odermatt et al., 2012]. Hyperion (Earth Observing-1 satellite) and Compact High Resolution Imaging Spectrometer (European Space Agency's Proba-1 mission) are currently the only sensors offering an adequate spatial resolution, combined with high spectral and radiometric resolutions, which have been successfully applied to coastal areas and lagoons. However, the wide applicability of these sensors is affected by a limited historical archive and by the need of ordering in advance the data to be acquired. Until a new generation of data will be available, methods to optimally extract information from existing satellite multispectral sensors with large existing historical archives (Landsat thematic mapper and Enhanced Thematic Mapper (ETM +) or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)) should be used.

Using data acquired by sensors mounted on the Landsat and ASTER satellite families, Volpe et al. [2011] recently applied a physically based, simplified Radiative Transfer model [Lee et al., 1998, 1999] (hereafter RT model) for the retrieval of SSC in shallow domains. The model was applied to the Venice Lagoon, and the coefficients were specifically calibrated and validated for this environment. An assessment of the spatial uncertainties in the estimation of the SSC was also provided. The choice of the study site was dictated by the fact that the Venice Lagoon is a worldwide famous example of tidal basin threatened by an intense anthropogenic pressure and by the possibility of taking advantage of a network of multiparametric probes that have been active for a long period of time. In the present study the RT model is used to obtain SSC maps from satellite images of the Venice Lagoon captured during intense storms. These maps are then used to test the ability of a numerical model, previously calibrated using only in situ point observations [Carniello et al., 2012], to describe the spatial variability in the SSC. The combined use of remote sensing and numerical modeling allows us to quantify, at the whole-system scale, the stabilizing effects of benthic vegetation and the sheltering effect and fetch interruption provided by islands and artificial structures. While the potential role of these sediment stabilization mechanisms was previously known from laboratory and limited-scale field studies, we can here fully quantify their large-scale implications.

2. Materials and Methods

2.1. The Numerical Model

The numerical model is composed of three modules. The first two modules are the hydrodynamic module and the wind wave module and make up the WWTM (wind wave tidal model) [see Carniello et al., 2011]. The third module, STABEM, is the sediment transport and bed evolution module [Carniello et al., 2012].
The hydrodynamic module solves the two-dimensional shallow water equations adapted to deal with flooding and drying in very irregular domains. The equations are solved using a semi-implicit staggered finite element method based on Galerkin’s approach. We refer the reader to Defina [2000] and D’Alpaos and Defina [2007] for a detailed description of the hydrodynamic model.

The wind wave model uses the water levels provided by the hydrodynamic model to compute the wave group celerity and to assess the wave processes affected by flow depth (e.g., energy dissipation by friction and wave breaking). The wind wave model solves the wave action conservation equation parameterized using the zero-order moment of the wave action spectrum in the frequency domain [Holthuijsen et al., 1989]. The spatial and temporal variations of the wave period are estimated with an empirical correlation function, which relates the mean peak wave period to the local wind speed and water depth [Young and Verhagen, 1996; Breugem and Holthuijsen, 2007; Carniello et al., 2011]. The WWTM also accounts for the spatial variability of the wind field adopting the interpolation technique of the available wind data proposed by Brocchini et al. [1995], which provides an improvement of the standard and long-used technique in meteorological data interpolation proposed by Cressman [1959]. The WWTM was widely tested by comparing its results to hydrodynamic and wind wave data collected at different tidal basins (e.g., Carniello et al. [2011] for the Venice Lagoon and Mariotti et al. [2010] for a system of lagoons at the Virginia Coast Reserve, USA). We refer the reader to Carniello et al. [2011] for a detailed description of the wind wave tidal model.

STABEM is based on the simultaneous solution of the advection diffusion equation and Exner’s equation and computes sediment resuspension and redistribution within the domain forced by wind waves and tidal currents. The model uses the approach suggested by Soulsby [1997] to compute the total bottom shear stress, thus accounting for the nonlinear wave-current interaction. Accordingly, the total bottom shear stress producing sediment resuspension, due to the combined action of tidal currents and wind waves, is enhanced beyond the sum of the two contributions. Because in shallow tidal basins resuspension events occur periodically and are usually characterized by bottom shear stresses that slightly exceed the critical shear stress for erosion, the model considers an original stochastic approach, similar to that suggested by Grass [1970], to correctly reproduce the near-threshold conditions for sediment entrainment. Following this stochastic approach, both the total bottom shear stress ($\tau_b$) and the critical shear stress for erosion ($\tau_c$) are treated as random variables characterized by a lognormal distribution, and the erosion rate is assumed to depend on the probability that $\tau_b$ exceeds $\tau_c$. This approach significantly improves the ability of the numerical model to reproduce the gradually varying transition between no sediment motion and fully developed entrainment [Carniello et al., 2012].

When modeling sediment transport and bed evolution in tidal environments, it is crucial to consider both cohesive and noncohesive sediment and the behavior of their mixtures. Accordingly, STABEM uses two size classes of sediments (noncohesive sand and cohesive mud, sum of clay and silt) to describe the bed composition, the transition between noncohesive and cohesive behavior of the mixture being determined by the mud content. The use of a sediment mixture requires a reliable reconstruction of the initial configuration of the bed composition, which is a difficult and site-specific task. We note that available field data are, in most cases, limited as compared to the spatial variability of bed composition, thus preventing the use of standard interpolation techniques. A possible approach to overcome this problem and reconstruct a reliable initial bed composition, when data are lacking or insufficient, is to perform long-term simulations starting from an approximate distribution of bed sediment composition and letting it evolve while maintaining the bathymetry fixed [e.g., Van der Wegen et al., 2010]. A different approach would be to relate the local bed composition to some morphological characteristics of the domain. The latter approach is used here for the specific case of the Venice Lagoon, where a reliable relationship between mean grain size and both the local bottom elevation and the distance from the nearest inlet was found [Carniello et al., 2012].

STABEM was calibrated and tested by comparing the computed SSC under different meteorological conditions and tidal forcing to a set of turbidity data collected at different stations (Seapoint Turbidity Meter, operating at 880 nm, monitoring with a half-hourly temporal resolution several key water quality parameters) distributed throughout the Venice Lagoon and spanning SSC values between 0 mg/l and 200 mg/l. Values of both the Percentage Model Bias and the Scatter Index showed a very good agreement between observed and modeled SSC values in all the considered meteorological conditions and, in particular, during intense
Bora wind events. We refer the reader to Carniello et al. [2012] for a detailed description of STABEM and of its calibration and testing.

### 2.2. The Radiative Transfer Model

The physically based estimation of the SSC spatial distribution from the analysis of satellite images was performed using a simplified RT model [Lee et al., 1998, 1999; Volpe et al., 2011] which links the directional remote sensing reflectance in the nadir direction (at a fixed wavelength of interest, \( \lambda \)) to the local turbidity within the water column. The RT model is “simplified” in the sense that it seeks a balance between a complete description of the underwater light field, which involves a large number of optical parameters of difficult evaluation, and a simpler radiative transfer formulation that uses a small number of easily identifiable absorption and scattering parameters [see Volpe et al., 2011]. The modeled remote sensing reflectance, equated to that obtained from remote sensing observations, is a function of the water depth, of the properties of pure water and water constituents and their concentrations, and of the optical properties of the bottom.

For a complete description of the model characteristics we refer the reader to Volpe et al. [2011]. It is, however, worth mentioning here that water body absorption and backscattering are influenced by the concentration and properties (e.g., the grain size distribution) of inorganic suspended sediments, the concentration of chlorophylls, and the presence of dissolved organic matter that affects water optical properties, also called “yellow substances”. The influence of these factors strongly depends on the optical wavelength, \( \lambda \), considered. The RT model used, consistent with previous literature [e.g., Petzold, 1972; Gallegos and Correll, 1990; Ferrari and Tassan, 1991; Li et al., 2003; Babin et al., 2003a, 2003b; Binding et al., 2005; Bowers and Binding, 2006], considers the value of remote sensing reflectance at \( \lambda = 650 \) nm, where the sensitivity to inorganic suspended sediment concentration is high, while effects due to chlorophyll and organic particles are limited [e.g., Mobley, 2004].

The total absorption coefficient is the sum of the absorption coefficients of pure water, inorganic particles, phytoplankton, and yellow substances. In particular, the absorption coefficient of inorganic particles is assumed to be a linear function of the SSC as proposed in Babin et al. [2003b]. Because the proportionality coefficient of the linear relationship strongly depends on the local sediment characteristics, it must be determined by calibration, while the choice of the absorption coefficient of pure water, phytoplankton, and yellow substances for the case of the Venice Lagoon are discussed in detail in Volpe et al. [2011]. A set of 13 multispectral satellite images was used to match field observations for the calibration and validation of the RT model. Field observations come from the same set of multiparametric probes used for the calibration of STABEM. Among the available satellite images acquired by different sensors (Landsat, ASTER, and Advanced Land Observation Satellite (ALOS)), only cloud-free acquisitions were selected in order to minimize errors due to heterogeneous atmospheric conditions. The calibration procedure of the RT model used field data characterized by SSC values in the range 0–130 mg/l.

In turbid waters, the scattering by inorganic particles dominates over other scattering sources which can, therefore, be neglected [Pope and Fry, 1997; Binding et al., 2005; Bowers and Binding, 2006]. As for the absorption coefficient, the total scattering coefficient by inorganic particles is assumed to be a linear function of the SSC [Babin et al., 2003a] and the proportionality coefficient of the linear relationship is determined by calibration.

The bottom albedo is a function of the type of bottom sediment and of the possible presence of vegetation and/or benthic organisms. A sensitivity analysis of the SSC retrieved by the RT model on the basis of bottom albedo within a range consistent with observations was performed by Volpe et al. [2011]. Bottom albedo was found to be important when the water depth is low and/or when the turbidity is low, but it is not usually known in a spatially distributed manner and may be time dependent (e.g., due to vegetation, algal, and microphytobenthos dynamics). The results of the sensitivity analysis allowed us to conclude that the bottom albedo does not significantly affect the SSC estimation for moderate to large turbidity (greater than about 30 FTU) and water depth greater than about 1.0 m [see Volpe et al., 2011, Figure 3].

### 2.3. Application to the Venice Lagoon

The numerical model (WWTM + STABEM) and the RT model were applied to the case study of the Venice Lagoon to compare reconstructed SSC maps obtained through STABEM with those retrieved from satellite remote sensing.
The Venice Lagoon is a ~550 km² shallow basin in the northeastern Italy connected to the Adriatic Sea by the three inlets of Lido, Malamocco, and Chioggia (Figure 1). The Lagoon is characterized by an average water depth of about 1.1 m and a maximum tidal range of about 1.5 m, with a main period of about 12 h. The hydrodynamics of the Lagoon is highly influenced by meteorological forcing. Many studies have demonstrated that the net loss of fine sediment and the related erosive trend which affect the Venice Lagoon are mainly driven by wind waves, which erode tidal and subtidal flats, and tidal currents, which drive suspended sediments out to the sea through the three inlets [e.g., Martini et al., 2004; Carniello et al., 2009; Molinaroli et al., 2009].

In the present study the RT model was used to produce maps of SSC from the available satellite images captured during intense Bora wind events: Bora is the most intense wind blowing from northeast, generating the highest waves within the Venice Lagoon and producing the most significant resuspension events. The selection of significant satellite images to be processed with the RT model encountered a number of difficulties: (i) sensors have a fixed revisit period (e.g., Landsat = 16 days, ASTER = 16 days, and ALOS = 46 days) and therefore only two or fewer images per month were available; (ii) events characterized by moderate to intense wind speed are not very frequent and rarely last more than 1 day, such that the probability of an acquisition during a resuspension event is quite low; and (iii) intense meteorological events are typically characterized by cloudy conditions, which prevent the acquisition of useful images.

For these reasons only two images were selected and analyzed: one Landsat 7 (pixel size 30 m) image acquired at 10:30 A.M. on 8 December 2001 and one Landsat 7 image acquired at 11:00 A.M. on 11 December 2005. Both acquisitions corresponded to significant resuspension events characterized by high Bora wind conditions exceeding the threshold value for sediment resuspension which can be assumed to be about 5 m/s for the specific case of the Venice Lagoon [Marani et al., 2010]. The first event (December 2001, Figure 2a) is a 2 day long wind event (the image was collected about 12 h after the event started) with an average wind speed of about 12 m/s in the central-southern part of the lagoon and about 6 m/s in the northern part. The second event (December 2005, Figure 2b) is characterized by a longer and more constant wind condition, lasting about 60 h (the image was collected about 48 h after the beginning; average wind speed of 13.5 m/s in the central southern part of the lagoon and about 8 m/s in the northern part). Wind velocities recorded at two different stations located in the southern (station W1) and in the northern (station W2) part of the lagoon (see Figure 1) are plotted in Figure 2. They clearly show the spatial nonuniformity of wind climate over the basin, especially when the highest wind velocities occur, and confirm the importance of accounting for the spatial variability in the wind field in order to accurately predict the wave-induced sediment resuspension.

A further important aspect to be considered when studying the spatial variability of SSC is the stabilizing effect of benthic vegetation, which shelters the bed from the action of currents and from wave-induced

![Figure 1. The Venice Lagoon bathymetry. Circles mark the position of the turbidity probes used to calibrate and test the sediment transport model (STABEM) and the radiative transfer (RT) model. Diamonds indicate the position of two of the anemometric stations (W1: "Diga Sud Chioggia" and W2: "Saline") used to force the WWTM (not all the stations considered for interpolating the wind field are reported in the figure for sake of clarity).](image-url)
bottom shear stress and increases the critical threshold for erosion through root reinforcement. We used available maps of the spatial distribution of benthic vegetation within the lagoon of Venice to account for this twofold effect of vegetation [Silvestri, 2004, 2008]. Because available vegetation maps and selected meteorological events are not simultaneous, the vegetation map that was temporally closest to the simulated event was selected for each numerical simulation. For the first event (December 2001) we thus used the vegetation cover obtained from a Landsat 7 ETM + acquisition of 14 September 2002 [Silvestri, 2004] (Figure 3a). For the second event (December 2005) we used the vegetation distribution mapped from a SPOT-5 acquisition of 2 September 2005 [Silvestri, 2008] (Figure 3b). Initial comparisons of computed and retrieved SSC distributions indicated the need to account for the stabilizing effect of benthic vegetation. It is worthwhile noting that quantifying the stabilizing effect of benthic vegetation at the scale of the entire basin is quite a difficult task. Different vegetation species (in the Venice Lagoon the most widespread phanerogams are Zostera marina and Cymodocea nodosa; see Figure 3) and macroalgae (Ulva rigida), due to their specific biophysical characteristics (presence or absence of a root apparatus, canopy stiffness, and density of colonization), affect in different ways both the local hydrodynamics and bed strength [Nepf and Vivoni, 2000; Romano et al., 2003; Venier et al., 2012]. In addition, their spatial distribution is strongly influenced by seasonal weather variations, environmental factors, and competition among species [Curiel et al., 2004; Rismondo et al., 2005; Temmerman et al., 2007; Marani et al., 2013].

Due to the lack of information on the actual specific distribution of different species at the time of the considered storm events (e.g., the images used to retrieve the vegetation maps were not simultaneous with the storm events also because the high turbidity would have prevented an accurate recognition process), the stabilizing effect of benthic vegetation was modeled in STABEM by setting to zero the sediment resuspension flux in the elements of the computational domain where vegetation is present [Carniello et al., 2011]. Such a simplified approach explores the maximum stabilization potential associated with submerged vegetation. While results are quite coherent with remote sensing estimates, this procedure is adopted to emphasize the importance of the process, and further, more detailed, parameterizations can be developed using a wider set of remote sensing data.
3. Results and Discussion

Figure 4 compares the instantaneous spatial distribution of the SSC obtained from the Landsat data acquired on 8 December 2001 at 10:30 A.M. (Figure 4a) with the map, referred to the same instant, provided by the numerical model STABEM when the stabilizing effect of the submerged vegetation is neglected (Figure 4b) and when it is accounted for (Figure 4c). As stated above, bottom albedo significantly affects satellite-retrieved SSC when the water depth is very shallow (i.e., smaller than about 1 m). Therefore, we assumed that SSC maps provided by the RT model can be safely used for comparison with STABEM’s results only where water depth is larger than 1.0 m. This occurs in the great majority of the central-southern part of the lagoon, excluding just a few narrow regions close to the land, and in a limited part of the northern lagoon: between the city of Venice and the Venice International Airport, and at the end of the San Felice channel in the northernmost part of the basin (Figure 1). Areas characterized by very shallow water depths (i.e., ≤ 1 m) were masked in the maps.

The comparison (Figure 4) shows a good agreement between model results and SSC maps provided by the RT model, in particular when focusing on the central part of the lagoon, between the Lido and the Malamocco inlets where the most intense SSC values occurred, and on the areas of the northern lagoon where the comparison with satellite data is meaningful. In the northern lagoon almost no resuspension can be observed in both the RT model and STABEM simulations. This behavior is typical during Bora wind events, because the northern basin is less exposed to wind from northeast, due to the sheltering effect provided by land and salt marshes which also systematically interrupt the fetch.

However, we note that the agreement between model results and the satellite image is not satisfactory in the southern part of the lagoon, specifically in the area between the Malamocco and Chioggia inlets. The observed discrepancies are likely to be ascribed to the stabilizing effect of vegetation which extended over a large fraction of this part of the lagoon (see Figure 3a and pink lines in Figure 4c). Interestingly, Figure 4c emphasizes that when the stabilizing role of vegetation is accounted for in the model, the
The agreement between model predictions and the satellite image is significantly improved also in the southern part of the lagoon. It is also interesting to note that the model effectively reproduces the shadowing effect provided by islands and artificial structures. Both the satellite image and the computed turbidity map, in fact, show that no resuspension occurs in the area, about 2 km wide, located downwind of the city of Venice: this is clearly due to the combined effects of sheltering and fetch interruption. The same behavior is observed for the area downwind of the Liberty Bridge, connecting the city of Venice to the land. Other artificial structures providing sheltering effect and fetch interruption within the lagoon are the bridge connecting the city of Chioggia to the mainland, in the southern lagoon (see Figure 1 close station VE10), and the reclaimed areas located in the central lagoon next to the Malamocco-Marghera channel. However, both these artificial structures are located in areas shallower than 1 m which prevent any safe comparison with model results. It is furthermore worth noting the agreement between numerical results and the satellite image when reproducing the reduced SSC which characterizes the deeper channels, e.g., the straight artificial Malamocco-Marghera channel in the middle of the lagoon in front of the Malamocco inlet and the two main channels branching out from the Lido inlet.

Figure 4. Resuspension event that occurred on 8 December 2001 at 10:30 A.M. Comparison among (a) the map of the suspended sediment concentration obtained analyzing the Landsat satellite image, (b) the SSC map computed by STABEM when the stabilizing effect of benthic vegetation is neglected, and (c) the same as Figure 4b when resuspension is set to zero in presence of vegetation. Shaded areas refer to areas characterized by water depth lower than about 1 m.
Figure 5 compares the second selected satellite acquisition (11 December 2005, 11:00 A.M., Figure 5a) with the corresponding numerical results (Figure 5b). Numerical results were obtained on the basis of the spatial distribution of the bottom vegetation mapped on September 2005 (Figure 3b and pink lines in Figure 5b) to account for the stabilizing effect of vegetation.

The SSC during the Bora wind event occurred in December 2005 was significantly higher compared to that of the previously discussed 2001 event because of the higher wind speed (Figure 2b). The agreement between modeled and satellite retrieved SSC maps is quite good for the central part of the lagoon. Some differences are observed close to the barrier islands of Pellestrina (between the Malamocco and Chioggia inlets) and Lido (between the Lido and Malamocco inlets) where the numerical model underpredicts sediment concentration values. The area close to the Pellestrina barrier island, in particular, was characterized by the presence of a wide submerged vegetation area, whose effects are simulated in the numerical model by assuming that no resuspension occurs in the presence of vegetation. However, unlike the case with the 2001 event, including or neglecting the vegetation effects does not significantly affect the solution and the reason for the observed discrepancies must be sought elsewhere.

The discrepancies can partly be ascribed to model overestimation of the sheltering effect provided by the barrier islands which is strictly related to the wind direction: wind direction in the 2005 event is, in fact, much more perpendicular to the barrier islands than in the 2001 event (compare wind direction shown in Figures 4 and 5). In addition, it is interesting to observe that the RT model, contrary to the 2001 event, predicts all over the lagoon relatively high sediment concentration whose values are, almost everywhere, consistently above 40–50 mg/l (light blue in the map of Figure 5a). We can speculate that some “residual” turbidity (e.g., wash load) is present as a background value in addition to native sediment resuspension. Such an observation is supported by the fact that prolonged rainfall occurred over the basin draining into the lagoon during the whole month of December 2005 (http://www.arpa.veneto.it/temi-ambientali/climatologia).
Further differences between STABEM and RT model results are observed at the lagoon inlets, and at the Lido inlet in particular, where satellite SSC retrievals are significantly larger than STABEM predictions. Noting that the satellite image was acquired when the lagoon was experiencing the maximum ebb (see Figure 2b), no sediment from the sea can be responsible for the large concentration shown by the satellite-retrieved map. On the contrary, dredging activities with large amount of sediment mobilization, related to the construction of the MOSE structure to protect the city of Venice from high tides (http://www.salve.it/uk/default.htm) have been ongoing in the period 2005–2007, and these activities, which are of course not represented within STABEM, could explain the observed differences.

We also compared the STABEM and RT model predictions at specific points within the lagoon, where the turbidity stations used to calibrate both models are located. Since SSC data from the RT model are sometimes characterized by a very high spatial variability, possibly due to the variance of the estimation error, we spatially averaged these data over a 300 × 300 m² square area centered at each turbidity station to reduce their uncertainty. For each square cell, the spatial variability within the cell was also estimated by computing the standard deviation of the in-cell values (100 pixels). It is worthwhile noting that varying the cell size in a range of 150 m, the estimation of the standard deviation was only marginally affected. Figure 6a shows the scatterplot comparing model results and satellite data for the two selected events, suggesting a good agreement between the predictions of the two models, which is improved at higher concentrations, except for VE8 station in the 2005 event. The satellite retrievals of SSC in the cells located near the VE8 station are characterized

Figure 6. (a) Scatterplot of modeled versus satellite retrieved SSC at the turbidity stations within the Venice Lagoon (see Figure 1) for the 8 December 2001 (white points) and the 11 December 2005 (black points) events; (b) scatterplot of modeled versus available in situ measured data for the 11 December 2005 event; (c) scatterplot of satellite retrieved versus available in situ measured data for the same event. Measured data for the 2001 event are not available since the turbidity probes (Seapoint Turbidity Meters) had not been installed yet. For the 2005 event, data from VE2 and VE3 stations are lacking while stations VE9 and VE10 had not been installed yet. The nominal error for the turbidity sensors is < 2%; the estimated accuracy for satellite data, considering a reference value of SSC = 100 mg/l, is ±10 mg/l [see Volpe et al., 2011, Figure 5].
by a large spatial variability (the standard deviation computed within the 10 × 10 pixel area near the station is $\sigma \approx 40$ mg/l, while for the other stations it is always $\sigma \leq 10$ mg/l) which suggests a local problem in the remote sensing observations. This is further confirmed by the comparison of STABEM and RT model predictions with field measurement (see Figures 6b and 6c, respectively). This comparison is possible only for the 2005 event, since in 2001 the turbidity stations were not yet active. The agreement for both models is rather good. Station VE8, where RT model overpredicts the sediment concentration, is located in an area of the northern lagoon where the flow depth is small (about 0.8 m), such that the bottom albedo might have significantly affect the remote sensing prediction.

Point by point comparison between the STABEM and RT model predictions is shown in Figure 7, where, in order to neglect the bottom albedo effect, areas characterized by shallow water depths (i.e., $\leq 1$ m) were masked. Both satellite and numerical results were gridded by averaging the data over 300 × 300 m$^2$ square cells. For each cell the difference between modeled SSC ($C_m$) and satellite retrieved SSC ($C_s$) was computed and normalized by a reference concentration ($C_{\text{max}}$), approximately corresponding to the maximum sediment concentration predicted by the numerical model (i.e., $C_{\text{max}} = 100$ mg/l for the 2001 event and $C_{\text{max}} = 200$ mg/l for the 2005 event). Shaded areas refer to areas characterized by water depth lower than about 1 m.

When considering the first event (Figure 7a), the agreement between model and satellite is quite satisfactory, with differences in the range of ±25% of the maximum SSC value in most of the domain. Only in the central part of the lagoon and in the area between the city of Venice and the land, upwind of the Liberty bridge, the numerical model locally overestimates the SSC with respect to the RT model result. When considering the second event (Figure 7b), the agreement is again reasonably good in most of the area between the Lido inlet and the Malamocco inlet and in the northern part of the basin. Significant differences can be observed in the central-southern part of the lagoon, where the numerical model underestimates the satellite-retrieved SSC.
particular, discrepancies are relevant upwind of the Malamocco-Marghera artificial channel: in this area, however, satellite data were extremely heterogeneous and produced unrealistically high SSC estimates (up to 800 mg/l) that are far outside the range of calibration of the RT model. Close to the barrier island of Pellestrina and in the sheltered areas, the underestimation is likely due to our poor knowledge of the biostabilizing effect associated with the bottom vegetation colonizing this area and to the presence of a particularly intense wash load during this period, as previously discussed.

4. Conclusions

In this paper we showed that in situ point turbidity measurements and remote sensing techniques can be profitably used to test the capability of sediment transport models to describe sediment dynamics in shallow lagoons and to provide helpful information to understand the sediment entrainment process in the presence of small-scale landforms, such as salt marshes, islands, and artificial structures (e.g., bridges, jetties, and reclaimed areas), the effect of channels cutting through the tidal flat surface, and the role played by benthic vegetation in the stabilization of bottom sediments.

SSC maps obtained by analyzing two satellite images acquired during intense resuspension events in the Venice Lagoon were successfully compared with the spatial distribution of the SSC computed using the numerical sediment transport model. The comparison highlighted the ability of the sediment transport model to reproduce the main features of the spatial distribution of SSC during intense resuspension events, both qualitatively and quantitatively. We found that the model could reproduce well the sheltering effect provided by salt marshes, islands, and artificial structures. In the Venice Lagoon this effect is typically observed in the areas located downwind of the city of Venice and of the Liberty Bridge connecting Venice to the land and is widespread in the northern part of the lagoon where negligible resuspension occurs also during intense stormy conditions because of sheltering effect provided by salt marshes.

The importance of benthic vegetation in stabilizing bottom sediment in shallow tidal environments also emerges from the comparison. In fact, the agreement between model results and the remote sensing retrievals of SSC was significantly improved when the presence of bottom vegetation was accounted for in the numerical model. This emphasizes that biostabilization processes, previously only quantified in the laboratory and at limited field scales, are extremely important for the biomorphodynamic evolution at the entire system scale and thus deserve further investigation.

Finally, our analyses show that the combined use of both in situ point observations, which provide information on the temporal evolution of the local turbidity, and of satellite images, which provide spatially distributed information about the instantaneous turbidity field, allow to effectively constrain a model of sediment transport dynamics both spatially and temporally. Our results thus establish a firm basis for the combined use of point measurements, satellite observations, and numerical sediment transport modeling as a useful tool for process understanding and for designing effective environmental management strategies.

References


