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Exploring the bottom stress variability in the Venice Lagoon

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Abstract

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

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

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

Keywords: Venice Lagoon; Hydrodynamic model; Wave model; Bottom stress; Erosion

1. Introduction

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

The Venice lagoon is a coastal lagoon connected to the Adriatic Sea by three inlets. The main driving force for the circulation are the tide (1 m of tidal range during spring tides) and the wind. The tide propagates in the lagoon along the deep narrow channels in midst shallow areas (1 m in average) and tidal marshes. Due to the high tidal energy stratification does not normally develop.

Two major wind regimes are present, the Bora from north–east and the Scirocco from south–east.

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These wind regimes superimpose on top of the tidal pumping action a strong circulation inside the lagoon, important for mixing and transport. They also create wind waves locally that are then responsible for the resuspension of sediments in the shallow parts of the lagoon.

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

As a preliminary step towards this direction, we present here a coupled hydrodynamic-wave model, reproducing the circulation of the Venice Lagoon and the effects that winds may have on the wave–current interactions. Particularly, the study is focused on the determination of the bottom stress values, the main forcing for erosion and deposition processes.

Apart from reproducing the actual situation during a strong meteorological forcing, three scenarios of a future climatic change have been devised. The first supposes an increase of the tidal excursion, the second a global sea level rise, and the last one the combination of both. With a modeling approach the effects that these climatic changes have on the bottom stress distribution (and therefore on the erosion processes going on in the lagoon) are studied and discussed.

In the following treatment the applied models are presented and their set-up is shown. Then results are discussed in detail, separating the effects of the waves and currents on the bottom stress. At the end the results are discussed and conclusions are drawn.

2. The models and the simulation set-up

In this section the models used are presented and the way the bottom stress has been computed is discussed. The models used are a hydrodynamic finite element model, a wave evolution model for shallow areas and a sub module to compute the bottom stress and its interaction between the currents and the waves.

2.1. The hydrodynamic model

The hydrodynamic model used is the two-dimensional finite elements numerical model developed at ISDGM during the 1990s (Umgiesser and Bergamasco, 1993) successfully tested in other circulation applications (Bergamasco and Umgiesser, 2000; Zampato and Umgiesser, 2000; Umgiesser, 2000) and coupled to a simple deposition model as well (Bergamasco et al., 2001). The numerical model provides as results the prognostic values of sea surface elevation and of the vertically integrated velocities. The main structure of the code solves the shallow water equations in the hydrostatic approximation expressed by the well-known equation set:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \eta}{\partial x} + RU + X = 0 \tag{2}$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\mathrm{d}\eta}{\mathrm{d}y} + RV + Y = 0 \tag{3}$$

where $H=h+\eta$ is the total depth of the water column (where h is depth of the water column and η is the sea surface elevation), f is the Coriolis parameter, t is the time, g is the gravity acceleration, R is the friction coefficient and X and Y contain all other terms, such as wind stress and non linear terms.

In the above written equations, the vertical integrated velocities (total transports) are used where $U = \int_{-h}^{\varsigma} u\mathrm{d}z$ and $V = \int_{-h}^{\varsigma} v\mathrm{d}z$, with u and v are the velocities along x and y direction.

The friction parameterisation used is given by $R=c_D\backslash u\backslash/H$, where c_D is the drag coefficient that depends on the bed roughness length (see later). This formulation corresponds to a quadratic friction law.

These equations are integrated in time by a semi-implicit algorithm. In this procedure the unknown transports from the momentum equation are substituted into the continuity equation resulting only in a linear system to be solved for the water levels. With the knowledge of the new water levels the unknown transports may be solved for explicitly.

The spatial discretization of the equations is done on a triangular finite element grid. These linear finite elements give enough flexibility to describe the complex geometry and bathymetry of the Venice Lagoon. On this grid the water levels are described by linear form functions and defined on the nodes (intersections) of the grid. On the other hand, the velocities are described by constant form functions over one element, which corresponds to the definition of the velocities on the centre of the elements.

This "staggered" approach of defining the various variables and unknowns is well known from the finite difference technique and allows for propagation properties that conserve energy and mass. The same is also valid in this case for the finite elements.

Moreover, as the average depth of the Venice Lagoon is about 1 m and in some regions the tidal amplitude may be greater than the water column, a drying algorithm is implemented (Zampato and Umgiesser, 2000). The shallow water flats during a tidal cycle are sometimes covered with water, and sometimes are dry: during the dry period these elements are taken out of the algebraic system and are later added again, once the surrounding water level is higher than the water inside the dry element. The specific implementation done here conserves the mass in each element.

2.2. The wave model

The SWAN model is an advanced third generation model, specifically developed for shallow waters. There is full consideration of all the dominant physical processes that control the evolution of the wave field. A description of the model is given by Booij et al. (1999) and Ris et al. (1999), while a focus on the Venice lagoon area can be found in Signell et al. (in press).

In SWAN the evolution of the wave field is described with the two-dimensional wave action density spectrum $N(\sigma, \theta)$ rather than the energy density spectrum $E(\sigma, \theta)$ since in the presence of currents, action density is conserved whereas energy density is not. The independent variables are the relative frequency σ (as observed in a frame of reference moving with the action propagation velocity) and the wave direction θ (the direction normal to the wave crest of each spectral component). The action density is equal to the energy density divided by the relative frequency: $N(\sigma, \theta) = E(\sigma, \theta)/\sigma$.

The evolution of the wave spectrum is described by the spectral action balance equation that for Cartesian coordinates is:

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \tag{4}$$

The first term in the left-hand side of this equation represents the local rate of change of action density in time, the second and third term represent propagation of action in geographical space (with propagation velocities c_x and c_y in x- and y-space, respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents (with propagation velocity c_σ in σ-space). The fifth term represents depth-induced and current-induced refraction (with propagation velocity c_θ in θ-space). The expressions for these propagation speeds are taken from linear wave theory. The term $S = S(\sigma, \theta)$ at the right hand side of the action balance equation is the source term in terms of energy density representing the effects of generation, dissipation and nonlinear wave–wave interactions.

The SWAN numerical model has been successfully used to model the evolution of waves in very shallow water. Tests carried out in wave flumes lead to relatively good agreement between experiments and SWAN (see e.g., Wood et al., 2001).

2.3. Bottom stress computation and its physical interpretation

The bottom stress is the main forcing factor for erosion and deposition processes. Both current and wave action contribute to it and the wave–current interactions enhance these values. In the particular lagoon environment the two contributions are crucial for a correct assessment of the stress.

The bottom stress due to currents only can be written as

$$\tau_c = \rho c_D u_c^2 \tag{5}$$

where u_c is the barotropic current velocity and c_D is the value of the bottom drag coefficient. This can be estimated adopting the definition of friction velocity and using the logarithmic profile to compute the velocities at the center of the layer (for a complete derivation, see Burchard, 2002 or also Burchard et al., 1999):

$$c_D = \kappa^2 \left[\ln^2 \left(\frac{z_0 + 0.5H}{z_0} \right) \right]^{-1}$$

where κ is the von Karman constant ($\kappa = 0.40$), H is the total water depth, ρ is the water density and z_0 is the bottom roughness length. Note that the height where the drag coefficient is evaluated should be really at $0.37H$, the height where the average velocity is assumed by a logarithmic profile. However, we prefer using the original equation, since the difference in c_D between the two formulations is normally less than 10% and the uncertainty in the choice of z_0 is much higher.

The bed shear stress due to wave only has been calculated following Soulsby (1997):

$$\tau_w = \frac{1}{2} \rho f_w u_w^2 \tag{6}$$

with $f_w = 1.39\ (z_0/A)^{0.52}$ expressing the friction factor, $A = u_w T_p / 2\pi$ where T_p is the wave peak period and u_w is the maximum bottom velocity from SWAN. This bottom velocity is totally uncorrelated from the current velocity computed with the hydrodynamic model, being the velocity due to the oscillatory motion of the wave movement. For consistency, the value adopted for the bottom roughness z_0 in the wave model is the same one as used by the hydrodynamic one, that is 5×10^{-4} m.

To compute the non-linear wave–current enhancement to the mean bottom stress τ_m, various models could be used (e.g. Grant and Madsen, 1979, 1982). In this paper we adopted the following empirical formulation of Soulsby (1995, 1997), because the other formulations do not really provide more physical insight in the problem and all formulations give, according to the author, comparable results:

$$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} \right] \tag{7}$$

The maximum shear stress, due to the combination of waves and currents, has been computed taking into account also the non-linear interactions:

$$\tau_{max} = [(\tau_m + \tau_w \cos\phi)^2 + (\tau_w \sin\phi)^2]^{0.5} \tag{8}$$

with ϕ representing the angle between the current and the waves (see Fig. 1 for reference). Since it is this maximum shear stress, and not the average stress τ_m, that is responsible for the mobilization of the bottom sediments, the following results are discussed in terms of the maximum stress given in Eq. (8).

2.4. The model setup and simulations

The hydrodynamic model has been applied to the Venice Lagoon with a grid consisting of 4359 nodes and 7845 elements (see Fig. 2). The resolution is variable from about 1 km in the shallow parts far from the inlets down to about 50 m in the small channels that run in the lagoon. The simulations are run with a 5-min time step until a dynamic steady state has been reached.

The model has been used in its barotropic version, since we are focusing only on the basic processes that regulate the bottom stress experienced by the water body. The usual logarithmic profile of the current velocity has been assumed.

The model has been forced by semidiurnal tides imposed at the three inlets and by an idealized wind regime, constant in time and space, a Scirocco wind blowing from S–E with idealized but realistic mag-

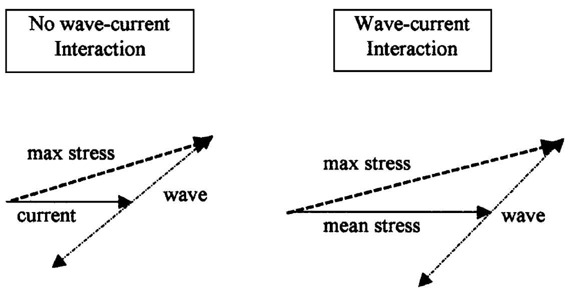

Fig. 1. Graphical representation of the computation of the maximum shear stress, due to the combination of waves and currents. The angle ϕ used in the equations is the (smaller) angle between the current mean stress and the wave propagation.

Fig. 2. Finite element grid of the Venice Lagoon adopted by the hydrodynamic model.

nitude of 10 m/s. As explained before, these Scirocco winds are quite frequent and strong and represent one of the major wind regimes in the Venice Lagoon. In an earlier work (Umgiesser et al., 2002) both wind regimes (Bora and Scirocco) have been investigated. It was found that the values for bottom stress and erosion did not depend so much on the direction of the wind, but were much more correlated with the wind speed. This is mainly due to the fact that the wind waves present in the lagoon are created locally, and due to the large shallow areas in the lagoon they are normally always fully developed. Therefore the choice of the wind regime is not crucial for the conclusions of this work, and the Scirocco winds have been used here.

At the model open boundaries, i.e., in the proximity of the three inlets directly communicating with the Adriatic Sea, the sea surface elevations are prescribed using a semidiurnal tide with an amplitude of 40 cm.

In the proposed tests, 25 frequencies and 24 uniformly distributed directions have been considered in the SWAN model. The frequencies are geometrically distributed with $f_{n+1} = 1.1\ f_n$ and $f_1 = 0.12$ Hz while the directions considered for the numerical discretization of the directional spectrum computed by SWAN were $0°$, $15°$, $30°$,…, $345°$. The model has been run in stationary mode, i.e. given the input wave conditions at the outer border of the grid, the model iterates until equilibrium conditions have been reached. Given the limited extension of the Venice

Lagoon area and the consequent limited time required for the wave energy to move from one end to the other, this is perfectly consistent with a sound representation of the physical truth.

The SWAN computational grid used for the tests (represented in Fig. 3) had a resolution of 100×100 m, and 305×421 grid points. For the simulation, the water level placed on the model bathymetry was the one derived by the hydrodynamic model.

Even if the hydrodynamic model is a finite element one, the wave model has been run on a regular 100-m grid. Therefore, for consistency, the current field has been interpolated to the regular grid used to compute the wave propagation as well as all other computations performed to explore the stress field and correlations.

In order to investigate the relative weight of the aforementioned contributions, we have devised different scenarios that explore the sensibility of the lagoon environment with respect to future climatic changes. Four different scenarios have been investigated. The first one is the reference scenario that serves for comparison and represents the actual situation. The other scenarios are the increase in amplitude of the

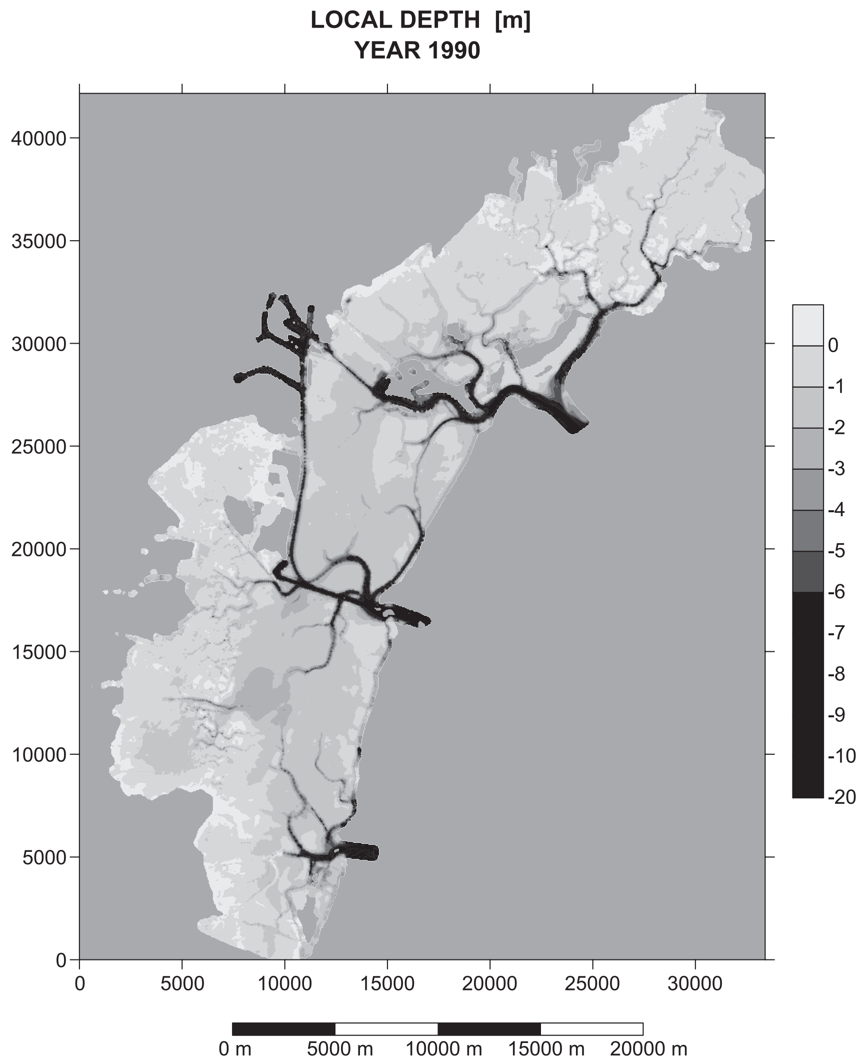

Fig. 3. Bathymetry of the Venice Lagoon as used by the wave model.

Table 1
Overview of the scenarios investigated with Scirocco winds of 10 m/s

Scenario	Tidal excursion (cm)	Mean sea level (cm)
Reference	± 40	0
A	± 60	0
B	± 40	+ 50
C	± 60	+ 50

tidal wave, an increase in the average value of the sea surface elevation and the combination of the two scenarios. Details can be found in Table 1. These scenarios are justified through the assumption that future climatic changes have an impact on the average sea level of the world oceans and on other factors that change the excursion of the tidal wave (IPCC, 1990, 1996, 2001).

3. Results

In the following the various tests that have been set up are described.

3.1. Currents and waves treated separately

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

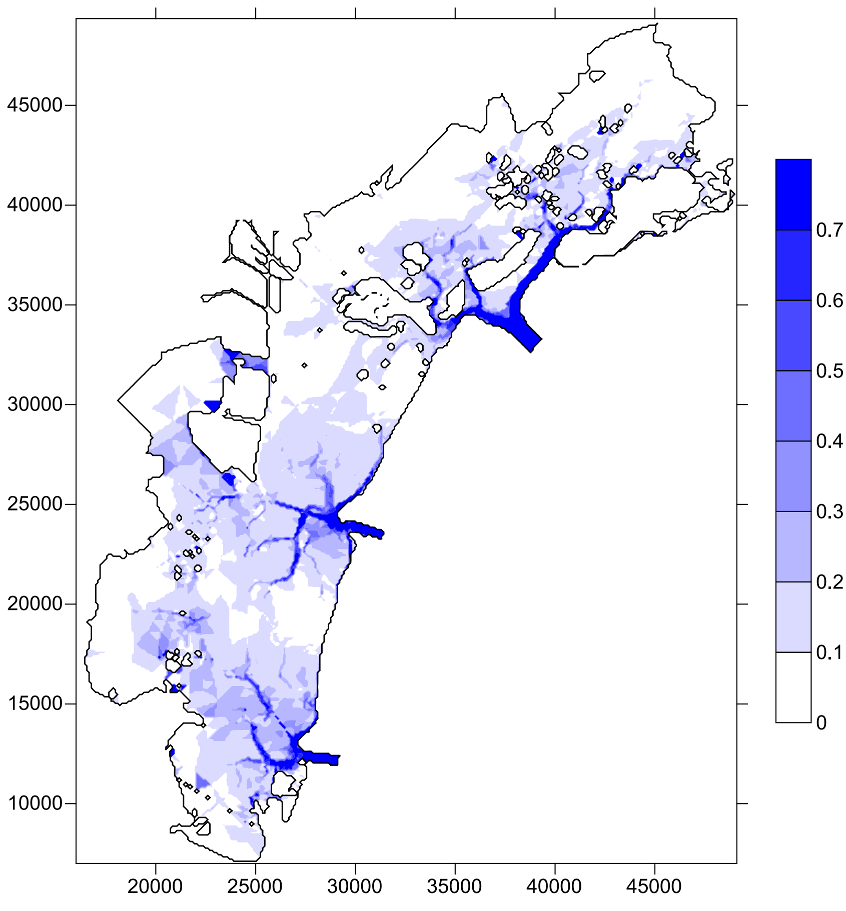

Fig. 4. Bottom shear stress (N/m^2) induced by currents only during a Scirocco event.

present here results of Scirocco wind forced situation (Fig. 4) where the bottom stress is computed only from currents as expressed by Eq. (5).

Fig. 5 presents the bottom stress using formula (6), i.e., taking into account only the wave contribution. The scale presents a maximum value of 0.7 N/m^2 as this value is considered to be the threshold above which cohesive sediments may be mobilized in the Venice Lagoon (Amos et al., 2000).

Comparing Figs. 4 and 5, the bottom stress induced only by currents is maximum along the deepest channels, i.e., where the hydrodynamics is more active. In the case where only waves have been taken into account, the channels show very low values, reflecting the fact that in deep regions wave effects are negligible. On the other hand, the shallower parts exhibit values higher than 0.7 N/m^2. Therefore, generally speaking, the two pictures are in a way complementary: where wave effects are higher, current effects are weaker.

3.2. Combined effect and non-linear stress enhancement

The non-linear effects of the combination wave–currents have been investigated using the formula (7) for the mean shear stress. Results show an enhancement of up to 100% in some shallow areas where currents are less important than the wave action, but the typical increase is in the order of 15–20%. Fig. 6 shows the areas of enhancement. It can be seen that the whole central lagoon and large parts of the northern and southern lagoon show an increase of around 15%. Some small areas (normally shallow

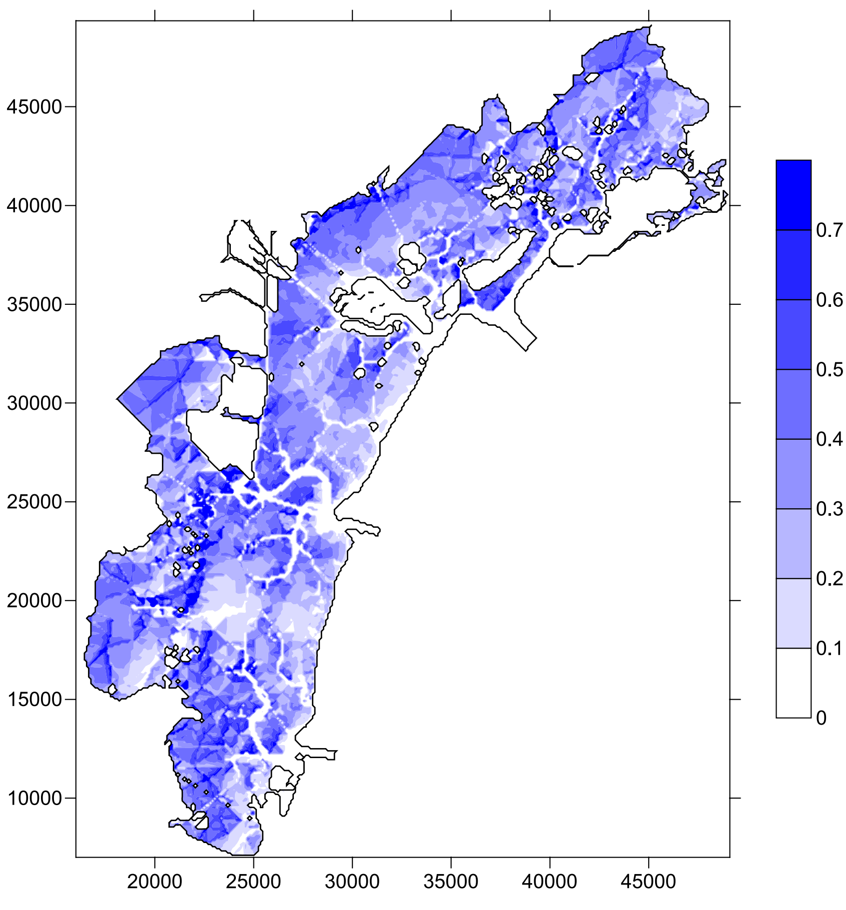

Fig. 5. Bottom shear stress (N/m^2) induced by waves only during a Scirocco event.

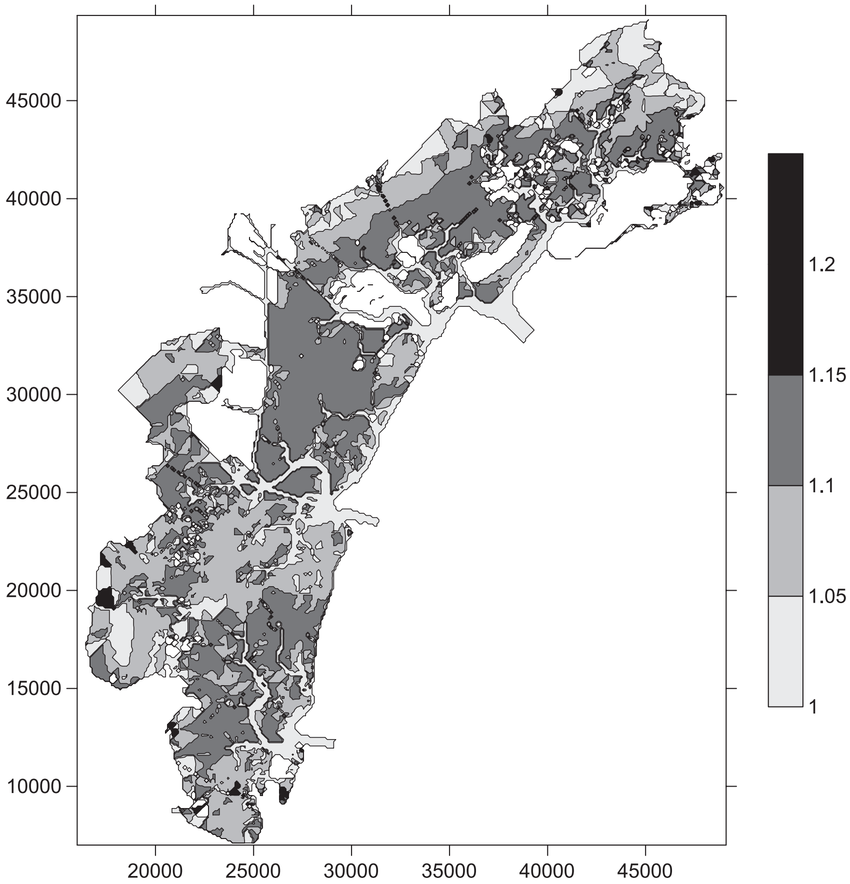

Fig. 6. Non-linear stress enhancement. Shown is the ratio between the bottom stress with current–wave interaction and the one without. Most of the parts in the lagoon show an enhancement of around 15%.

water flats) show much higher values, whereas a large region just south of the central part and a stripe close to the mainland in the northern part show lower enhancement.

In these areas of stress increase it is therefore important to include also the combined effect of currents and waves. On the other hand in the deep channels the wave current enhancement is rather low. Both findings can be deduced from Eq. (7) that shows that the enhancement effect is strongest in areas of high wave action.

Fig. 7 presents the combined effect of the waves and the currents; here the maximum stress using formula (8) is plotted during strongest inflow. Interesting features are the existence of a low stress area in the southern lagoon, between the southernmost and central inlet. Another interesting point is the very low stress levels in the second part of the *Fisolo* channel, the one starting from the central inlet Malamocco and then bends in a meander to the right, easily recognizable also in Fig. 6. Highest stress values are instead found inside the Malamocco inlet and in the shallow area enclosed by the *Fisolo* and the *Canale dei Petroli*, the channel that runs straight from the Malamocco inlet to the mainland.

These results may be compared to a map that shows the areas of erosion and deposition in the Venice Lagoon, prepared by Magistrato alle Acque–Servizio Informativo (1993) using bathymetric data collected between 1970 and 1990; the central part of the map is shown in Fig. 8. It can be seen that the same features that have been identified through the levels of stress in Fig. 7 are also present in Fig. 8. Especially striking is the maximum of erosion in the

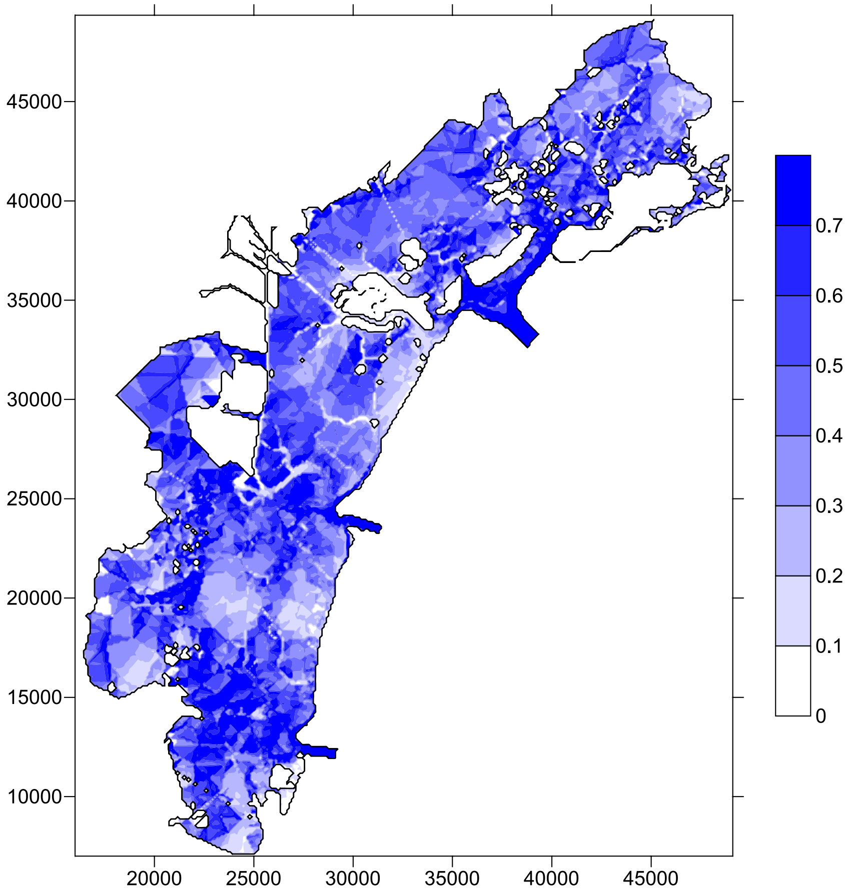

Fig. 7. Maximum stress (N/m^2) due to wave and currents, computed using the formulation (8), during a Scirocco event.

shallow area between the two channels, and the maximum of deposition in the end of the *Fisolo*. The area of minimum stress in the southern lagoon can also be identified in both figures.

3.3. Scenarios of climatic variations

In this section results of three scenarios that deal with climatic variations are presented. The three scenarios, apart from the reference run, that have been set up are summarized in Table 1.

Results of the simulations (and also the others scenarios) are shown in Table 2. Here the percentage of the area where the bottom stress exceeds 0.7 N/m^2 due to the various forcings of wave, current and the combination of both is presented. The value of 0.7 N/m^2 has been chosen because this is the average value for the lagoon of the critical erosion threshold that has been determined through experiments during the EU funded F-ECTS project measurement campaign (Amos et al., 2000). This critical value is valid for winter conditions; in summer, the threshold is higher due to bio-stabilization of algae.

In Fig. 9 the fraction of the areas that are exposed to erosion for the above-mentioned Scirocco wind during maximum inflow are shown. The effects due to waves only, currents only and the combination of both are shown. With low values of the critical erosion threshold, the waves are much more important. At a value of 0.3 N/m^2 the waves put into erosion nearly 55% of the whole area of the lagoon, whereas the currents amount to less than 10%. At a critical erosion threshold of 0.7 N/m^2 the influence of the waves and the currents are becoming comparable, and at still

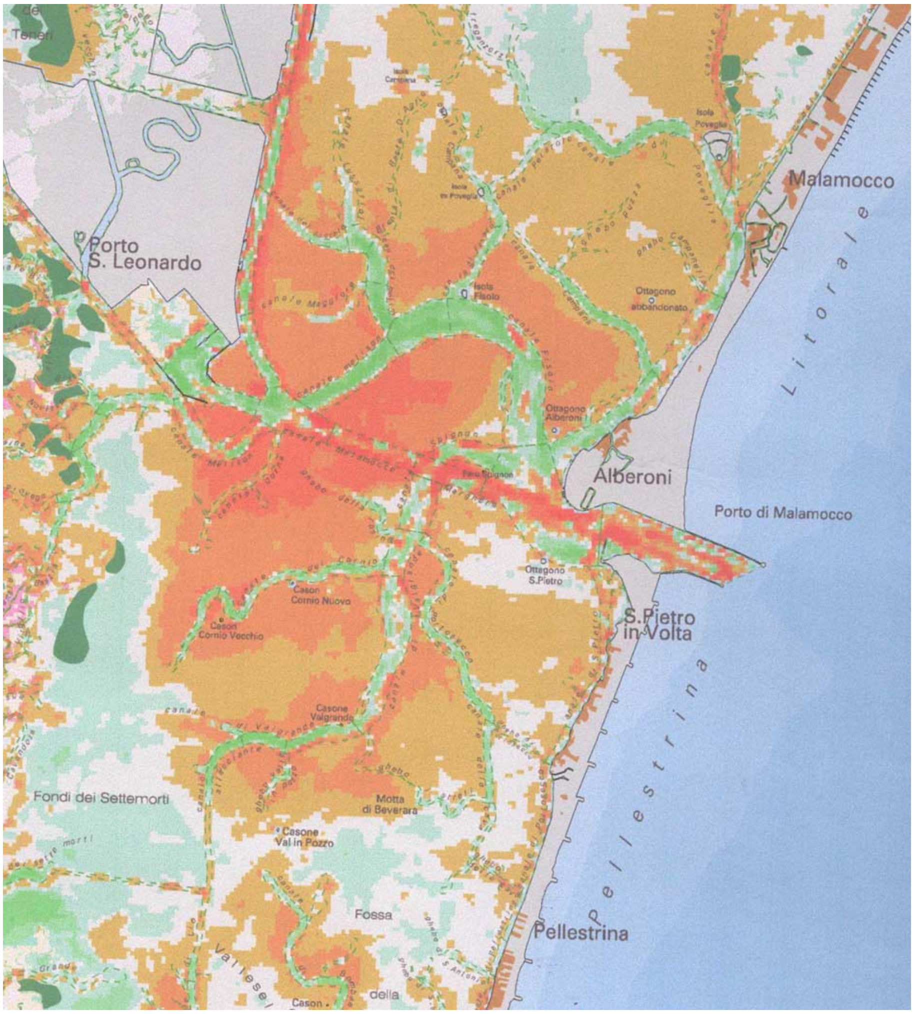

Fig. 8. Detail of map (Magistrato alle Acque–Servizio Informativo, 1993) that shows the areas of erosion (red) and deposition (green) in the years from 1970 to 1990. Darker colors show higher rates (Courtesy of Consorzio Venezia Nuova).

higher values currents become more important. The combined effect of waves and currents at low threshold values is less than the sum of the single forcings (see Fig. 9), but normally the combined effect comprises a larger area than the sum of the single effects. This is especially evident between 0.4 and 0.7 N/m^2 where the enhancement may be even more than twice the sum of the single contributions.

3.3.1. The reference run

The first conclusions that can be drawn from Table 2 is that wave induced bottom stress has values which are not varying strongly during the tidal cycle (column Twave in Table 2). It seems, however, that the maximum of the stress (highest percentage of area with stress higher than critical value) is not happening during the extreme excursions of the water level (maximum or minimum) but during intermediate conditions. This quite surprising result has two explanations. The first one is the fact that for the lagoon of Venice it is very difficult to define the time of minimum (or maximum) water level. During the tidal cycle the tidal wave shows a phase shift that varies with respect to the inlets: about one hour for the

Table 2
Percentage of areas where the value of the bottom stress exceeds 0.7 N/m^2 due to only wave, only current and the combined effect of both

Scenario	Situation	Wet points	Twave	Tcurr	Tmax
Ref	max	34046	2.79	0.20	5.92
Ref	out	33647	4.19	3.69	12.68
Ref	min	31161	2.29	0.68	8.74
Ref	in	33266	3.87	3.83	17.94
A	max	34054	2.95	0.49	5.97
A	out	33811	4.12	5.47	13.62
A	min	30019	1.89	1.87	9.17
A	in	33062	3.69	6.24	23.26
B	max	34054	1.92	0.02	3.13
B	out	34054	2.51	2.96	7.50
B	min	33893	3.77	0.07	10.92
B	in	34054	3.13	3.31	13.06
C	max	34054	1.53	0.18	2.37
C	out	34054	3.01	4.61	9.86
C	min	33643	4.05	0.67	11.61
C	in	34054	3.34	5.57	18.91

The number of wet points in the finite difference representation is also given. For every scenario the four situations of maximum and minimum water level (max, min), outflow (out) and inflow (in) are given.

Venice island to 2 h in the more remote parts of the lagoon and up to 3 h for the northernmost parts which show the highest phase shift. This strong phase shift of the northern lagoon makes it possible that average values in these areas are lower during incoming tide and higher during outgoing tide. Therefore, if we identify the period of maximum elevation, some areas of the lagoon are still in situation below maximum water level.

The second reason why highest stress values do not coincide with minimum or maximum water levels is that the highest waves are not always associated with the shallower areas. Clearly, when passing from deep areas to shallower ones the effect of the wind becomes stronger, creating higher waves. However, once the depth reaches a critical value, the waves become limited by the water depth and do not grow anymore. This critical depth depends on both the fetch of the wind and the wind velocity.

Fig. 10 shows the results of a simulation where the bottom stress is computed at water depths ranging from 0.2 to 10.0 m for different fetches. Generally, the stress increases with decreasing water depths; however, for certain shallow depth values, the wave height reaches the breaking limit and does not grow any further, and consequently the bottom stress does not change even in case of increasing fetch. As an example, for a fetch of 5 km the maximum bottom stress is achieved for a water depth of 40 cm, whereas, being the bottom stress related to the wave characteristics, for a depth of 20 cm the stress value is actually lower. Even for depths of up to 1 m the bottom stress is higher than for 20 cm water depth.

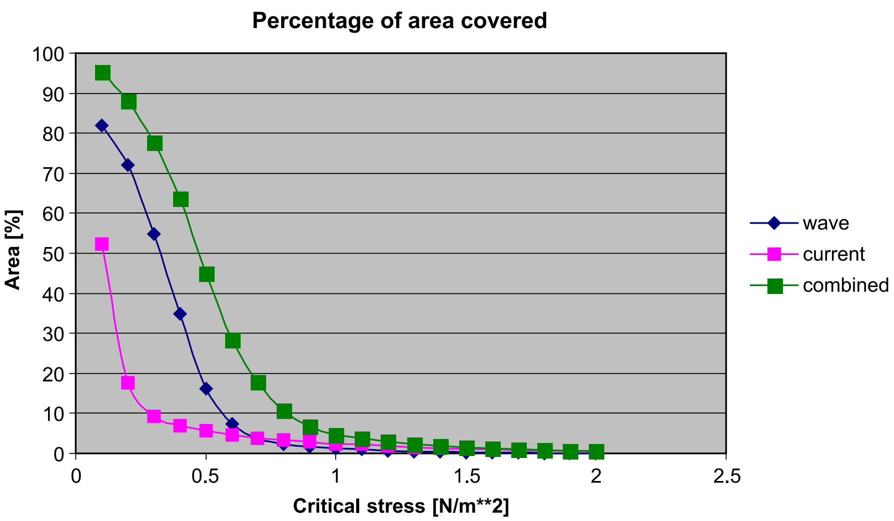

Fig. 9. Variation of the area in erosion in dependence of the critical shear stress of erosion. The contributions of only waves, only currents and the combined effect are shown. The situation is during inflow with a Scirocco wind of 10 m/s.

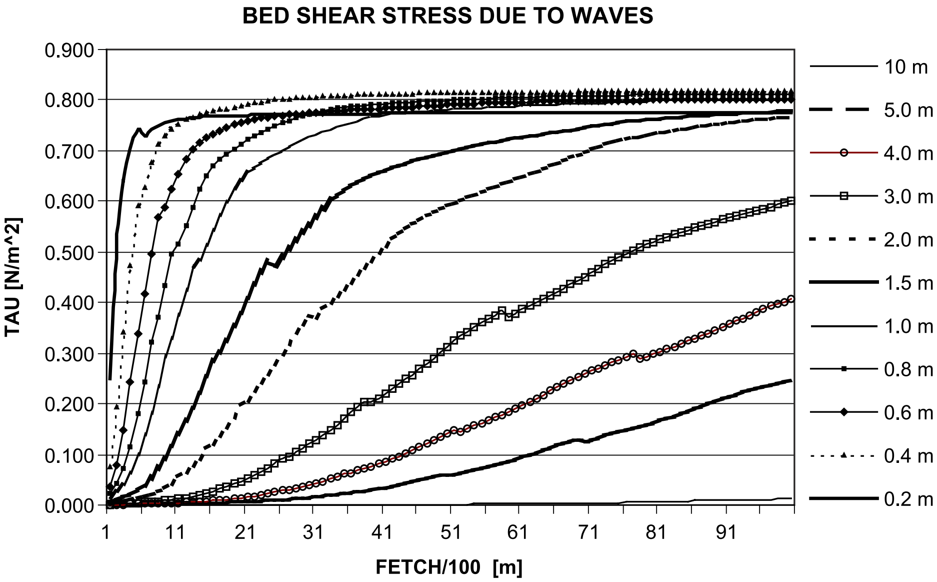

Fig. 10. Variation of bottom stress due to waves depending on water depth and fetch of the wind. The diagram has been created with a Scirocco wind of 10 m/s.

For large values of the fetch it seems that the bottom stress is limited by a value of 0.82 N/m^2 for a wind of 10 m/s. This number is only slightly larger than the value for the critical shear stress of 0.7 N/m^2, which could show the long-term filtering capacity of the lagoon with respect of the grain size distribution of the sediments.

For the bottom stress due to currents the tidal influence can be seen clearly from Table 2 (column Tcurr). The percentage of the area higher than the critical value is about the same both in inflow and outflow (3.7%), but much lower for high tide (0.6%) and low tide (0.2%). As expected, the bottom stress is stronger during lower tide. The number of wet points is also similar for maximum in and outflow, and considerably lower for low tides than for high tides ($\sim$ 34 000 against $\sim$ 31 000).

When looking at the maximum stress of the combined wave current movement (column Tmax) it is surprising to note how the percentage of area that exceeds the critical value is significantly higher than the sum of the two single contributions. This is clearly an effect of the non-linear wave–current interaction that can be inferred also from Eqs. (7) and (8). Nearly 18% of the area is in erosion during inflowing tide, and even during maximum water level nearly 6% are above the critical level. It should be noted that during inflowing tide the percentage is higher than during out-going tide. This might be due to the vector summation of both contributions of currents and waves and to the fact that water levels in the northern lagoon are in average lower during incoming tide than during the period of outgoing tides.

3.3.2. Scenario A

In this scenario it is supposed that the tidal excursion in the Venice Lagoon is increased from $\pm$ 40 to $\pm$ 60 cm. Since the excursion with amplitude of 40 cm corresponds to an average spring tide, the value of 60 cm might be seen as the situation during very strong spring tides.

However, this first scenario investigated also can be justified through another reasoning, i.e., the interaction of the tide with the meteorological forces, causing higher oscillations in the northern Adriatic Sea. This might be especially true because the main seiches of the Adriatic Sea have frequencies close to the main tidal components and strong meteorological events can stimulate these seiches that, once created, are damped out very slowly and the oscillations can persist for weeks. During these periods of strong seiches the tides experienced in the Venice Lagoon seem to be of higher amplitude.

Results can be found again in Table 2. For the wave contribution it can be seen that only during maximum tide the new scenario enhances the bottom stress, whereas in all other situations the effect is slightly reduced. The highest difference can be found during ebb tide, where the depth limitation of the waves might become important. However, all variations are of minor importance.

The picture changes if one looks at the stress caused by the tidal currents. Now the stress enhancement is clearly visible. During ebb tide nearly three times the area compared to the reference scenario is now in erosion (i.e., shows bottom stress values higher than 0.7 N/m^2). During inflowing tide the percentage of area in erosion increases from 3.8% to 6.2%. It must also be noted that the number of wet points during high tide is nearly identical to the reference situation, but there are about 1000 more dry points in excess. Clearly, during high tides nearly all tidal flats are already covered by water even with an amplitude of 40 cm, but during ebb tide a water level that is 20 cm lower uncovers a larger area.

The combined effect of waves and currents increases slightly when compared to the reference situ-

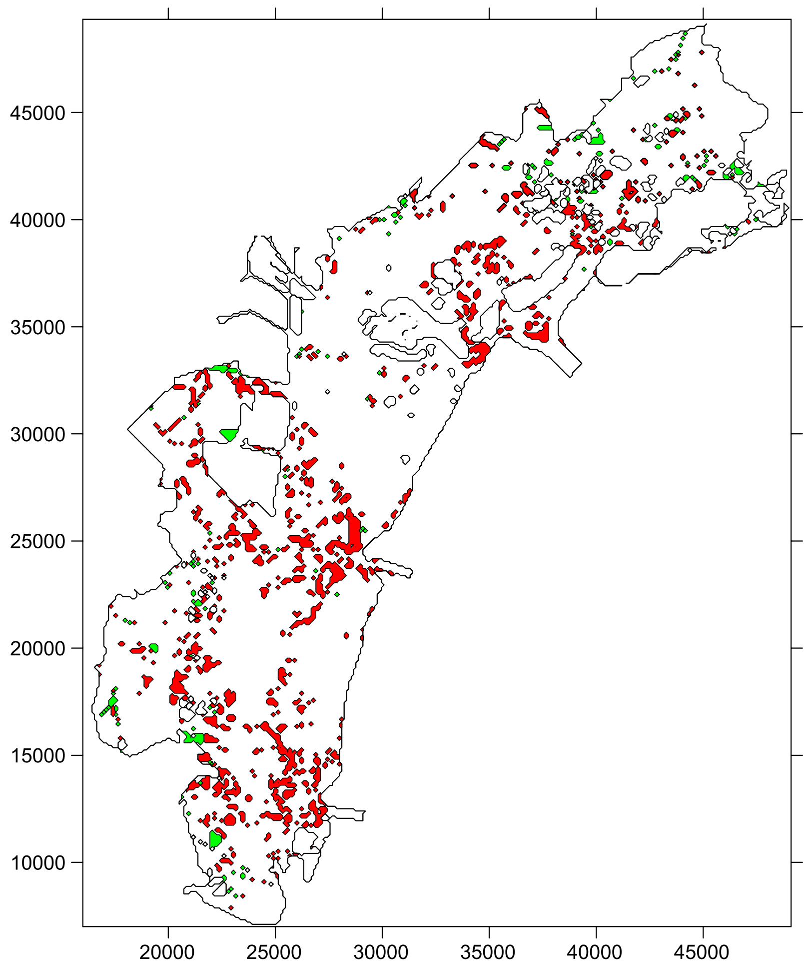

Fig. 11. Differences between scenario A (higher amplitude of the tidal wave) and the reference run. The image refers to a situation during maximum inflow, when differences are strongest. In red areas that change from non-erosion to erosion, in green areas that change from erosion to non-erosion. The erosion threshold is 0.7 N/m^2.

ation in all cases but the situation of incoming tides. In this case the increase is much stronger from 17.9% to 23.3%. This means that now nearly one forth of the lagoon is in erosion. For this case of incoming tide Fig. 11 shows the differences with respect to the reference run. It can be seen how the strongest changes can be found close to the Malamocco (central) inlet, but also close to the other inlets more areas are now in erosion. It is interesting to note that it seems that the most affected parts are the borders of the big channels, just in the shallow parts. It seems that these areas are much more vulnerable than other shallow areas and the erosion of these areas will clearly contribute to the filling up of the channels that are situated nearby.

3.3.3. Scenario B

This scenario simulates a sea level rise of 50 cm in the Adriatic Sea, a rise that can be justified through the last estimations of the *Intergovernmental Panel on Climate Change.* In its first report (IPCC, 1990) the sea level rise until 2100 has been estimated to be 66 cm. Wigley and Raper (1992) have projected a sea level rise for the next 100 years of 48 cm. In the second report (IPCC, 1996) the average sea level rise is given by 49 cm and in its last report (IPCC, 2001)

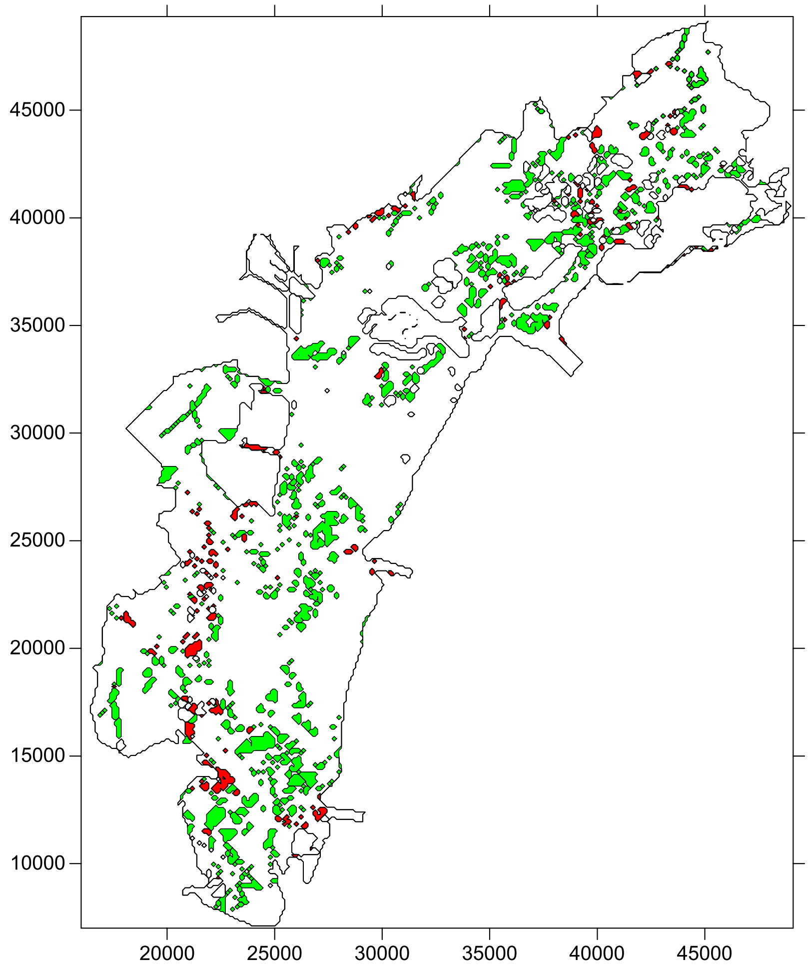

Fig. 12. Differences between scenario B (effect of sea level rise) and the reference run. The image refers to a situation during maximum inflow, when differences are strongest. In red areas that change from non-erosion to erosion, in green areas that change from erosion to non-erosion. The erosion threshold is 0.7 N/m^2.

this value is basically confirmed with a rise of 48 cm, oscillating between 9 and 88 cm.

The value of 50 cm used here represents therefore a reasonable average of what one can expect in the next 100 years for the Venice Lagoon and for the Adriatic Sea. The results can be again seen in Table 2; in the case of waves only, because of the deeper water the bottom stress is generally reduced when compared to the reference run and only during low tide the bottom stress is enhanced. In this case the total area of erosion rises from 2.3% to 3.8%. Clearly, in the case of ebb tide, the low water level is offset by the global sea level rise and therefore the areas that experience erosion (3.8%) are much more similar to the situation of in- (3.9%) and out-flowing (4.2%) tide in the reference scenario.

In the current only case the values are not really much different. During the period of high currents the bottom stress is slightly reduced due to the deeper water. Interestingly, the number of wet points is nearly constant (34 000) except in the case of low water, where slightly less points are covered with water. Thus, the sea level rise of 50 cm is high enough to cover all the tidal marshes in the lagoon.

Finally, the combined effect of waves and currents shows again a general decrease of the bottom stress levels, except in the case of low tide, where the waves have higher importance and are enhanced also in the case of waves only forcing. Fig. 12 shows the situation of inflowing tides, where the decrease of the stress levels is strongest with respect to the reference situation. As can be seen the areas of stress decrease do not completely correspond to the areas of enhancement in scenario A, but some overlapping region is certainly evident, especially close to the inlets. The areas of stress decrease are little shifted into the interior part of the lagoon, further away from the inlets. Especially the northern lagoon with its large shallow areas will benefit from this scenario.

3.3.4. Scenario C

This scenario combines the two scenarios A and B and simulates a sea level rise as well as a higher excursion of the tidal wave in the Venice Lagoon. Clearly, since scenario A showed an overall enhancement of the bottom stress and scenario B a little decrease, the combined effect of both scenarios will show some cancellation and the overall effect will be less strong.

The wave only case, as in case B, shows a general decrease of the areas in erosion, except in the case of ebb tides. As for scenario B, in this test the SWAN model was run raising the water level by 50 cm, as indicated in Table 1. This is quite similar to scenario B, since the waves are much more sensitive to the higher water depth and not to the higher excursion of the tidal wave. On the other hand, currents are much more influenced by the larger amplitude, because this results in higher currents in the channels. This effect is strongest during maximum inflow. Finally, the combined effect of waves and currents shows very similar value with respect to the reference run, giving a decrease during flood period and maximum outflow, whereas during ebb tide and maximum inflow a slight decrease of the eroded areas is observed.

4. Conclusions

This paper deals with the computation of bottom stress in the Venice Lagoon. Due to the very shallow nature of the lagoon it has been seen that the waves will be a major contributor to the total stress that is controlling the erosion and deposition mechanisms at the sediment water interface. It is therefore necessary to have a valid tool that allows the computation of the wave climate in the region.

The absolute values of the bottom stress must still be treated with some care. Clearly it depends through Eqs. (5) and (6) on the bed roughness length z_0. In the case of the waves this means that by doubling its value the bottom stress due to waves will increase by a factor of 40%. In the case of the stress due to currents the picture is a little bit more difficult since by changing z_0 also the current speed will change and the effects on the bottom stress should be less strong.

Even if there is some uncertainty in the absolute values of the stress level it has to be pointed out that the comparison with the erosion and deposition patterns is extremely encouraging. This comparison can by no means be seen as a validation of the model, since only one particular wind regime has been studied. However, since the Scirocco wind is one of the most frequent winds blowing over the lagoon, we feel that this good agreement with the empirical data is not merely coincidental but shows that the model is simulating the processes that are responsible for erosion in the Venice Lagoon.

The scenarios that have been investigated deal with a future climatic change that is supposed to influence both the tidal excursion and the mean sea level as well. The two supposed changes alter the levels of bottom stress in two different directions. Higher amplitudes of the sea oscillations drive stronger currents and therefore enhance the bottom stress and the erosion in the lagoon, while higher sea levels raise the average depth and therefore reduce the bottom stress especially due to wave action. The combined effect of the two scenarios actually results in a partial cancellation of the two single effects and gives a level of the bottom stress that is comparable to the reference run.

However, it seems that the most vulnerable areas are the shallow areas that run side by side with the big channels, especially close to the inlets. These would mean that in these areas the eroded material could directly be deposited in the nearby channels, resulting in a general flattening of the bathymetry of the lagoon.

It is interesting to note that the highest increase of the bottom stress levels coincides with the inflowing phase of the tide. Therefore, the effects of the erosion are in a certain sense mitigated by the fact that the material eroded is not directly exported from the lagoon to the Adriatic Sea, but some time is left, between the inflowing and the out-flowing phase, during which some of the sediment can deposit again before leaving the lagoon.

The models implemented and applied to the lagoon of Venice are well suited to study the physical processes that govern erosion, deposition and sediment transport, showing great potentialities also for future studies, especially for investigating the effect of changing boundary conditions on a system in equilibrium. After coupling this framework of models with a sedimentation module it will be possible to study in detail the processes responsible for the erosion of the Venice Lagoon and the impact that future climate changes may have on its environment.

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