Simulation of wind waves in shallow microtidal basins: application to the Venice Lagoon, Italy

L. Carniello & A. Defina
Department IMAGE, University of Padova, Italy.
A. D’Alpaos
Department of Geosciences, University of Padova, Italy.

ABSTRACT: A number of studies and field observations have demonstrated the crucial role of wind waves on sediment resuspension in shallow microtidal basins, where tidal fluxes alone prove unable to produce the bottom shear stresses necessary to mobilize tidal-flat sediments. Tidal currents, in fact, are seen as the main process governing the morphological evolution of the system in proximity of the inlets and within the channels, whereas, in shallow unchanneled areas, tidal currents mainly act enhancing wind-wave bottom shear stress and redistributing sediments within the system. We recently developed numerical model combining wind-wave effects with the influence of tidal fluxes, in a shallow basin (Carniello et al., 2005). The highly irregular bathymetry and morphological features usually characterizing shallow tidal environments with deep channels, emergent salt marshes, and extensive tidal flats, suggested the introduction of specific hypotheses while solving the wave-action conservation equation to describe wind-wave generation and propagation. In particular we considered a monochromatic wave and assumed that the direction of wave propagation instantaneously adjusts to the wind direction. The wave period characterizing the monochromatic wave reproduced by the model was assumed to be constant in space and time. In the present contribution we present a reconsideration of the above model, by relaxing some of the previous assumptions, in particular by assuming a variable wave period. Wind-wave data collected in the Venice Lagoon, are used to test and modify the relationship between wave period, wind speed and local water depth suggested by Breugem and Holthuijsen (2007). The improvement in the wind-wave field description obtained by introducing such an estimation of the local wave period reveals to be noteworthy. The results of a number of simulations carried out by considering different storm events support our claims.

1 INTRODUCTION

The lagoon of Venice is a wide, shallow micro-tidal basin in the North East of Italy. A large part of the lagoon is occupied by salt marshes and extensive tidal flats, which are dissected by an intricate network of channels departing from the three inlets of Lido, Malamocco, and Chioggia (Figure 1).

Recent studies and field campaigns have shown that the salt marshes and tidal flats within the Venice lagoon are under erosion with a net sediment loss for the entire tidal basin (e.g. Day et al., 1999; Marani et al. 2003; Fagherazzi et al 2006). A further important trend within the lagoon is the flattening of the bottom topography, as proved by the gradual but persistent reduction of salt marshes and by the silting of the tidal channels (Defina et al. 2007).

Because of the above considerations it is clear that a correct description of local sediment resuspension is crucial for understanding and assessing the evolution trend of the Venice lagoon.

Tidal currents alone are unable to explain the erosion of salt marshes and tidal flats. Tidal currents, in fact, produce shear stresses large enough to carry sediments into suspension only in the large channels near the three inlets. In contrast, sediment resuspension on salt marshes and tidal flats is mainly caused by shear stresses induced by wind waves (Carniello et al. 2005).

Since shallow tidal basins have a very irregular morphology with large and sharp changes in bottom elevation, islands, and temporarily dry areas, a specific framework must be adopted to model wind wave propagation in these environments.

Following a phase-averaged Eulerian approach (e.g. Donelan 1977; Holthuijsen et al., 1989; Booij et al., 1999) to describe wind wave generation and propagation, we proposed a simplified, computationally efficient model (Carniello et al. 2005) which reproduces the wind-wave generation and propagation inside the lagoon of Venice by solving the wave action conservation equation on an unstructured triangular mesh of arbitrary shape with a first order fi-
nite volume explicit scheme. The wave model is coupled with a hydrodynamic model for tide propagation based on a finite element scheme (Defina, 2000). Both models share the same computational grid, thus enabling us to accurately reproduce irregular domains and to correctly account for the interactions between waves and tides.

2 MODEL DESCRIPTION

2.1 The Hydrodynamic Model

The hydrodynamic model solves the two-dimensional shallow water equations modified introducing a refined sub-grid modeling of bathymetric data to deal with flooding and drying processes in very irregular domains. For a complete description of the model we refer the reader to Defina (2000), Carniello et al. (2005) and D’Alpaos & Defina, (2007).

The effect of wind shear stress at the free surface is considered in the model assuming a uniform wind field over the whole domain. Both the analyses of the field data referred to wind speed and direction in different location within the Venice lagoon and the results obtained with the model, suggest that such an assumption is acceptable in many cases especially in stormy conditions characterized by wind speed higher than about 10-15 m/s. Notwithstanding the study of the influence exerted by a non-uniform wind field deserves further attention.

At each time step, the hydrodynamic model yields water levels which are used by the wind wave model to assess wave group celerity and bottom influence on wave propagation.

2.2 The Wind Wave-Tidal Model

The wind wave model is based on the conservation of the wave action, \( N \), which is defined as the ratio of wave energy, \( E \), to the relative wave frequency, \( \sigma \).

The wave action conservation equation, in the most general spectral formulation is (Hasselmann et al., 1973):

\[
\frac{\partial N}{\partial t} + \frac{\partial c_{gx}N}{\partial x} + \frac{\partial c_{gy}N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = S \sigma
\]  

The first term of (1) represents the local rate of change of action density in time, the second and third terms represent the propagation of wave action in space (\( c_{gx} \) and \( c_{gy} \) are the x and y components of the wave group celerity). The fourth term represents depth induced and current induced refraction, \( \theta \) being the wave direction. \( S \) on the right-hand side of (1) includes the source terms.

Some terms of equation (1) can be neglected (Carniello et al. 2005) by making two main justifiable assumptions, i.e.:

1) that the direction of wave propagation instantaneously adjusts to the wind direction, which implicitly neglects refraction. Indeed, it is almost impossible to correctly evaluate wave refraction in a very irregular domain with sharp and frequent discontinuities of the bottom, when using a comparably coarse grid.

Given the irregular bathymetry of the Venice lagoon and the uncertainties affecting the modeling of non-linear wave interactions (Lin et al. 2002), we set up the wind wave model on the basis of some justifiable assumptions which will be briefly discussed in the following. In particular, following a monochromatic approach, we assumed the wave period, characterizing the monochromatic wave reproduced by the model, to be constant in space and time. In the present contribution we discuss on the possibility of partially relaxing such an assumption, by considering a variable wave period which is assumed to be a function of water depth and wind speed (Young and Verhagen, 1996a).

We then present the results of some preliminary simulations carried out through the nearly improved wind-wave model, and compare such results with data collected at one station within the Venice lagoon. A set of conclusions closes the paper.
2) that a monochromatic wave, can be considered neglecting non linear wave-wave and wave-current interactions such that $\sigma$ is constant both in space and time. The monochromatic wave assumption allows us to neglect the fourth term in (1).

According to the above assumptions both the fourth and fifth term of the wave action conservation equation (1) can be neglected, thus obtaining:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} c_{gx} N + \frac{\partial}{\partial y} c_{gy} N = \frac{S}{\sigma}$$  \hspace{1cm} (2)

The wind wave model solves equation (2) and computes the significant wave height, $H$, on the basis of the linear theory. The term $S$ on the right hand side of equation (2) describes all the external physical phenomena contributing to wave energy. They can be either positive, e.g. wind energy input, or negative, e.g. bottom friction, whitecapping, and depth-induced breaking. For a complete description of the formulations implemented in the model to describe the various source terms, we refer the reader to Carniello et al. (2005).

The results obtained when assuming a constant wave period ($T=2$ s in Carniello et al., 2005) compared sufficiently well with the available data measured within the Venice lagoon. In particular it was evident the influence of water level on wave height and the strong coupling between wind waves and hydrodynamics.

Notwithstanding the close inspection of the field data and a sensitivity analysis of the effect induced by different values of the wave period, suggest that, in order to improve the wave field description, it is crucial to include the estimation of the wave period variation in the solution of the wave action conservation equation.

Spectral models, which solve the complete wave action conservation equation (1), explicitly include the description of the processes responsible for the spectrum modification in the frequency space (i.e. quadruplet wave-wave interaction and triad wave-wave interaction). The spectrum evolution associated with the wave propagation actually produces the spatial and temporal variation in the peak wave period.

Given the relatively poor performance of spectral models in shallow tidal basins (Lin et al., 2002), mainly due to the fairly limited approximations of the wave-wave interaction processes (e.g. Breugem and Holthuijsen, 2007), we maintain the monochromatic assumption in the solution of the wave action conservation equation (2) which allows for a noteworthy reduction of the computational effort. Notwithstanding the monochromatic approach does not strictly imply that the wave period is constant in space and time. Equation (2) expresses the conservation of the wave action $N$, i.e. the conservation of the wave energy $E$ over the relative wave frequency $\sigma$, whose solution does not require the a priori estimation of the wave period.

The evaluation of the wave period is obtained using the parameterized relationship suggested by Breugem and Holthuijsen (2007) which describes the correlation between wave period, local water depth and wind speed:

$$\tilde{T} = a \tilde{Y}^b$$  \hspace{1cm} (3)

Here $\tilde{T} = gT/\bar{U}_{\text{wind}}$ and $\tilde{Y} = gY/\bar{U}_{\text{wind}}^2$ are the dimensionless formulations for the peak period and the water depth, respectively, where $g$ is gravity, $\bar{U}_{\text{wind}}$ is the wind speed (measured at an elevation of 10 m above still water level), $T$ is the peak period and $Y$ is the water depth. The values of the two coefficients, suggested by the authors on the basis of their data analysis, are: $a = 5.0$ and $b = 0.375$.

The empirical relationship (3), based on the analysis of the wide set of observations of wave growth collected by Young and Verhagen (1996a,b), actually conceptualized the effect of the processes responsible for the spectrum modification in the frequency space.

The analysis of the data (wave period, tidal level, and wind speed and direction) collected at the 2BF stations (see Figure 1) from October 2002 to May 2003 confirms that the relationship between the dimensionless wave period $\tilde{T}$ and the dimensionless water depth $\tilde{Y}$ is actually well described by a power law. Notwithstanding the values of the coefficients $a$ and $b$ suggested by Breugem and Holthuijsen (2007) do not fit our data, in particular they produce an overestimation of the dimensionless wave period $\tilde{T}$.

The best fitting to our data is gained by assuming $a = 3.5$ and $b = 0.35$.

3 PRELIMINARY RESULTS AND DISCUSSION

All the simulations discussed in this section have been performed using a refined mesh reproducing the actual configuration of the Venice lagoon and a portion of the Adriatic sea in front of the three inlets. The mesh has been constructed on the basis of the most recent and accurate bathymetry of the lagoon provided by the Venice Water Authority.

The hydrodynamic model, briefly presented in the previous section, has been widely tested elsewhere (e.g. Defina, 2000; D’Alpaos & Defina, 2007).

Since the precise description of the instantaneous value of the local water depth is crucial to correctly predict the wave field in shallow waters, we report herein, as an example of the application, the results of the simulation of the period 2-5 March 2003, which was characterized by fine weather. Computed water levels at the Saline, Chioggia, and 2BF stations compare quite well with field data (Figure 2).
Let us now consider the preliminary results obtained through the wind-wave model. Available data at 2BF station consist of synchronous water levels, wave heights, wave periods, wind speeds and directions. All these data are given as averaged or significant values over a fifteen-minute period. Among all the data collected during the field campaign, lasted from October 2002 to May 2003, we selected two meteorological events characterized by Bora wind, the geomorphic dominant wind condition for the Venice lagoon. The two events refer to the following periods of time: i) 16-17 February 2003, characterized by a quite constant Bora wind of about 12 m/s; ii) 2-4 April 2003, characterized by Bora wind with speed up to 16 m/s.

The first comparison between computed values and measured data concentrates on the wave period. Although the coefficients of the relationship (3), used to estimate the wave period as a function of the local water depth and wind speed, were obtained by fitting the data collected at the same 2BF station, it is interesting to analyze the variation in time of the wave period, and in particular how wave-period values obtained on the basis of the power-law relationship (3) compare with observed ones. The results obtained forcing the numerical model with the wind speed and direction measured at the 2BF station (Figure 3 and Figure 4 - solid lines) show that the modulation of the wave period induced both by level oscillation and wind-speed variation compares quite well with measured data. In the same Figures we also report (Figure 3 and Figure 4 - dashed line) the value of the constant wave-period we should have assumed according to the previous version of the model (Carniello et al., 2005). Figure 3 and Figure 4 clearly show that the assumption of the value $T=1.7$ s (which is the average value over the whole available dataset) for the wave period leads to a quite rough approximation of such a parameter.

The wind speed measured at the 2BF station is shown in Figure 5a and Figure 6a. The analysis of synchronous wind speeds and measured wave heights (Figure 5b and Figure 6b) clearly highlights the almost instantaneous increase in wave height which follows an increase in the wind speed (e.g. 15 February 2003 10.00 PM). Moreover, when considering meteorological conditions characterized by quite constant wind speed (e.g. from 16 February 2003 9.00 AM to 17 February 2003 12.00 AM and 2 April 2003 7.00 PM to 4 April 2003 12.00 AM), the effect of the wave-height modulation related to tidal oscillation, clearly emerges.
Figure 5b and Figure 6b further show the comparison between measured and computed wave heights. The computed values of the wave height refer to the numerical simulation carried out by considering both the wave period as a function of the water depth and wind speed (solid line) and the constant wave period T=1.7 seconds (dashed line).

The results of the refined model which assumes the wave period as a function of the water depth and wind speed, show a fairly good agreement between measured and computed wave heights. Moreover, it clearly emerges that the modulation of the wave height, induced both by level oscillation and wind speed variation embedded in the variation of the wave period, is quite well reproduced by the model. As an example, please note the capability of the model in reproducing the sharp increase in wave height following the abrupt increase in the wind speed recorded on February 15 at about 10.00 PM.

The results obtained by assuming a constant wave period (T=1.7 s), show that in this case the model is not as well capable in reproducing wave heights which meet the observed ones. Moreover, it is very difficult to reproduce the modulation of wave heights induced by level oscillations and wind speed variations, which is a critical and necessary step when considering e.g. the morphological implications of wind-wave related processes. Obviously, a better result would have been obtained, with the model which considers a constant wave period, by considering, for each simulation, a different value for the constant wave period (e.g. Carniello et al., 2005), deduced by averaging the measured wave period on the basis of the data characterizing a specific event. Nevertheless such an approach highly reduces the predictive capability of the numerical model.

Figure 6. 2-4 April 2003. Measured wind speed at the 2BF Station (a). Comparison of measured (circles) and computed wave height at the 2BF station (b). The wave height is computed considering both the wave period as a function of the water depth and wind speed (solid line) and the constant wave period T=1.7 seconds (dashed line).

4 CONCLUSIONS

In this work a model proposed by Carniello et al. (2005) which describes the generation and propagation of wind waves in shallow micro-tidal basins is briefly presented and discussed, in order to improve the description of the wave field. The wave model is coupled with a hydrodynamic model that uses the same domain discretization, thus optimizing the transfer of data between the tidal and the wave components of the model.

The model by Carniello et al. (2005) assumes a monochromatic wave characterized by a wave period which is maintained constant during the computation. A close inspection of the field data highlighted the importance of including in the model the estimation of the wave period variation. Therefore we modify the monochromatic assumption used in Carniello et al. (2005) by considering that the local value of the wave period varies as a function of local parameters.

The major conclusions of this study are listed below:

i) The power law relationship suggested by Breugem and Holthuijsen (2007), which describes the correlation between wave period, local water depth and wind speed actually applies also to the data collected in the Venice lagoon. Notwithstanding the best fitting to our data is obtained assuming different values of the coefficients included in the power law with respect to those suggested by
Breugem and Holthuijsen (2007). This emphasizes that such coefficients might be site dependent.

ii) The numerical results show that the modulation of the wave period induced both by level oscillation and wind speed variation is quite well reproduced by the model using the power law relationship, and compares very well with measured data.

iii) The improvement obtained in the description of the wave height including the power law in the model is quite evident. The agreement between measured data and computed values is very good and the modulation of the wave height induced both by level oscillation and wind speed variation is well reproduced by the model. On the basis of these preliminary results the analysis will be extended considering different meteorological condition and, possibly, data collected at different stations.

iv) Given the crucial role of wind waves on sediment resuspension on tidal flats, the improvement obtained in the modeling of the wave field will reflect positively on the description of the morphological evolution of shallow micro-tidal basins.

REFERENCES


