WIND WAVES IN SHALLOW MICROTIDAL BASINS AND THE TRANSITION FROM TIDAL FLATS TO SALT MARSHES

Sergio Fagherazzi(1), Luca Carniello, Andrea Defina, Luigi D’Alpaos(2)

(1) Department of Earth Sciences and Center for Computational Science, Boston University. 675 Commonwealth Avenue, 02215 Boston MA e-mail: sergio@bu.edu
(2) Department of Engineering IMAGE, University of Padua, Via Loredan 20, 35131 Padua, Italy

ABSTRACT

Shallow microtidal basins are characterized by extensive areas of tidal flats and salt marshes that lie within specific ranges of elevation. Both landforms are inherently flat and their evolution strongly depends on the balance between sedimentary and erosive processes. Here we present a stochastic point model for tidal flat evolution to study the transition from tidal flats to salt marshes. The model accounts for sediment deposition, tidal oscillations, and sediment resuspension by wind waves. The case study to which the model is applied is the Venice lagoon, Italy.

Model results show that the transition from tidal flats to salt marshes occurs abruptly when the deposition rate reaches a critical value related to the local wind climate. The equilibrium elevation of tidal flats depends on the relationship between shear stress caused by wind waves and depth. It is found that wind wave shear stresses peak for a specific water depth which is a function of the local wind and wave climate. Above this critical depth tidal flats are unstable, since an increase in elevation reduces wave height and therefore erosion, preventing the system from recovering equilibrium conditions. The variability of tidal flat elevation is finally related to deposition rates, tidal oscillations, and wind and waves characteristics.

Keywords: wind waves, tidal flats, salt marshes, sediment transport

1 INTRODUCTION

Typical conceptual and numerical models of marsh formation envision a gradual transformation of sandflats and mudflats in response to sediment build-up and plant colonization [Beeftink 1966; French and Stoddart 1992; Fagherazzi and Furbish 2001]. However, the evidence points to abrupt transitions to one of two distinct stable outcomes. Salt marshes emerge from tidal flats in locations where sedimentation is enhanced by lower tidal velocities, by higher sediment concentrations, or by the sheltering effects of splits and barrier islands [Allen 2000; Dijkema 1987]. Alternatively, in areas with consistent sediment resuspension caused by a combination of tidal fluxes and wind waves, tidal flats are dominant. In tidal flats sediment deposition is balanced by erosion, and the bottom elevation is constantly maintained below mean sea level [Allen and Duffy 1998]. Sediment resuspension by wind waves is decisive, since tidal fluxes alone are unable to produce the bottom shear stresses necessary to mobilize tidal flat sediments [Carniello et al. 2005].

Following the Fagherazzi et al. [2006] conceptual model, for a prescribed, geomorphically significant, wind intensity we can plot the total shear stress (sum of the waves and tidal currents shear stresses) as a function of tidal flat elevation in a microtidal basin. The bottom shear stress, after reaching a maximum, decreases in shallow water where dissipative processes (bottom friction, wave breaking, and whitecapping) limit the maximum height of the wind waves (Figure 1). This maximum of shear stress bears important consequences for the morphological transition from tidal flats to saltmarshes and for the overall redistribution of sediments in shallow coastal basins.
Fagherazzi et al. [2006] assume an average annual sedimentation rate that is site-dependent, but constant during bottom evolution and suppose that the sediment resuspended on tidal flats during a storm is directly proportional to the difference between bottom shear stress and the critical shear stress for sediment erosion.

Figure 1 Morphological evolution of tidal flats as a function of bottom shear stresses produced by wind waves. The trajectories are based on the assumption of constant annual deposition and specified wind speed and duration. Trajectory of bottom elevation for a point starting in the stable branch of the curve: a) deposition lower than peak erosion; b) deposition higher than peak erosion. Trajectory of bottom elevation for a point starting in the unstable branch of the curve: c) deposition lower than erosion; d) deposition higher than erosion. The shear stress curve has been calculated for a characteristic wind speed of 8 m/s and assuming an average tidal current velocity of 0.16 m/s, the typical value for tidal flats in the Venice lagoon, Italy.

We begin our analysis from a tidal flat with an elevation below mean sea level. At the initial stages of the evolution the water depth is so high that the wave-induced bottom shear stress is smaller than the critical shear stress for erosion, so that the bottom elevation increases in time due to deposition (Fig. 1a, right side). At a certain point the bottom elevation is high enough so that the waves start resuspending bottom sediments. Following this transition we subtract the average annual erosion from the average annual deposition (see Fig. 1a) at every time step. Since the erosion rate is proportional to the difference between shear stress and the critical shear stress, then the average annual erosion is proportional to the distance between the solid line (wave shear stress) and the dotted line (critical shear stress) in Fig. 1a. If the annual deposition is smaller than the maximum erosion, the tidal flat inevitably evolves to a position on the curve in Fig. 1a where the average annual deposition balances the average annual erosion, and the bottom elevation is in dynamic equilibrium (bold square in Fig. 1a). We refer to the branch of the curve from the peak to the right as morphologically stable, since deposition is counteracted by an increase in erosion due to higher shear stresses at the bottom.
In this part of the curve the tidal flat adjusts its elevation to a position of dynamic equilibrium that depends on deposition rate and wave erosion.

If the annual deposition is greater than the maximum erosion, then the vertical accretion of the tidal flat passes the peak and any further increase in elevation leads to smaller bottom shear stresses. Less erosion produces a marked increase in elevation, in a self-reinforced process that eventually gives form to an emergent salt marsh (see Fig. 1b). Once the elevation becomes higher than mean-sea level the accretion dynamics is marginally affected by waves. The only factors that determine the final marsh elevation are sediment supply, organic production driven by vegetation encroachment, and sediment compaction. The marsh is stable up to large fluctuations in relative sea level and storm intensity, so that it can be considered a resting point of our dynamics.

The left branch of the curve is morphologically unstable, because an increase in deposition beyond the maximum induces a fast vertical accretion. All the elevations lower than the peak are unlikely to maintain a stable tidal flat, since the processes at play tend to fill up the area and create a salt marsh. The unstable character of the left branch is even more evident if we consider as initial condition a point on this part of the curve (Fig. 1c and 1d). The initial configuration could persist only if the local deposition rate exactly balances the erosion rate, otherwise the bottom elevation will evolve toward either a stable tidal flat, if the annual deposition rate is smaller than the local erosion rate (Fig. 1c), or emergent salt marsh, if the annual deposition rate is higher than the erosion rate (Fig. 1d).

This simplified conceptual model needs to be expanded to account for different wind intensities and durations, and for the modulation effect of the tides that, by changing current velocities and water depth, has a significant impact on the long-term evolution of tidal flats. This full analysis will be performed herein with a stochastic point model of tidal flat evolution.

2 POINT MODEL OF TIDAL FLAT BOTTOM EVOLUTION

We develop a stochastic point model for tidal flat evolution and apply it to the Venice lagoon, Italy, which is a microtidal basin (tidal range of 0.7m) that have experienced large sediment loss during the last century [Fagherazzi et al. 1999, Rinaldo et al. 1999a, 1999b; Marani et al., 2003; Fagherazzi et al., 2006]. In our approach we consider a point in a tidal flat and analyze its evolution in time by applying the mass balance [Exner, 1925] equation:

\[ \frac{d?_b}{dt} = D - E \]  

(1)

where \( ?_b \) is the sediment density assumed herein equal to 1800 Kg/m\(^3\) from field measurements of Amos et al. [2004], \( z_b \) is bottom elevation, \( D \) the deposition rate and \( E \) the erosion rate.

The deposition rate at each point in the basin depends on the local availability of suspended sediment, on the sediment input from rivers debouching near the tidal flats, on the net export of material to the ocean, and, more generally, on the characteristics of sediment transport in the nearshore area. Since the characterization of sediment deposition patterns is outside the scope of this analysis, we assume the deposition rate as an independent variable and we then study the effect of different deposition rates on the long-term evolution of tidal flat elevations.

In tidal flats the erosion of bottom sediments occurs by the combined effect of wind waves and tidal currents, which generate shear stresses that entrain bottom sediments in suspension. Entrainment occurs only for shear stresses exceeding a critical value \( \tau_{cr} \). Once the critical shear stress is reached, the sediment is eroded at a rate that is commonly set as a function of the difference between the actual and the critical shear stress [Sanford and Maa 2001; Parchure and Mehta, 1985]. Here we use the formulation already adopted in Cappucci...
et al. [2004] to simulate tidal flat erosion due to wind waves in the Venice lagoon [see also Fagherazzi and Furbish, 2001]:

\[
\frac{1}{2} \rho E \left( \frac{t_{\text{tot}}}{t_{\text{cr}}} \right)^{1.2} \frac{t_{\text{tot}}}{t_{\text{cr}}}
\]

(2)

where \( t_{\text{tot}} \) is the total shear stress due to currents and waves, \( t_{\text{cr}} \) is the critical shear stress for erosion, which for the Venice lagoon assumes a value of 0.7 Pa [Amos et al. 2004], and \( M \) is a constant of proportionality that we set equal to 4.12x10^{-4} kg/N/s after Sheng and Lick [1979].

3 TIDAL CURRENTS AND WIND WAVES BOTTOM SHEAR STRESSES

In microtidal environments the resuspension of bottom sediments in areas far from the inlets and the tidal channels is mostly due to wind waves during storm activity [Carniello et al., 2005]

However, oscillations of the water surface in the basin produce tidal fluxes that enhance bottom shear stresses, favoring sediment erosion and transport. Tidal currents are a function of the basin geometry, bathymetry, and the presence of nearby tidal channels. In general, the current velocity is negligible at high and low tide (slack water) and maximum in proximity of mean-sea level, when the variation in water elevation per unit time is maximum.

The total bottom shear stress used in (2) is a nonlinear combination of the wave shear stress and the tidal current shear stress [Soulsby, 1997]:

\[
\frac{1}{2} \rho u_{\text{max}} \cos(\theta) \sin(\phi) \left( \frac{t_{\text{wave}}}{t_{\text{curr}}} \right) \left( \frac{t_{\text{curr}}}{t_{\text{wave}}} \right)^{0.2}
\]

(3)

where \( t_{\text{wave}} \) is the shear stress produced by wind waves, and \( t_{\text{curr}} \) is the shear stress caused by tidal currents. In this paragraph we outline the procedure to obtain both values in time.

In a simplified framework we can express both tidal oscillations and fluxes as:

\[
? \sin(\omega t) \quad u \cos(\omega t)
\]

(4)

where \( ? \) is the water level, \( a \) is the amplitude of the tidal oscillation assumed to be of 0.35m in the Venice lagoon, \( \omega \) is tidal wave frequency, \( u_{\text{max}} \) is the maximum local tidal velocity. We assume a characteristic maximum velocity \( u_{\text{max}} = 0.16 \text{ m/s} \) typical of the tidal flats in the Venice lagoon [Cappucci et al., 2004].

The corresponding shear stress is:

\[
\frac{1}{2} C_f u^2
\]

(5)

where \( C_f \) is a friction coefficient assumed herein to be 0.01 from model calibration and \( ? \) is the water density.

Wind waves are instead generated by the transfer of energy from the wind to the water surface. Starting from a flat water surface, the wind generates waves that increase in height until the energy dissipation produced by different processes limits the wave growth. Whitecapping and depth induced breaking reduce the maximum wave height for a given water depth, while bottom friction further enhances wave decay by intense energy dissipation. An
equilibrium is reached when the energy generated by the wind action equals the total energy dissipated by bottom friction, whitecapping, and breaking. In this situation the sea is fully developed; that is when the height of the wave is the maximum possible for that particular bathymetry and wind speed. More importantly, this condition develops the highest bottom shear stresses, which ultimately lead to bottom sediment erosion. The equilibrium condition can be expressed as:

\[ E = E_{bf} + E_{wc} + E_b \]  

(6)

where \( E \) is the wave energy generated by the wind, \( E_{bf}, E_{wc}, \) and \( E_b \) are the energy dissipation due to bottom friction, whitecapping, and breaking respectively.

Following Booij et al. [1999] and Carniello et al. [2005] all these terms can be expressed as a function of wave energy, so that (6) becomes:

\[
\frac{2\sinh(2kh)}{m} \left[ \frac{2a}{H} \frac{Q}{\beta} \frac{H_{\text{max}}}{E} \right] - \frac{k}{\sinh(2kh)} \left[ E_{bf} + E_{wc} + E_b \right] = E
\]

(7)

where \( E \) is the wave energy, \( H, T, \) and \( k \) are the wave height, period and wave number respectively, \( h \) is the water depth, and the parameters \( a \) and \( \beta \) depend on the wind velocity \( U_w \). The values of all the other parameters utilized to solve (7) are reported in Carniello et al. [2005].

Equation (7) is iteratively solved to determine the wave height as a function of the wind speed and water depth at each location in the Venice Lagoon. Once the wave height is known we can derive the bottom shear stresses from the expressions:

\[ b \cdot \frac{1}{2} f_w \cdot u_m^2 \]

with \[ u_m = \frac{H}{T \sinh(2kh)} \]  

(8)

where \( f_w \) is a friction factor and \( u_m \) is the maximum horizontal orbital velocity at the bottom associated with the wave. \( u_m \) directly depends on wave height \( H \) and water depth \( h \) so that higher waves produce larger bottom shear stresses.

If on one hand bottom shear stresses produced by wind waves are limited in shallow waters due to dissipative processes, on the other they are also limited in very deep waters where the bottom is too far from the surface to be modified by wave oscillations. This explains the peak in bottom shear stress present in Fig. 1, and the bimodal distribution of elevations in tidal basins [Fagherazzi et al., 2006].

In the model the deposition rate is set a priori and kept constant during the simulation. However, as indicated by Krone [1962], high shear stresses and erosive conditions hinder deposition, so that deposition is active only for shear stresses less than a threshold that is indicated as 0.56 Pa in our model, according to the field results of Amos et al. [2004].

4 WIND INTENSITY AND DURATION

In order to simulate the evolution of tidal flat elevation in a basin we need to reproduce the wind characteristics (intensity, duration, and frequency) in time. To this end we use a Monte Carlo approach based on long term wind data for the Venice lagoon. To reproduce wind intensities we use 26 years of wind statistics in the Venice lagoon, whereas for the wind duration we use high resolution measurements collected every 15 min from October 2002 to March 2003. From the data we derive two probability distributions that are used in
Montecarlo simulations.

5 MODEL RESULTS

The temporal evolution of the tidal flat elevation is studied by simulating long-term wind conditions under different scenarios of sediment deposition.

The model simulation procedure consists of seven steps: a) a rate of sediment deposition in (1) is selected a priori; b) two values of wind intensity and duration are extracted from the probability distributions derived from the wind data; c) the tidal elevation and velocity are calculated for the duration of the wind every 30 minutes from (4); d) given the wind intensity and the water depth the wave height is computed from (6) and (7); e) given the wave height the bottom shear stresses are computed from (8); f) The wave shear stresses and the tidal current shear stresses are combined to determine the total shear stress in (3) g) the erosion is calculated from (2) and the bottom elevation updated in (1).

Figure 2 Calculation of bottom shear stresses and elevation as a function of time. a) wind velocity as given by the Montecarlo model; b) tidal level; c) wave height; d) wave bottom shear stresses; e) tidal current velocity; f) bed shear stress due to tidal current; g) total shear stress; h) water depth with respect to mean sea level

An example of model results is presented in Figure 2. The temporal series of wind intensity produce waves of elevation up to 0.6m. Only wind speeds exceeding 3 m/s produce significant waves, and the tidal elevation has a marginal effect on modulating the wave height (but the tidal effect becomes important in shallow tidal flats). The wave shear stress is then added to the cyclic tidal current shear stresses (Fig. 2f) to produce the total shear stress (Fig. 2g) responsible for bottom erosion (Fig. 2h). Superimposition of tidal shear stress to wave shear stress appears to be crucial for bottom erosion. Short wind events of few hours produce erosion only when they occur during ebb or flood events, but are not effective during slack
Prolonged wind durations spanning at least half a tidal cycle are more effective in eroding the tidal flat bottom, since they are always combined to peak tidal discharges.

Figure 3 Tidal flat elevation as a function of time for different deposition rates. All simulations start from -1.5 m below m.s.l. For deposition rates higher than $0.85 \times 10^{-4}$ kg/s/m² the tidal flat becomes a salt marsh.

Then, the temporal variation of bottom elevation for different deposition rates is studied. Starting with a tidal flat elevation of -1.5 m, we run the model with different deposition rates ranging from 0.4 to $1.0 \times 10^{-4}$ kg/m²/s (Figure 3).

By analyzing the simulations outcomes one can see that after an initial transient period the tidal flat reaches a dynamic equilibrium elevation at which the average erosion equals the deposition rate. The equilibrium elevation strongly depends on the deposition rate, as it was postulated in Fagherazzi et al. [2006]. For increasing deposition rates the average tidal flat elevation increases, until the critical elevation (corresponding to the peak in Figure 1) is reached. Then, as expected, for higher deposition rates the tidal flat becomes a salt marsh.

By plotting the equilibrium elevation of the tidal flat as a function of the deposition rate it is possible to note that the elevation at first slowly increases and then rapidly approaches the critical point (Fig. 4). Near the transition between tidal flats and salt marshes the oscillation in bottom elevation are greater, since erosion is magnified by large wave heights (we are near the peak in shear stress of Fig. 1). The transition from tidal flat to salt marsh is not deterministically defined, but depends on the statistical properties of the wind. Long periods of calm wind conditions can favor deposition and the transition from tidal flats to salt marshes, whereas an intense storm can transform an incipient salt marsh in a tidal flat, so that flats having an elevation around the peak in shear stress can reverse their evolution trend from salt marsh to tidal flat and vice versa. For example, Fig. 5 shows different elevation trajectories with the same deposition rate of $0.87 \times 10^{-4}$ kg/s/m² but a different sequence of storms. In two simulations the tidal flat evolves toward salt marshes, due to the reduced wind conditions, whereas in two simulations the tidal flat is maintained at an average elevation of -1.05m, probably following a period of intense storminess. It is important to stress that within this range of elevations the transition from salt marsh to tidal flat is less likely than the transition from tidal flat to salt marsh. In fact, given the high deposition rates, the accumulation of sediments is strong during low wind conditions, and unless a major storm hits the area during the transition period the tidal flat inexorably becomes a salt marsh.
Figure 4 Tidal flat equilibrium elevation as a function of deposition rate. Elevations above -1m become unstable and are transformed in salt marshes. The standard deviation of the equilibrium elevation is also indicated.

It is worth noting that for depths close to the critical one bottom elevations experience large oscillations in time, since wind waves produce the highest shear stresses. Under these conditions the system is highly dynamic, with each storm having a strong impact on the tidal flat elevation. Our model results clearly indicate that tidal flats experiencing strong variations in elevation in time are near critical conditions, and they can easily evolve into a salt marsh in few years. These results are confirmed in Fig. 4, showing the dynamic equilibrium elevation as well as its variance as a function of deposition rate. The variance was extracted from a time period of 10 years once the equilibrium elevation was reached.

Figure 5 Tidal flat elevation as a function of time for a deposition rate of $0.87 \times 10^{-4}$ kg/s/m². The different trajectories only depend on the random succession of storms.

The equilibrium elevation grows with the deposition rate, until it reaches the critical elevation. For higher depositions the tidal flat becomes a salt marsh. The variance increases with the deposition rate, being maximum just before the critical elevation (Fig. 4).

The curve in Figure 1 was derived by Fagherazzi et al. [2006] with only one, geomorphologically significant, wind intensity, whereas in natural conditions tidal flats are subject to a series of wind events of different intensity and duration. This notwithstanding, it
is remarkable how the critical depth that separates the stable from the unstable component in
Fig. 7 is very close to the value of 1m, as derived by Fagherazzi et al. [2006].

6 CONCLUSIONS

Simulations of tidal flat evolution carried out with a simple stochastic model for wind
waves resuspension show that the transition from tidal flats to salt marshes is not a continuous
process, but occurs abruptly when the deposition rate reaches a critical value related to the
local wind climate.

Given a specific deposition rate below the critical value, wind driven sediment
resuspension maintains the tidal flat below mean sea level. The equilibrium elevation depends
on the relationship between shear stress caused by wind waves and depth. It is found that
wind wave shear stresses peak for a specific water depth which is a function of the local wind
and wave climate. Above this depth tidal flats are unstable, since an increase in elevation
reduces wave height and therefore erosion, preventing the system from recovering
equilibrium conditions.

Tidal flats having an equilibrium elevation close to the peak in shear stress have depths
that vary in time, since each storm has a high impact on bottom sediments. Therefore a high
variability in tidal flat elevation in time is a possible signal of instability and incipient
transformation to salt marsh.

All these results are limited to meso- and microtidal flats, where the chief geomorphic
agent for sediment resuspension is wind driven waves. In areas where the tidal excursion is
high, tidal fluxes and their spatial variability shape the landscape and dictate the transition
between tidal flats and salt marshes.

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